Nuclear Energy

Supply Chain Deep Dive Assessment

U.S. Department of Energy Response to Executive Order 14017, "America's Supply Chains"

February 24, 2022

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About the Supply Chain Review for the Energy Sector Industrial Base

The report "America's Strategy to Secure the Supply Chain for a Robust Clean Energy Transition" lays out the challenges and opportunities faced by the United States in the energy supply chain as well as the federal government plans to address these challenges and opportunities. It is accompanied by several issue-specific deep dive assessments, including this one, in response to Executive Order 14017 "America's Supply Chains," which directs the Secretary of Energy to submit a report on supply chains for the energy sector industrial base. The Executive Order is helping the federal government to build more secure and diverse U.S. supply chains, including energy supply chains.

To combat the climate crisis and avoid the most severe impacts of climate change, the U.S. is committed to achieving a 50 to 52 percent reduction from 2005 levels in economy-wide net greenhouse gas pollution by 2030, creating a carbon pollution-free power sector by 2035, and achieving net zero emissions economy-wide by no later than 2050. The U.S. Department of Energy (DOE) recognizes that a secure, resilient supply chain will be critical in harnessing emissions outcomes and capturing the economic opportunity inherent in the energy sector transition. Potential vulnerabilities and risks to the energy sector industrial base must be addressed throughout every stage of this transition.

The DOE energy supply chain strategy report summarizes the key elements of the energy supply chain as well as the strategies the U.S. government is starting to employ to address them. Additionally, it describes recommendations for Congressional action. DOE has identified technologies and crosscutting topics for analysis in the one-year time frame set by the Executive Order. Along with the policy strategy report, DOE is releasing 11 deep dive assessment documents, including this one, covering the following technology sectors:

- Carbon capture materials,
- Electric grid including transformers and high voltage direct current (HVDC),
- Energy storage,
- Fuel cells and electrolyzers,
- Hydropower including pumped storage hydropower (PSH),
- Neodymium magnets,
- Nuclear energy,
- Platinum group metals and other catalysts,
- Semiconductors,
- Solar photovoltaics (PV), and
- Wind.

DOE is also releasing two deep dive assessments on the following crosscutting topics:

- Commercialization and competitiveness, and
- Cybersecurity and digital components.

More information can be found at www.energy.gov/policy/supplychains.

Acknowledgements

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Authors
Finan, Ashley, Director, NRIC
Foss, Andrew, Technical Program Lead, INL
Goff, Michael, Senior Advisor, DOE-NE
King, Christine, Director, GAIN
Lohse, Christopher, Innovation and Technology Manager, GAIN

Contributors
Cairns-Gallimore, Dirk, Nuclear Engineer, DOE-NE
Caponiti, Alice, Deputy Assistant Secretary for Reactor Fleet and Advanced Reactor Deployment, DOE-NE
Carmack, Jon, Senior Advisor, DOE-NE
Griffith, Andrew, Deputy Assistant Secretary for Nuclear Fuel Cycle and Supply Chain, DOE-NE
Golub, Sal, Associate Deputy Assistant Secretary for Nuclear Fuel Cycle and Supply Chain, DOE-NE
Huff, Kathryn, Senior Advisor for Nuclear Energy, DOE Office of the Secretary

Reviewers
Bragg-Sitton, Shannon, National Technical Director, DOE-NE Integrated Energy Systems, and Director, Integrated Energy and Storage Systems Division, INL
Byman, Raymond, Life Cycle Logistics Manager, U.S. Department of Defense
Crosland, Martha, Deputy Assistant General Counsel, DOE Office of the General Counsel
Cunliff, Colin, Physical Scientist, DOE Office of Policy
Dixon, Brent, Deputy National Technical Director, DOE-NE Systems Analysis and Integration Campaign, INL
Eddins, Janelle, Lead, Advanced Reactor Development, DOE-NE
Forbes, Stewart, Attorney-Advisor, DOE Office of the General Counsel
Gabriel, Brian, Industrial Analyst, U.S. Department of Defense Office of the Under Secretary of Defense, Acquisition and Sustainment
Gehin, Jess, Associate Laboratory Director, Nuclear Science & Engineering Directorate, INL
Grace-Tardy, Ami, Assistant General Counsel for Legislation, Regulation, and Energy Efficiency, DOE Office of the General Counsel
Hahn, Alison, Director for Nuclear Reactor Deployment, DOE-NE
Henderson, David, Program Manager, Advanced Modeling & Simulation, DOE-NE
Igogo, Tsisilile, Lead Coordinator, DOE Office of Policy
Jarrell, Josh, Manager, Used Fuel Management Department, INL
Kim, Michael, U.S. Office of Management and Budget
Lientz, Amy, Director, Supply Chain – Energy Industry, INL
McRae, Ben, Assistant General Counsel, DOE Office of the General Counsel
Petry, Kim, Acting Deputy Assistant Secretary for Spent Fuel and Waste Disposition, DOE-NE

Regalbuto, Monica, Lead, Integrated Fuel Cycle Solutions Initiative, INL
Rice, Savannah, Science, Technology, and Policy Fellow, DOE Office of Fossil Energy and Carbon Management, Division of Minerals Sustainability
Stalcup, Travis, Program Examiner, U.S. Office of Management and Budget
Taiwo, Temitope, National Technical Director, DOE-NE Systems Analysis and Integration Campaign, and Director, Nuclear Science and Engineering Division, Argonne National Laboratory
Tarter, J.B., Attorney-Advisor, DOE Office of the General Counsel
Ünel, Burçin, Senior Fellow, DOE Office of Policy
Veeder, Christy, Senior Advisor, Office of Energy Jobs, DOE Office of Policy

List of Acronyms

ARDP	Advanced Reactor Demonstration Program
ASME	American Society of Mechanical Engineers
BWR	Boiling Water Reactor
CINTAC	Civil Nuclear Trade Advisory Committee
CSC	Convention on Supplemental Compensation for Nuclear Damage
DOE	U.S. Department of Energy
EEA	Emergency Energy Alert
ERCOT	Electric Reliability Council of Texas
GAIN	Gateway for Accelerated Innovation in Nuclear
GCAM	Global Change Assessment Model
FIRST	Foundational Infrastructure for Responsible Use of Small Modular Reactor Technology
HALEU	High-Assay Low-Enriched Uranium
INL	Idaho National Laboratory
ITA	International Trade Administration
ITC	Investment Tax Credit
LEU	Low-Enriched Uranium
LWR	Light Water Reactor
MTU	Metric Ton of Uranium
NE	Office of Nuclear Energy (U.S. Department of Energy)
NEIMA	Nuclear Energy Innovation and Modernization Act
NPP	Nuclear Power Plant
NQA	Nuclear Quality Assurance
NRIC	National Reactor Innovation Center
NRC	Nuclear Regulatory Commission
NWPA	Nuclear Waste Policy Act
OECD	Organisation for Economic Co-operation and Development
O&M	Operating and Maintenance
PTC	Production Tax Credit
PWR	Pressurized Water Reactor
SMR	Small Modular Reactor
SMR PPP	Small Modular Reactor Public-Private Program
TRISO	Tri-structural Isotropic
WIPP	Waste Isolation Pilot Plant

Executive Summary

The U.S. nuclear energy supply chain, which enables the largest source of clean power in the country and supports approximately half a million jobs, encompasses a wide range of activities from uranium extraction and enrichment to plant construction, operation, decommissioning, and waste management. The U.S. nuclear industry is poised to diversify further in coming years as advanced nuclear plants with different coolants, fuels, sizes, and delivery methods are developed, demonstrated, and deployed to provide low-carbon energy for broader applications. The U.S. nuclear industry engages in international trade, subject to stringent government policies and oversight, both through imports—particularly for uranium and some other input materials with low domestic production—and through exports. However, China, Russia, and other global competitors are now involved in significantly more nuclear projects around the world.

This report responds to Executive Order 14017 by describing the current and potential future roles for nuclear energy in the United States and abroad, the various segments of the nuclear energy supply chain, and the main risks facing the sector. Some issues, such as uranium imports, relate both to existing nuclear reactors and advanced reactors under development, while other issues, such as production of high-assay low-enriched uranium, relate primarily to plans for advanced reactors.

The strength of the nuclear supply chain is directly tied to the strength and growth of the nuclear energy sector. A strong and growing nuclear energy sector is needed for a strong supply chain. Therefore, the needs, risks, opportunities, and challenges discussed in this report extend beyond uranium and input material supply to address reactor license extensions, retirements due to low electricity prices and other factors, growth opportunities, global competition from state-owned enterprises, intergovernmental agreements, long-term nuclear waste policy, and other interrelated issues.

Over the longer term, many of the vulnerabilities and risks can be reduced through strong market signals and actions that increase demand for clean nuclear energy. Although existing nuclear infrastructure is operating efficiently and is continuing to reduce operating costs, several plants are facing increased competition due to the low price of natural gas, accelerated deployment of subsidized renewable energy, and the structure of the electricity markets that generally does not reward clean electricity produced by nuclear power.

Find the policy strategies to address the vulnerabilities and opportunities covered in this deep dive assessment, as well as assessments on other energy topics, in the Department of Energy 1-year supply chain report: "America's Strategy to Secure the Supply Chain for a Robust Clean Energy Transition."

For more information, visit www.energy.gov/policy/supplychains.

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1 Introduction

Nuclear power plants (NPPs) produce 20 percent of the total electricity supply in the United States today and are the largest source of carbon-free energy.[1] The current fleet comprises 93 reactors, and most are licensed to operate for 60 years. Six reactors have recently extended their operating licenses another 20 years to 80 total years of operation, and approximately 19 other reactors are pursuing similar extensions. Nuclear energy use in the United States has both near- and long-term implications for U.S. decarbonization goals through continued operation of existing nuclear power capacity, addition of advanced reactors for the power sector, and potential applications of nuclear technologies beyond the power sector, such as heat and synthetic fuel production. Numerous net-zero models illustrate the wide range of future energy supply that could be expected for nuclear, depending on the costs of nuclear technologies, the costs of other energy options, and government policies, such as production tax credits (PTCs), investment tax credits (ITCs), clean energy standards, and carbon taxes. Modeling results for the contribution of nuclear in the power sector vary from approximately 10 percent to 70 percent. *The Long-Term Strategy of the United States: Pathways to Net-Zero Greenhouse Gas Emissions by 2050* includes scenarios with substantial increases in U.S. nuclear capacity and electricity generation.[2]

Two recent studies show how license extensions for current U.S. NPPs and innovation in nuclear are key to lowering the costs of achieving decarbonization goals. Kim et al. (2021) study estimates a cost savings of $330 billion from the contribution of the first 20-year license extension from 40 to 60 years (which has already been approved for 85 percent of today's fleet). Further extending the fleet to 80 or 100 years would yield even larger cost savings. This study also shows that the combination of license extensions for existing nuclear plants and construction of additional units would further increase the cost savings by several hundred billion dollars. The Decarb America (2021) study focuses in particular on breakthroughs in advanced nuclear technologies that could spur additional deployment.[3] The modeling reveals that with nuclear innovation, decarbonization can be achieved at the second-lowest cost impact across the various scenarios. Savings in the nuclear innovation scenario come from reduced spending on the electricity grid and on renewables compared to the other scenarios. When all technologies achieve cost effective innovation, nuclear would provide 40 percent of power generation.

With this background on the potential contributions from nuclear energy for meeting national decarbonization goals in a cost-effective manner, the remainder of this report describes the nuclear energy supply chain and investigates challenges for continued operation of today's fleet and construction of advanced reactors. To successfully extend the existing domestic fleet of light water reactors underscores the importance of maintaining and improving this supply chain. New deployments for advanced nuclear technologies will require establishing new areas of supply chain and scaling those capabilities. Therefore, the supply chain represented here is a snapshot of existing and advanced nuclear in a time of significant innovation and change. As such, it is important to revisit this analysis in the future to ensure vulnerabilities are proactively identified and addressed.

Direct employment at U.S. nuclear power plants is approximately 70,000 workers at an average wage of $39/hour, which is double the national median wage.[4] Inclusion of secondary jobs supported by the U.S.

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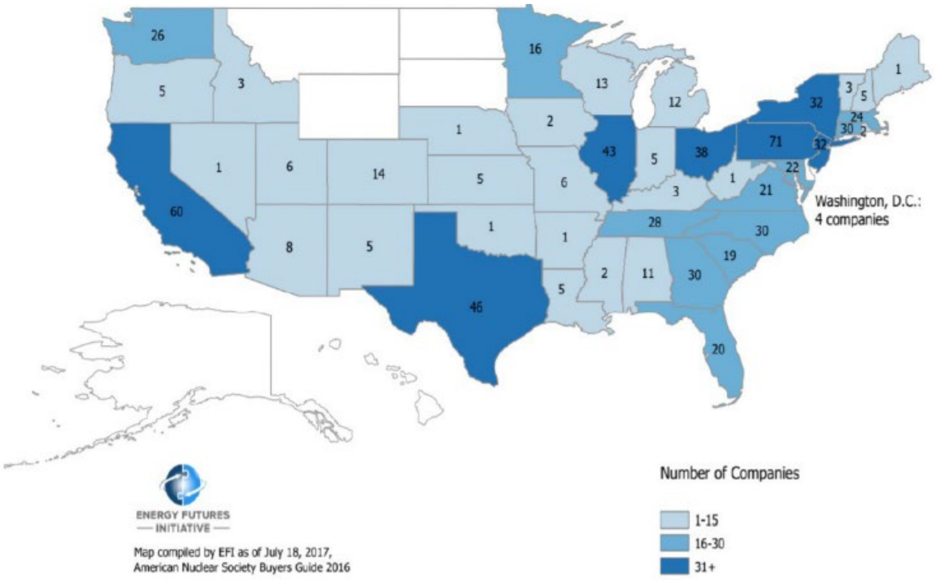
[1] U.S. Energy Information Administration (2021), *Monthly Energy Review*, December, Table 7.2a Electricity Net Generation: Total (All Sectors) (link).

[2] U.S. Department of State and Executive Office of the President (2021), *The Long-Term Strategy of the United States: Pathways to Net-Zero Greenhouse Gas Emissions by 2050*, November, pp. 26 and 29 (link).

[3] Nicholas Montoni, Ph.D., Rachel Smith, Lindsey Walter, Marika Tatsutani, Lesley Jantarasami, and Conrad Schneider (2021), *Clean Energy Innovation Breakthroughs*, Decarb America Research Initiative, October 19 (link).

[4] Energy Futures Initiative (2021), *Wages, Benefits, and Change*, April, p. 9 (link); the Nuclear Energy Institute expresses direct employment as "nearly 100,000 people" (link), which may represent staffing before recent plant retirements and any staff reductions that may also have occurred at active plants.

nuclear industry raises total employment to 475,000 workers.[5] Nuclear energy provides more local permanent jobs, and at higher average wage, than other energy sources. The industry's annual output value as measured by electricity sales is approximately $40 billion. Through economic multiplier effects, each dollar of spending by nuclear plant operators creates an additional $1.04 in the local economy and $1.87 nationwide.[6] The industry contributes $12 billion annually to federal and state taxes.[7] In addition to nuclear plant construction and operation workers, the industry supports employment and economic activity at a wide array of supplier companies. The U.S. Nuclear Industry Council has over 80 member organizations (primarily vendors), and the Nuclear Energy Institute has over 300 (including utilities, universities, and other categories of organization in addition to vendors).[8] Figure 1 shows the number of companies in the nuclear supply chain by state; the national total is more than 700 companies.



Map compiled by EFI as of July 18, 2017,
American Nuclear Society Buyers Guide 2016

Figure 1. Number of Nuclear Supply Chain Companies by State[9]

This report builds on previous assessments of critical materials and supply chain issues by the Department of Energy (DOE) and other organizations, especially the DOE critical minerals studies from 2011 and January 2021, nuclear supply chain evaluations by MPR Associates for DOE in 2005 and 2018, analyses by the national laboratories, U.S. Geological Survey, Congressional Research Service, International Energy Agency, and other sources cited throughout this report. Input was also provided through direct stakeholder feedback during the preparation of this report. The DOE assessment of critical minerals from January 2021 contains the following summary regarding nuclear energy.

> The Office of Nuclear Energy [NE] is focused on the development and demonstration of advanced reactor designs that will rely on a variety of critical minerals and materials, such as helium coolants, graphite structures and moderators, advanced moderators using zirconium and yttrium hydrides, and molten salt coolants using beryllium and lithium. Many critical minerals and materials are also essential for continued operation of the

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[5] Brattle Group (2015), *The Nuclear Industry's Contribution to the U.S. Economy*, report by Mark Berkman and Dean Murphy, July 7 (link); this economic impact analysis was prepared before recent nuclear plant closures.

[6] Nuclear Energy Institute (2012), *Nuclear Energy's Economic Benefits – Current and Future*, April (link).

[7] American Nuclear Society (2021), *The U.S. Nuclear R&D Imperative*, p. 2 (link).

[8] U.S. Nuclear Industry Council (2022), "USNIC Member Organization" (link); Nuclear Energy Institute (2022), *Member Roster*, October (link).

[9] Energy Futures Initiative (2017), *The U.S. Nuclear Energy Enterprise: A Key National Security Enabler*, p. 10 (link).

> existing nuclear fleet that supplies nearly 55 percent of our nation's carbon free energy. And because existing and advanced reactors rely on a predictable and stable supply of enriched uranium for fuel, NE is focused on the development of technologies to separate and recycle uranium, as well as supporting domestic uranium production, conversion, and enrichment. NE will survey the existing fleet and advanced reactor communities to determine a list of critical materials and quantities to inform an evaluation of the full supply chain, plans to conduct R&D [research and development] activities to reduce the lifecycle costs of uranium production, and looks to establish a national uranium reserve.[10]

The nuclear supply chain encompasses the full lifecycle of nuclear energy, from upstream activities, such as resource extraction, material manufacturing, component manufacturing, construction, and the fuel cycle, to plant operation and eventual dismantling, decommissioning, disposal, and potential recycling (Figure 2). This report focuses on policies and near-term actions to strengthen the U.S. nuclear energy supply chain. Longer-term issues, such as nuclear waste disposal and simultaneous decommissioning of many U.S. nuclear plants (potentially at much greater scale than currently), are discussed briefly in this report and could be assessed in more detail in future versions.

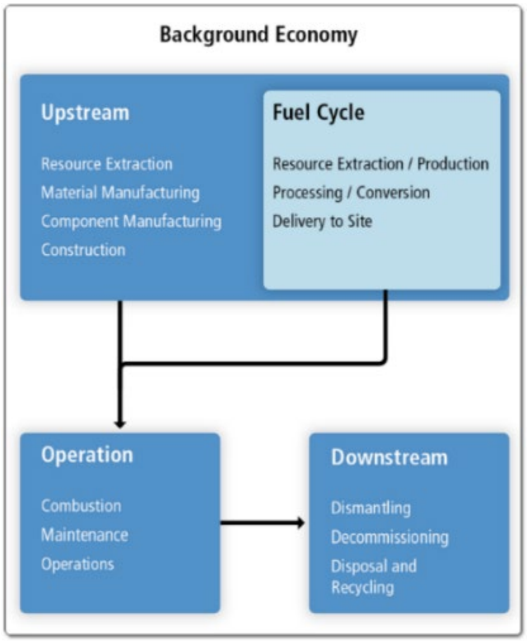

Figure 2. Generalized Life-Cycle Stages for Energy Technologies[11]

The DOE Office of Nuclear Energy issued its *Strategic Vision* in January 2021 with specific goals, objectives, performance indicators, and actions to achieve its mission of meeting U.S. energy, economic, and environmental needs. The following items provide an overview of the goals, along with selected objectives and performance indicators from the *Strategic Vision*.[12]

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[10] U.S. Department of Energy (2021), *Critical Minerals and Materials: U.S. Department of Energy's Strategy to Support Domestic Critical Mineral and Material Supply Chains (FY2021-FY2031)*, January, p. 5 (link).

[11] Emanuele Massetti, Marilyn A. Brown, Melissa Lapsa, Isha Sharma, James Bradbury, Colin Cunliff, and Yufei Li (2017), *Environmental Quality and the U.S. Power Sector: Air Quality, Water Quality, Land Use and Environmental Justice*, ORNL/SPR-2016/772, Oak Ridge National Laboratory, January 4 (link).

[12] U.S. Department of Energy (2021), *Office of Nuclear Energy: Strategic Vision*, January, p. 4 (link). Summaries in the numbered items include verbatim excerpts from the source as well as paraphrases. The internal organizational goal has been omitted from the list.

1. *Enable continued operation of existing U.S. nuclear reactors*. This goal relates to reducing costs and identifying potential sources of additional revenue to enhance financial viability. DOE will support demonstration of hydrogen production, accident tolerant fuels, and digital systems at existing nuclear plants.
2. *Enable deployment of advanced nuclear reactors*. DOE will enable the development of reactors that expand market opportunities for nuclear energy with a diversity of designs. Performance indicators include demonstration of a fueled microreactor core fabricated by advanced manufacturing techniques, a nuclear-renewable hybrid energy system, and at least two additional advanced reactor designs.
3. *Develop advanced nuclear fuel cycles*. The three objectives for this goal are to address gaps in the domestic nuclear fuel supply chain, address gaps in the domestic nuclear fuel cycle for advanced reactors and evaluate options to establish an integrated waste management system. Performance indicators include producing at least 5 tons of high-assay low-enriched uranium (HALEU) from non-defense DOE material.
4. *Maintain U.S. leadership in nuclear energy technology*. The three objectives for this goal are to facilitate global opportunities for the U.S. nuclear sector, maintain world-class research and development capabilities, and develop highly trained scientists to support the future nuclear workforce. Performance indicators include establishing coordination and assistance programs with nuclear newcomer countries and moving forward on the Versatile Test Reactor.

1.1 Nuclear in the Energy System and Industrial Base

1.1.1 Nuclear in Current U.S. Energy System

The United States is the world's largest producer of nuclear power. The United States began building commercial nuclear reactors in the 1960s. For the last 30 years, nuclear generation has supplied 20 percent of electricity in the United States with significantly higher capacity factors than other energy sources (the fleet-wide capacity factor exceeded 93 percent in 2019). The nuclear power industry has maintained this level of output for decades largely due to a robust nuclear supply chain. Since the mid-1970s, research, service providers, and innovation have enabled a 7.3 GW increase in capacity of the existing fleet — equivalent to 7 new reactors, (primary contributors: shorter refueling outages and power uprates). Currently, the United States has 93 operational reactors at 52 plant sites in 28 states.[13] Two units are under construction at Plant Vogtle in Georgia. The average age of today's fleet is 41 years including three reactors that started operation 52 years ago. Approximately 20 percent of the reactors are on single unit sites. The majority of the fleet is able to benefit from economies of scale and spread operating costs across multi-unit sites.

In the United States, nuclear power plants were initially licensed to operate for 40 years. Prior to reaching the end of their license, plant operators may apply for extensions for up to 40 years of additional operation. These license extensions are currently granted in two phases: license renewal from 40 to 60 years and subsequent license renewal from 60 to 80 years. License renewals represent the most inexpensive option for future electricity generation for the operator. At the end of a nuclear reactor's initial 40-year license, initial capital costs are likely to have been fully recovered and decommissioning costs are likely to be fully funded. The operating licenses for today's operating fleets are as follows: 8 reactors licensed for 40 years, 79 licensed for 60 years, and 6 licensed for 80 years. According to research conducted by the Electric Power Research Institute and DOE, there are no general technical issues that would impact the safe operation of a nuclear power plant during the subsequent license renewal period. As such, 9 reactors have active applications with the Nuclear Regulatory Commission and another 10 reactors have publicly announced plans to extend their

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[13] American Nuclear Society, *Nuclear News*, March 2021, pp. 82-83 (link).

licenses to 80 years. Figure 3 shows three different scenarios for retirement of today's fleet: 1) based on current license basis, 2) based on anticipated changes to current license basis, and 3) based on extending 54 reactors to 80-year licenses. The scenarios illustrate that under current license basis 92 percent of operating reactors would shut down by 2050 and 74 percent would shut down by 2050 with anticipated license renewals. However, if 54 reactors extended operation to 80 years, only 20 percent of operating reactors would shut down by 2050.

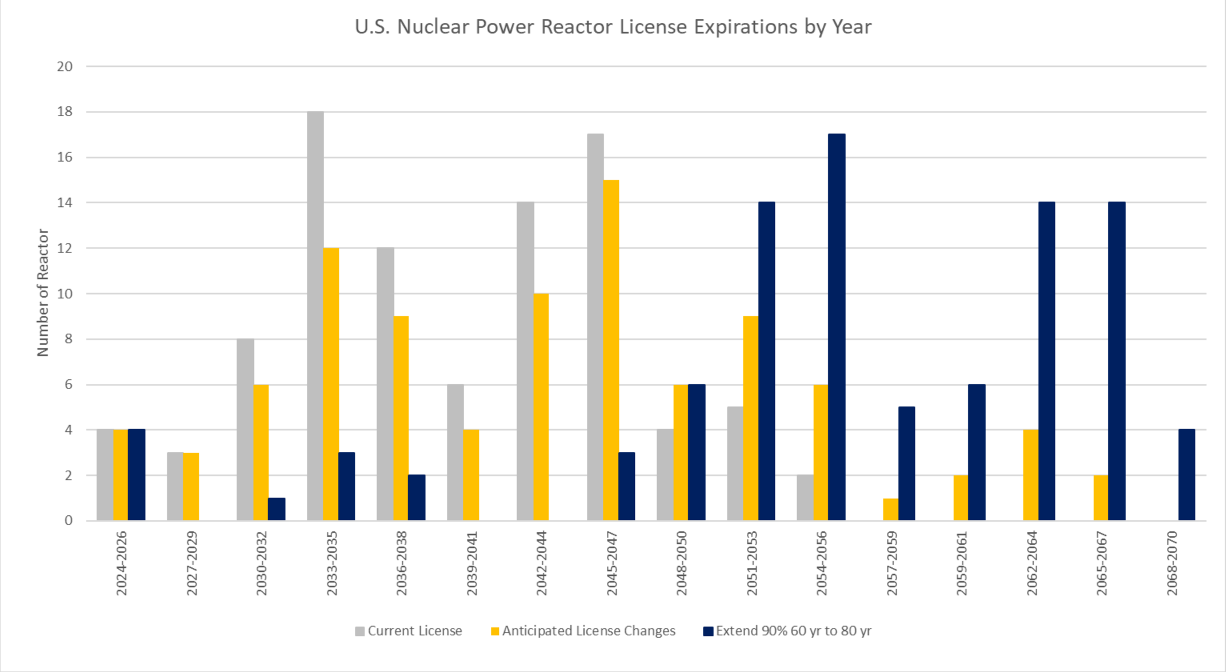

Figure 3: NPP License Expirations in 3-year Increments

1.1.2 Future Trajectories for Nuclear Energy

The civilian nuclear sector is poised to diversify in the coming years, as existing power plants continue to operate, and new advanced reactors may be added to the electric grid. One form of diversification is production of heat, hydrogen, synthetic liquid fuels, and other energy carriers for consumers beyond the electricity sector. Figure 4 shows that electricity generation accounts for only about one-third of total U.S. energy production (35.6 quadrillion Btu out of 92.9 quadrillion Btu in total in 2020). The large quantities of natural gas and petroleum consumed outside the electricity sector for buildings, manufacturing, and vehicles cause two-thirds of U.S. CO_2 emissions.[14] Nuclear energy can serve these needs for heat and fuel while lowering emissions (alongside future deployments of carbon capture and storage technologies to reduce the emissions intensity of fossil fuel use). Utilization of nuclear energy beyond the electricity sector has been studied by the DOE Crosscutting Technology Development Integrated Energy Systems program, the Electric Power Research Institute, the International Atomic Energy Agency, and others.[15]

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[14] U.S. Environmental Protection Agency (2021), *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2019*, April, p. ES-13 (link).

[15] Integrated Energy Systems (link); Electric Power Research Institute (2021), *Nuclear Beyond Electricity-Motivating and Valuing the Flexibility of Nuclear Energy Systems*, March 4 (link); Electric Power Research Institute (2021), *Nuclear Beyond Electricity-Landscape of Opportunities: Initial Survey and Near-Term Actions*, March 15 (link); International Atomic Energy Agency (2019), *Nuclear–Renewable Hybrid Energy Systems for Decarbonized Energy Production and Cogeneration*, IAEA-TECDOC-1885, October (link).

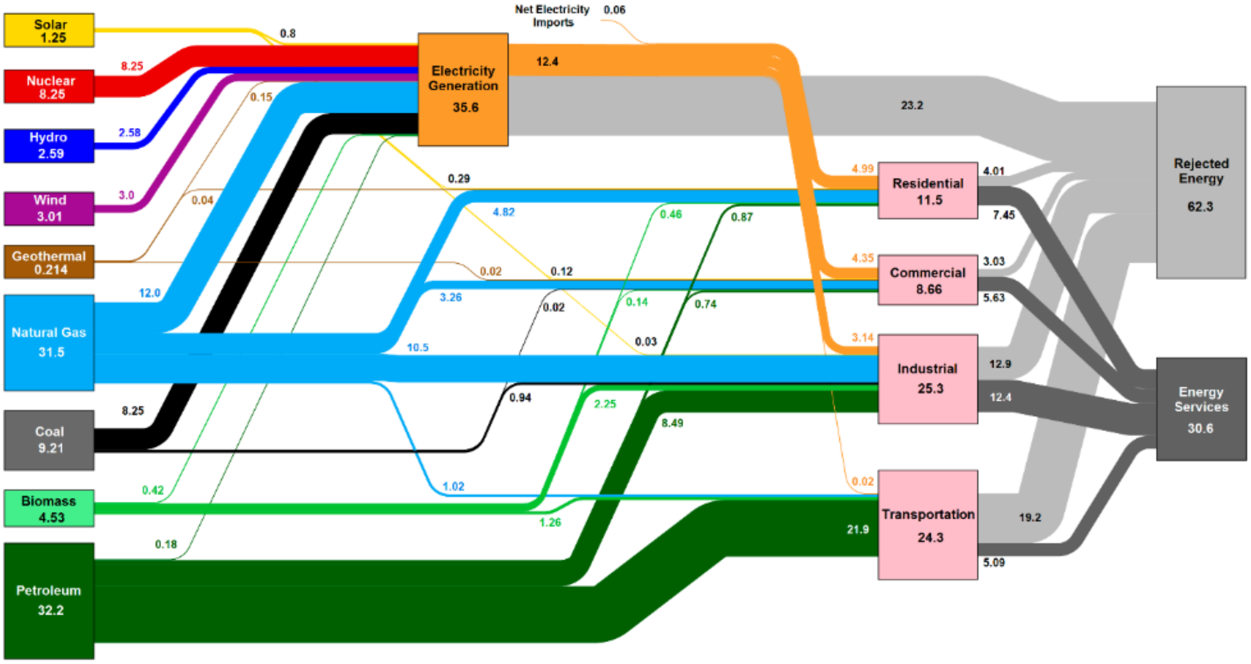

Figure 4. U.S. Energy Production and Consumption in 2020 in Quadrillion Btu (Quads) [16]

The second form of future diversification in nuclear energy is alternative sizes. The United States and other countries have chosen to build large reactors and multi-unit plants for connection to bulk electric grids to take advantage of economies of scale and multiples (lowering costs per kW of electricity production through efficiencies in plant siting, equipment purchases, project management, and accumulation of experience). Smaller reactors have several advantages, however, such as lower capital investment and operating cost, avoidance of "megaproject" complexities, innovative fabrication and delivery strategies, and alignment with smaller scales of energy demand off the bulk electric grid. DOE supports several programs for small modular reactors (less than 300 MWe) and microreactors (between 1 and 20 MWe).[17] Some forms of smaller reactors, such as the NuScale design, are similar to existing large reactors because they use light water as coolant and consume low-enriched uranium, whereas other forms rely on different coolants and nuclear fuels. Although the diseconomies of scale may lead to high costs for initial units ("first of a kind"), factory fabrication and other efficiencies from economies of multiples are expected to lower costs significantly for subsequent unit deployments, eventually leveling off at "N^th^ of a kind" costs below large reactors. Several studies by the national laboratories and others have identified cost reduction strategies to ensure the financial viability of new reactor deployments.[18]

The third form of future diversification, which overlaps with the two forms described above, is the use of different coolants and fuels. Some of these reactor designs rely on moderators, such as graphite, to slow neutrons for fission reactions in the thermal range of the neutron spectrum, whereas other designs have no moderators and perform fission with fast neutrons. Design and demonstration of alternatives to light-water reactors, which became the conventional approach to nuclear energy production in the United States and most

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[16] Lawrence Livermore National Laboratory (2021), Estimated U.S. Energy Consumption in 2020 (link).
[17] U.S. Department of Energy (2021), *Advanced Reactor Types* (link).
[18] Abdalla Abou Jaoude, Andrew Foss, Yasir Arafat, and Brent Dixon (2021), *An Economics-by-Design Approach Applied to a Heat Pipe Microreactor Concept*, INL/EXT-21-63067, Idaho National Laboratory, July (link); Nuclear Energy Agency, *Unlocking Reductions in the Construction Costs of Nuclear: A Practical Guide for Stakeholders*, 2020 (link); Jacopo Buongiorno et al. (2018), *The Future of Nuclear Energy in a Carbon-Constrained World*, MIT Interdisciplinary Study, September (link); Energy Innovation Reform Project (2017), *What Will Advanced Nuclear Reactors Cost?* (link).

of the world, began concurrently in the mid twentieth century. For example, the sodium-cooled Experimental Breeder Reactor I began operation at Idaho National Laboratory in 1951, followed by Experimental Breeder Reactor II in 1964. The Molten Salt Reactor Experiment was conducted at Oak Ridge National Laboratory in the 1960s, and the Fort St. Vrain high-temperature nuclear reactor began operation in 1972. These non-LWR designs, which are labeled advanced or Generation IV reactors, have inherent safety features and other advantages related to fuel and waste.[19] Adding these alternative reactor designs to the U.S. energy system will require HALEU and some different material inputs than LWRs, as discussed further in Sections III and IV. There are different types of advanced reactors and some of the types can have overlap (e.g., fast or thermal neutron spectrum). Figure 5 provides a general overview developed by the Nuclear Innovation Alliance of various reactor types. This figure is not an exhaustive list of all the advanced reactor variations but depicts many of the various options. Figure 6 shows large reactors, small reactors, and advanced reactors contributing heat and electricity in a potential future low-carbon energy system.

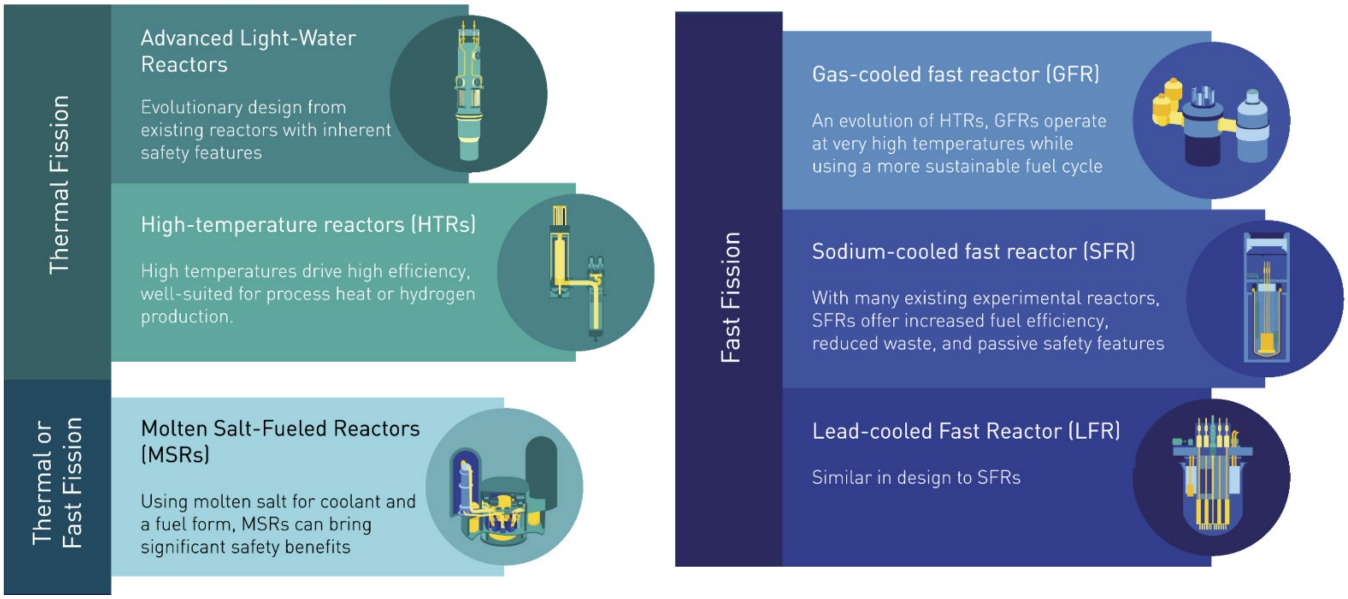

Figure 5. Example Varieties of Different Advanced Nuclear Reactors as Prepared by Nuclear Innovation Alliance[20]

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[19] Igor L. Pioro, editor (2016), *Handbook of Generation IV Nuclear Reactors*, Woodhead Publishing (link); Jacopo Buongiorno et al. (2018), *The Future of Nuclear Energy in a Carbon-Constrained World*, MIT Interdisciplinary Study, September (link); D. Petti, R. Hill, J. Gehin, et al. (2017), *Advanced Demonstration and Test Reactor Options Study*, INL/EXT-16-37867, Rev. 3, January, p. 64 (link).

[20] Nuclear Innovation Alliance (2021), *U.S. Advanced Nuclear Energy Strategy for Domestic Prosperity, Climate Protection, National Security, and Global Leadership*, February, p. 3 (link).

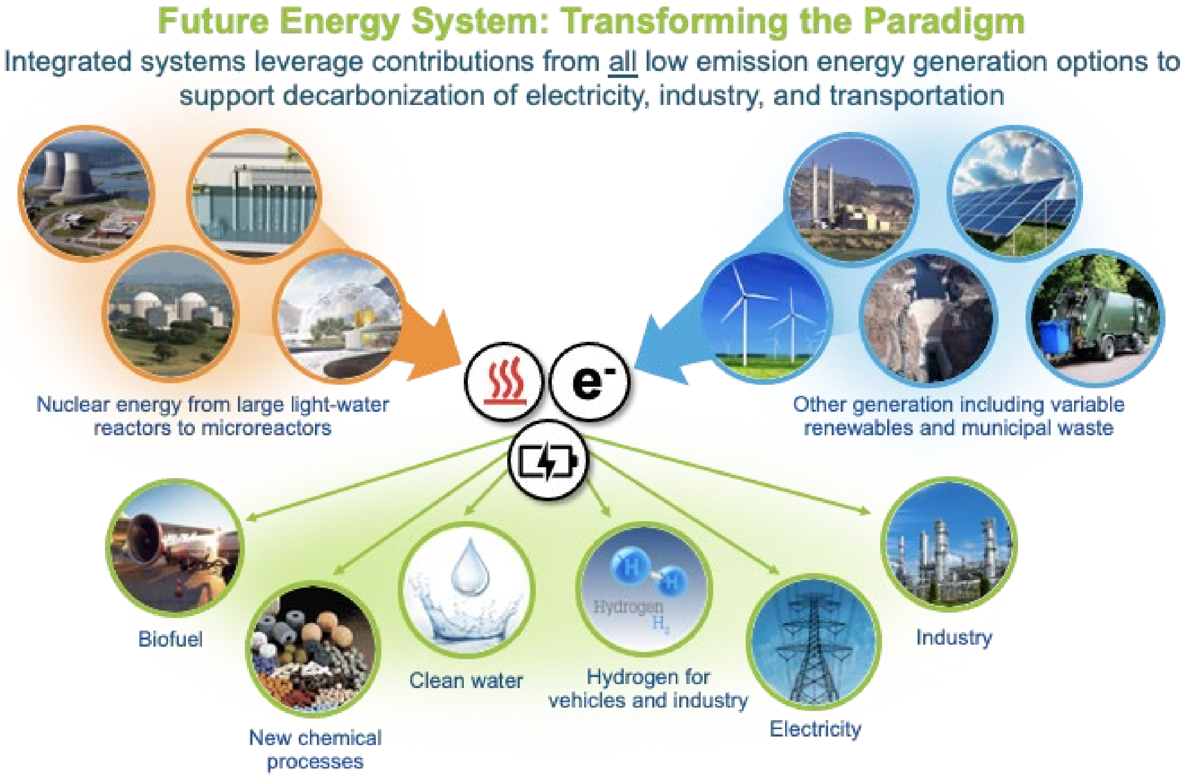

Figure 6. Nuclear Energy in Integrated Energy Systems[21]

Several dozen companies, National Laboratories, and universities are working on advanced nuclear reactors across the United States. Many of these organizations have received financial support from DOE for research collaborations with the National Laboratories through the Gateway for Accelerated Innovation in Nuclear (GAIN) program. Several are also participating in the Advanced Reactor Demonstration Program (ARDP). Profiles of these advanced nuclear developers have been prepared by Third Way, Nuclear Innovation Alliance, and others.[22]

1.2 Market Assessments for Nuclear Energy

1.2.1 U.S. and Global Projections

Projections for U.S. and global nuclear total installed capacity are presented in Table 1. The ranges represent multiple domestic and international models focused on U.S. 2030 Nationally Determined Contribution on a path to net-zero in 2050. *The Long-Term Strategy of the United States: Pathways to Net-Zero Greenhouse Gas Emissions by 2050* shows possible growth in U.S. nuclear capacity between 2030 and 2050 within the ranges shown in Table 1.[23] Most models agree that new nuclear plants are not widely deployed domestically on a large scale until after the mid-2030s, evidenced in the global predictions for 2050 shown in Table 1. As such,

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[21] Idaho National Laboratory, Oak Ridge National Laboratory, and Argonne National Laboratory (2022), "Integrated Energy Systems" (link).

[22] Third Way (2021), "Advanced Nuclear Industry: The Next Generation" (link); Nuclear Innovation Alliance (2021), *Advanced Nuclear Reactor Technology: A Primer*, September (link); Congressional Research Service (2019), *Advanced Nuclear Reactors: Technology Overview and Current Issues*, Report No. 45706, April 18 (link); Resources for the Future (2019), "Advanced Nuclear Reactors 101," explainer by Vincent Gonzales and Lauren Dunlap, March 26 (link); Columbia University Center on Global Energy Policy (2017), *A Comparison of Advanced Nuclear Technologies*, report by Andrew Kadak (link); Third Way (2015), *Introducing the Advanced Nuclear Industry*, June (link).

[23] The *Long-Term Strategy* included scenarios with "cumulative nuclear capacity additions ranging up to 90-100 GW through 2050." U.S. Department of State and Executive Office of the President (2021), *The Long-Term Strategy of the United States: Pathways to Net-Zero Greenhouse Gas Emissions by 2050*, November, p. 29 (link).

numerous expert recommendations encourage the innovation necessary to deploy advanced reactors and extend the existing fleet as much as possible.

Table 1. Projected U.S. and Global Nuclear Total Installed Capacity from Net-Zero Models

Year	U.S. Capacity [24] [25] [26] [27] [28]	Global Capacity [29]
2030	89 – 105 GW	515 GW
2035	76 – 111 GW	(not estimated)
2050	72 – 262 GW	812 GW

Nuclear energy's primary role in a net-zero future will be to provide the clean firm generating capacity necessary to an energy system with a significant amount of variable energy sources. Recent net-zero studies from Princeton University[30] estimated that the United States needs to maintain between 500 and 1,000 GW of firm generating capacity as it transitions to net zero greenhouse gas emissions and a 100 percent carbon-free electricity system. Today, the United States has about 950 gigawatts (GW) of firm generating capacity installed broken down as follows: natural gas (547 GW), coal (238 GW), and nuclear (101 GW). It will be necessary to scale up a range of sources of clean firm power to replace unabated natural gas and coal. Nuclear is one of several firm generation sources that can produce electricity with zero or near-zero emissions of greenhouse gases. Other options include coal or natural gas with carbon capture and sequestration, use of hydrogen or other zero-carbon fuels in combustion turbines or fuel cells, geothermal energy, and biomass power plants that capture and store carbon emissions.

Over the next decade, existing natural gas and nuclear reactors will be the firm resources that will ensure reliability as wind and solar power expand. By (1) phasing out coal-fired power plants; (2) maintaining existing nuclear and gas capacity; (3) reducing the total generation from natural gas power plants; and (4) increasing electricity generation from wind and solar power to roughly 50 percent of U.S. electricity, CO_2 emissions in the electricity sector can be reduced over the next decade by 70-80 percent. Reaching 100 percent carbon-free electricity in 2035 will require some combination of replacing existing fossil-fueled firm capacity with new clean firm capacity and retrofitting existing fossil capacity to capture carbon emissions or converting gas power plants to use zero-carbon fuels. New clean firm capacity will also be needed to replace any aging nuclear power plants that retire in coming years.

Considering different deployed cost scenarios for advanced nuclear in conjunction with a range of gas prices shows the sensitivity of these two parameters to the deployment of nuclear and thus the final share of generation mix in 2050, shown in Figure 7. With low gas prices, advanced nuclear is too expensive to be widely deployed. With high gas prices, by contrast, advanced nuclear is deployed at varying rates across the capital cost range.

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[24] Eric Larson et al. (2020), *Net-Zero America: Potential Pathways, Infrastructure, and Impacts*, Interim Report, Princeton University (link).

[25] James H. Williams et al. (2021), *Carbon-Neutral Pathways for the United States*, AGU Advances, 2, e2020AV000284 (link).

[26] The America's Pledge Initiative on Climate Change (2019), *Accelerating America's Pledge: Going All-in to Build a Prosperous, Low-Carbon Economy for the United States.* Published by Bloomberg Philanthropies with University of Maryland Center for Global Sustainability, Rocky Mountain Institute, and World Resources Institute. New York (link).

[27] U.S. Energy Information Administration (2021), *Annual Energy Outlook 2021*, Reference Case, Table 9: Electricity Generating Capacity (link).

[28] Nicholas Montoni, Ph.D., Rachel Smith, Lindsey Walter, Marika Tatsutani, Lesley Jantarasami, and Conrad Schneider (2021), *Clean Energy Innovation Breakthroughs*, Decarb America Research Initiative, October 19 (link).

[29] International Energy Agency (2021), *Net Zero by 2050: A Roadmap for the Global Energy Sector* (link).

[30] Eric Larson et al. (2020), *Net-Zero America: Potential Pathways, Infrastructure, and Impacts*, Interim Report, Princeton University (link).

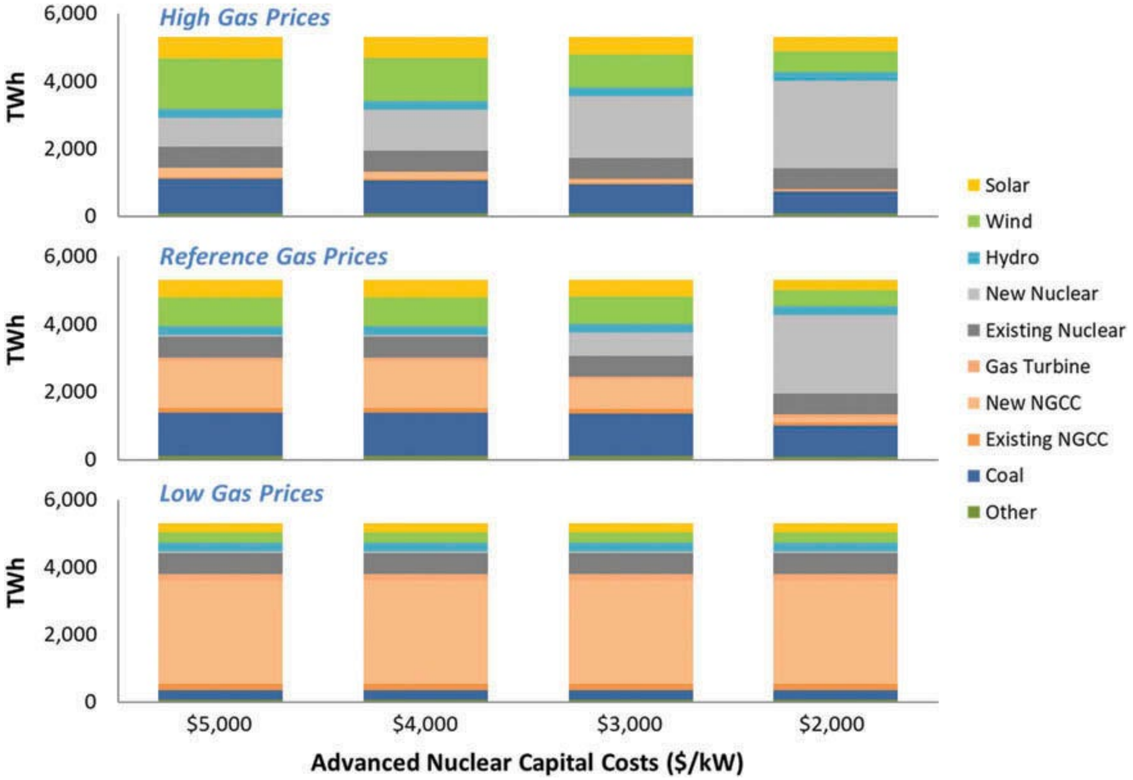

Figure 7. Generation mix in 2050 for four advanced nuclear capital cost cases (per kW electric) and three natural gas fuel price cases[31]

Nuclear energy has the potential to be deployed on a much larger scale than currently and provide an expanded set of energy services, such as hydrogen production, provided that costs of new nuclear decline and supply chains are scaled up. For example, the Decarb America (2021) report finds that a 30 percent decline in capital costs for advanced nuclear—from $7,000/kW in 2020 to approximately $5,000/kW in 2050—could enable nuclear energy to expand to provide approximately 40 percent of electricity generation and 30 percent of clean hydrogen supply by 2050.[32] Similarly, the Princeton Net Zero America (2021) study finds that the scenario with nuclear capital costs decreasing to $1,800/kW could significantly shift the clean energy mix in 2050 toward nuclear (mostly from reduced reliance on solar).[33]

The U.S. International Trade Administration (ITA), under the U.S. Department of Commerce, conducted an analysis in 2017 estimating "the global civil nuclear market to be valued between $500 and $740 billion over the next ten years and to have the potential to generate more than $100 billion in U.S. exports and thousands of new jobs."[34] Table 2 lists the top 25 export markets for the U.S. civil nuclear industry from the ITA study. The Department of Commerce also created a Civil Nuclear Trade Advisory Committee (CINTAC) to support U.S. nuclear exports.[35] A recent report by researchers at Idaho National Laboratory and Boise State University

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[31] Ibid.

[32] Nicholas Montoni, Ph.D., Rachel Smith, Lindsey Walter, Marika Tatsutani, Lesley Jantarasami, and Conrad Schneider (2021), *Clean Energy Innovation Breakthroughs*, Decarb America Research Initiative, October 19 (link).

[33] Eric Larsen et al. (2021), Net-Zero America: Potential Pathways, Infrastructure, and Impacts. Annex B: Sensitivity of transition modeling results to input, August 20, Figure B27 (link).

[34] U.S. International Trade Agency (2017), *2017 Top Markets Report: Civil Nuclear*, August, p. 8 (link).

[35] U.S. International Trade Agency (2021), Civil Nuclear Trade Advisory Committee (link).

noted that the global market for microreactors could reach hundreds of units annually by 2040 and thousands by 2050.[36]

Table 2. Top 25 Export Markets for U.S. Civil Nuclear (including some countries with nuclear phase-out policies)[37]

1. UK
2. China
3. India
4. UAE
5. Japan
6. Mexico
7. Czech Republic
8. Poland
9. Saudi Arabia
10. Turkey
11. Canada
12. France
13. ROK
14. South Africa
15. Romania
16. Spain
17. Slovakia
18. Ukraine
19. Switzerland
20. Brazil
21. Belgium
22. Sweden
23. Argentina
24. Finland
25. Germany

1.2.2 Coal Plant Retirements

Nuclear reactors could be installed at retired or soon-to-retire coal plant locations to facilitate siting, utilize grid connection infrastructure and some of the internal components (depending on details of the coal and nuclear plant types), reuse the cooling water intake system, take advantage of the local trained/skilled workforce, and provide continued availability of low-cost, reliable, dispatchable electricity. Market factors have led to the retirement of many U.S. coal plants in recent years, and this trend is expected to continue. The reference case projection in the Energy Information Administration's *Annual Energy Outlook 2021* indicates a decline in U.S. coal plant capacity by nearly 100 GW by 2030.[38] In scenarios that meet the Administration's goal for carbon-pollution free electricity by 2035, unabated fossil generation declines to zero.

Repowering the retiring coal plants with nuclear reactors would reduce the need for high-voltage long-distance transmission lines in two ways. First, siting new nuclear units at existing coal plants would reuse the existing transmission connections for the coal plant. Second, the proximity of existing coal plants to populous areas with high electricity demand, especially in the eastern United States, limits the need for new transmission. The best wind and solar areas in the United States, by contrast, are mostly in the less densely populated Plains and Southwest regions.[39] Based on this geographic comparison, replacing coal power with nuclear power at the same site near demand centers would require less investment in transmission lines than building large solar and wind farms in remote parts of the country.[40]

Repowering coal plants with nuclear reactors has been studied by the National Laboratories and other researchers,[41] and private nuclear developers are devoting increasing attention to this siting strategy. Table 3 links coal plant positions to nuclear plant positions based on the NuScale 924 MWe design. Many of the positions require similar technical expertise, and the actual number of former coal plant workers who could be rehired as nuclear plant workers will depend on plant-specific design and operational details, as well as characteristics of the local community. Rehiring former coal plant workers for a new nuclear plant would be

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[36] David Shropshire, Geoffrey Black, and Kathleen Araújo (2021), *Global Market Analysis of Microreactors*, INL/EXT-21-63214, Idaho National Laboratory (link).

[37] U.S. International Trade Agency (2017), *2017 Top Markets Report: Civil Nuclear*, August, p. 12 (link).

[38] U.S. Energy Information Administration (2021), *Annual Energy Outlook 2021*, Reference Case, Table 9: Electricity Generating Capacity (link).

[39] U.S. Department of Energy (2021), "Collection of NREL Maps" (link).

[40] Niskanen Center and Clean Air Task Force (2021), *How Are We Going to Build All That Clean Energy Infrastructure?*, August (link); Federal Energy Regulatory Commission (2021), "Building for the Future Through Electric Regional Transmission Planning and Cost Allocation and Generator Interconnection," July 27, 86 *Federal Register* 40266 (link); Paul L. Joskow (2020), "Transmission Capacity Expansion Is Needed to Decarbonize the Electricity Sector Efficiently," *Joule* 4:1-3 (link).

[41] R.J. Belles and O.A. Omitaomu (2014), *Evaluation of Potential Locations for Siting Small Modular Reactors near Federal Energy Clusters to Support Federal Clean Energy Goals*, ORNL/TM-2014/433, Oak Ridge National Laboratory, September (link); Staffan Qvist, Paweł Gładysz, Łukasz Bartela, and Anna Sowiżdżał (2020), "Retrofit Decarbonization of Coal Power Plants—A Case Study for Poland," *Energies* 14(1):120 (link).

most extensive when the necessary skills overlap closely and the community is relatively remote (offering few other opportunities for new employment for the former coal plant workers and a limited labor pool other than the former coal plant workers for staffing the new nuclear plant).

Table 3. Comparison of coal plant positions and nuclear positions for NuScale 924 MW_e SMR[42]

Coal Plant Position	# Dedicated Coal Positions	SMR Position	# Dedicated SMR Positions	Position Type	Degree of Retraining Required
Operations Supervisor	5	Senior Reactor Operator	5	Supervisor	High
Control Room Operator	10	Reactor Operator	15	Operator	High
Field Operator	15	Non-Licensed Operator	25	Operator	Low
Lab Operator/Chemistry/Scrubber	4	Chem Tech	14	Craft	Medium
Maintenance Supervisor	2	Maintenance Supervisor	3	Supervisor	Medium
Mechanical Craft	12	Mechanical Craft	21	Craft	Low
I&C Craft	9	I&C Craft	10	Craft	Medium
Electrician Craft	5	Electrician Craft	11	Craft	Low
Technician	11	Technician	13	Laborer	Low
Security Officer	20	Security Officer	48	Laborer	Low
Sub-Total	**93**		**165**		
All Other Positions	14		72	42 are O&M Support (Planners, Outage, etc.)	Medium
Total On-Site Positions	**107**		**237**		
Possible Centralized Positions			33		
Total Positions			**270**		

Sources: NuScale; ScottMadden analysis

1.2.3 Nuclear Energy for Hydrogen Production and Industrial Heat

Nuclear energy could also provide low-carbon heat and/or electricity for facilities and processes outside the power sector, alongside other clean energy options for deep decarbonization. Several previous studies have compared the outlet temperatures and sizing requirements for nuclear reactors to serve these alternative uses, noting that advanced reactor concepts would operate at higher temperatures than current nuclear plants, and thus could potentially supply high-quality heat to a larger range of industries.[43] Figure 8 shows the location of chemical, metal, mineral, and pulp and paper facilities that could potentially receive heat and electricity from nuclear reactors. Low-carbon nuclear energy could also produce synthetic hydrocarbon fuels, hydrogen, ammonia, and methanol for a wide array of consumers. Nuclear energy could be used to convert the carbon in coal to useful products, such as plastics, thus utilizing the natural resource and expanding economic activity in coal communities without releasing the carbon to the atmosphere.[44] The future scope of nuclear applications beyond the power sector will depend on many factors, including techno-economic comparisons with other low-

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[42] ScottMadden (2021*), Gone with the steam: How new nuclear power plants can re-energize communities when coal plants close*, October (link); see also NuScale (2021), *NuScale SMR Technology: An Ideal Solution for Repurposing U.S. Coal Plant Infrastructure and Revitalizing Communities* (link); Good Energy Collective (2021), *Opportunities for Coal Communities Through Nuclear Energy: An Early Look*, December (link); World Nuclear News (2022), "Digital platform launched for repowering coal plants," January 25 (link).

[43] Colin McMillan et al. (2016), *Generation and Use of Thermal Energy in the U.S. Industrial Sector and Opportunities to Reduce its Carbon Emissions*, INL/EXT-16-39680; NREL/TP-6A50-66763 (link); Jacopo Buongiorno et al. (2018), *The Future of Nuclear Energy in a Carbon-Constrained World*, MIT Interdisciplinary Study, September, Appendix F (link); Andrew Foss, John Smart, Haydn Bryan, Chris Dieckmann, Brian Dold, and Paul Plachinda (2021), *NRIC Integrated Energy Systems Demonstration Pre-Conceptual Designs*, INL EXT-21-61413, Idaho National Laboratory, April (link); Mark F. Ruth et al. (2020), *The Technical and Economic Potential of the H2@Scale Concept within the United States*, NREL/TP-6A20-77610, National Renewable Energy Laboratory, October (link).

[44] Elizabeth Worsham, Samuel Kerber, and Cristian Rabiti (2021*), Case Study: Hybrid Carbon Conversion Using Low-Carbon Energy Sources in Coal-Producing States*, INL/EXT-21-61758, Idaho National Laboratory, February (link).

carbon energy sources and the extent of government support for further research, development, and demonstration.[45]

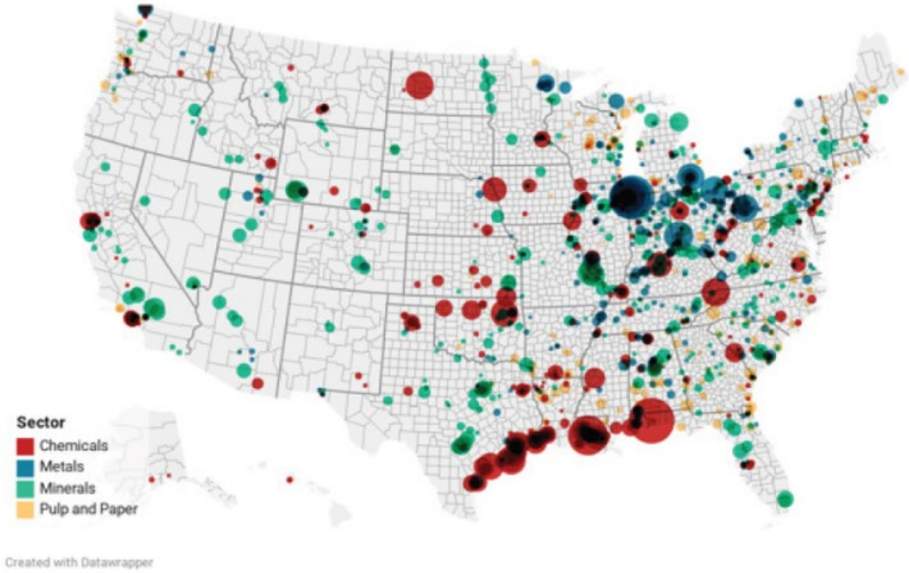

Figure 8. Energy-Intensive Industrial Facilities in the United States[46]

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[45] Electric Power Research Institute (2021), *Nuclear Beyond Electricity – Motivating and Valuing the Flexibility of Nuclear Energy Systems*, brief by Daniel Monaghan and Andrew Sowder, March (link); Electric Power Research Institute (2021), *Nuclear Beyond Electricity – Landscape of Opportunities: Initial Survey and Near-Term Actions*, March (link); Electric Power Research Institute and LucidCatalyst (2021), *Rethinking Deployment Scenarios for Advanced Reactors: Scalable Nuclear Energy for Zero-Carbon Synthetic Fuels and Products*, December 23 (link).

[46] Niskanen Center (2021), *Decarbonizing the U.S. Industrial Sector*, report by Nader Sobhani (link).

2 Supply Chain Mapping

The nuclear energy supply chain is vast and diverse covering everything from uranium extraction and enrichment to general construction of buildings at a reactor site to the equipment and components required for operation. The current supply chain is global and relies on companies and materials located throughout the world. Due to the vast size, this report does not cover all the areas of the nuclear supply chain and the supply chain is divided into two distinct segments: a mature supply chain for the existing fleet of light-water reactors, and a developing supply chain to support a future fleet of advanced reactors.

2.1 Technology Overview

2.1.1 Large Nuclear Reactors for Regional Electric Grids

The current nuclear supply chain is built around supporting large grid-scale nuclear reactors. All the U.S. grid-scale reactors are LWRs from a few developers. The components that support a large grid scale LWRs are vast. Figure 9 illustrates the numerous systems and components for one type of LWR in the United States.

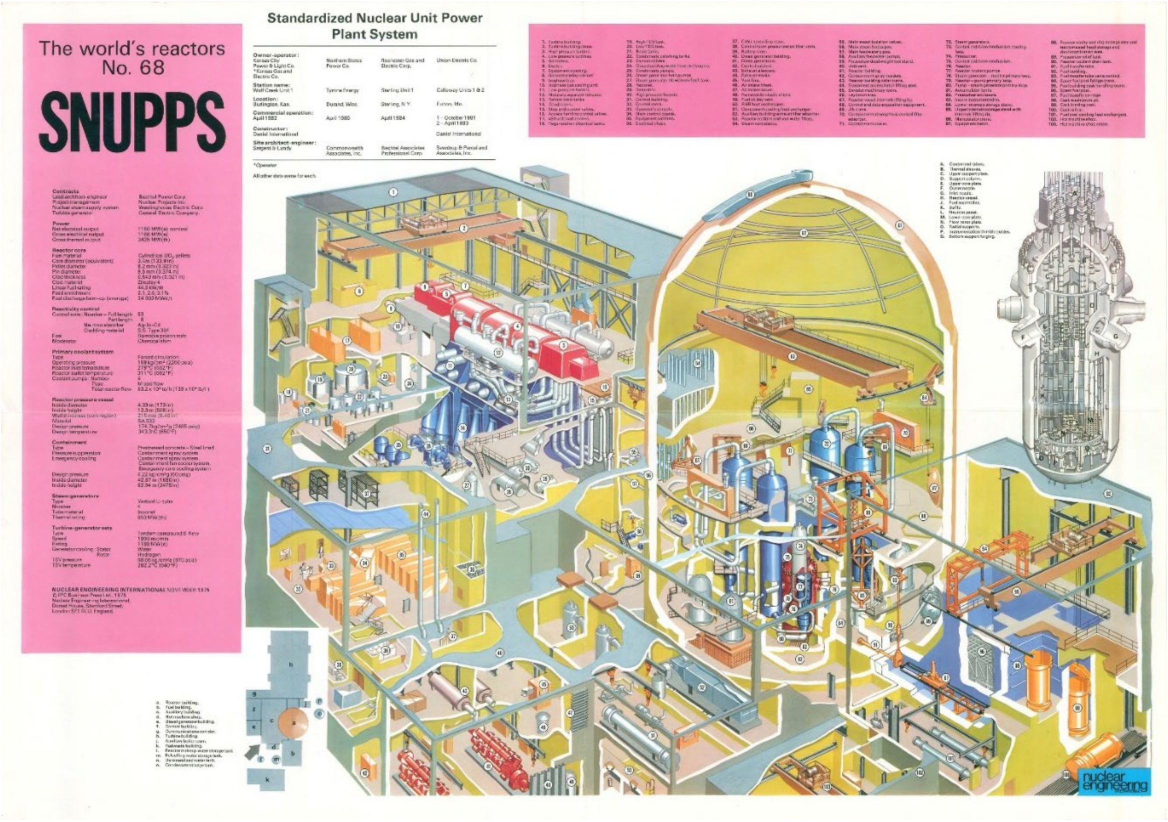

Figure 9. Example Diagram of a Large Existing Nuclear Plant[47]

As illustrated above, large nuclear plants contain vessels, piping, castings, structural steel, concrete, cabling, and instrumentation and controls. Due to the large number of components, there is an extensive international supply chain that supports these plants. In the United States, new construction of large LWRs is limited to two AP1000 plants in Georgia. Figure 10 shows the AP1000 global supply chain which demonstrates that while

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[47] Nuclear Engineering International (1975), *SNUPPS: Standardized Nuclear Unit Power Plant System* (link). The figure is intended to show the vast number of systems and components in a typical LWR. Details are difficult to read in the figure because of this complexity.

there are a number of U.S. suppliers, there are also suppliers in South Korea, Japan, Italy, Switzerland, Brazil, and Canada. In relation to the AP1000 supply chain, this figure only shows the fabrication of components; there is also the additional supply chain that covers the raw materials that are needed as input which adds many other countries to the supplier list.

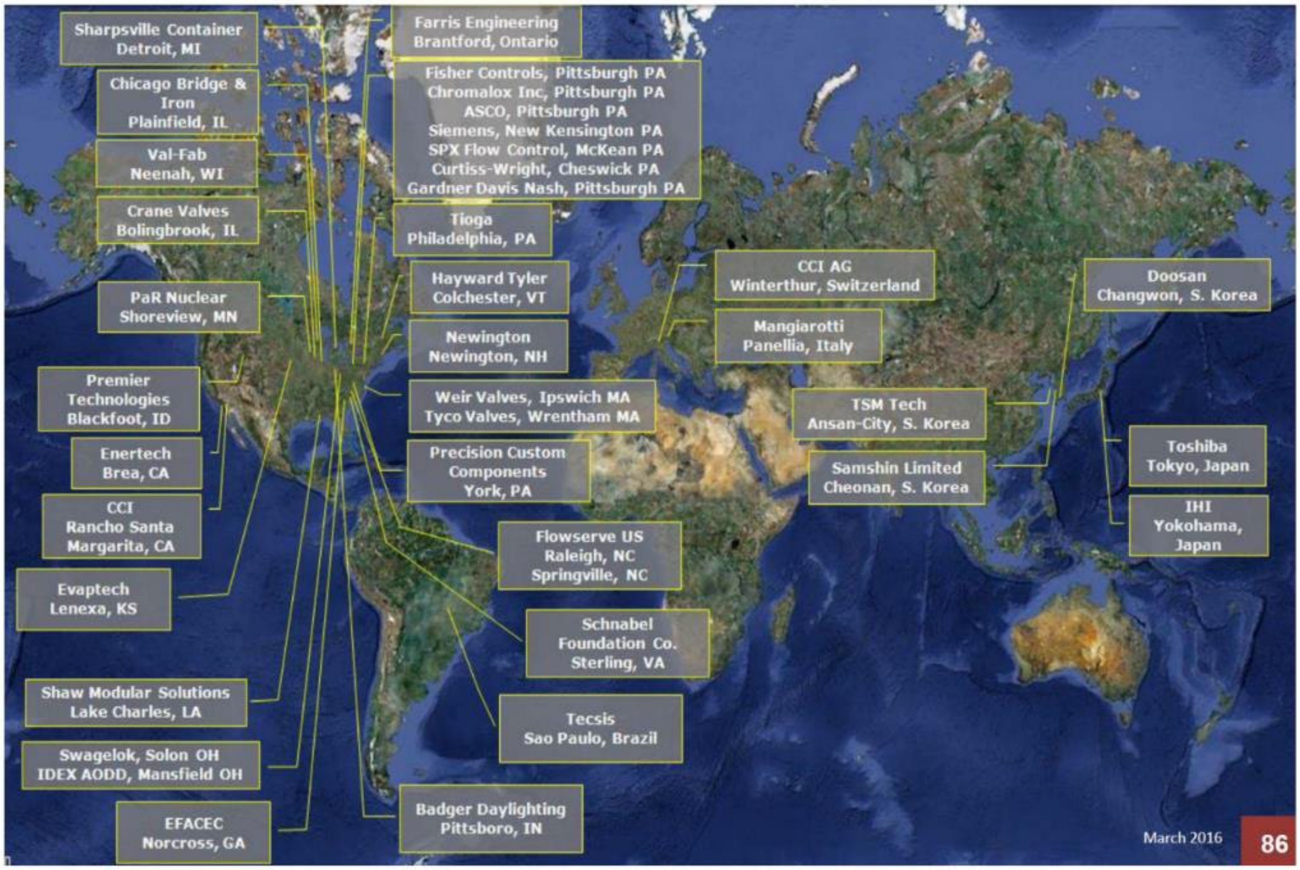

Figure 10. Westinghouse AP1000 Global Supply Chain[48]

2.1.2 Small Modular Reactors and Microreactors

The next generation of nuclear reactors will likely include small modular reactors (SMRs) and microreactors. The term SMR is related to the size of the reactor. SMRs can be LWRs, high temperature gas reactors, liquid metal, or molten salt designs. One of the main reasons for selecting an SMR is to reduce the amount of construction at a reactor site and rely on more factory fabrication. This move to factory fabrication reduces deployment costs by streamlining facility construction. Currently, none of these factory fabrication facilities exist, and they will need to be established to develop the supply chain for advanced reactors. The move to factory fabrication could add transportation logistical challenges in moving large or heavy components. Most SMRs will serve as grid scale electricity generators, support process heat applications, or help develop carbon free fuels (hydrogen or ammonia) to utilize in a zero-carbon economy.

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[48] MPR Associates (2018), *United States Nuclear Manufacturing Infrastructure Assessment*, Report No. 1660-0001-RPT-001, Rev. 1 (link).

Microreactors are another type of advanced reactor under development that could be utilized for off-grid locations that are remote from grid connections or utilized in a micro-grid application.[49] Microreactors will also employ factory fabrication and refurbishment where the reactor could be refueled or maintenance performed in the factory. The goal of a microreactor is to be transportable to almost anywhere and to be self-sufficient for a set period. After this period ends, it can be directly removed from the site. Figure 11 shows examples of how a microreactor could be transported. This limits the amount of site work required for construction as all work would be performed at a central facility. As with SMRs, there are no facilities currently established to fabricate and deploy microreactors.

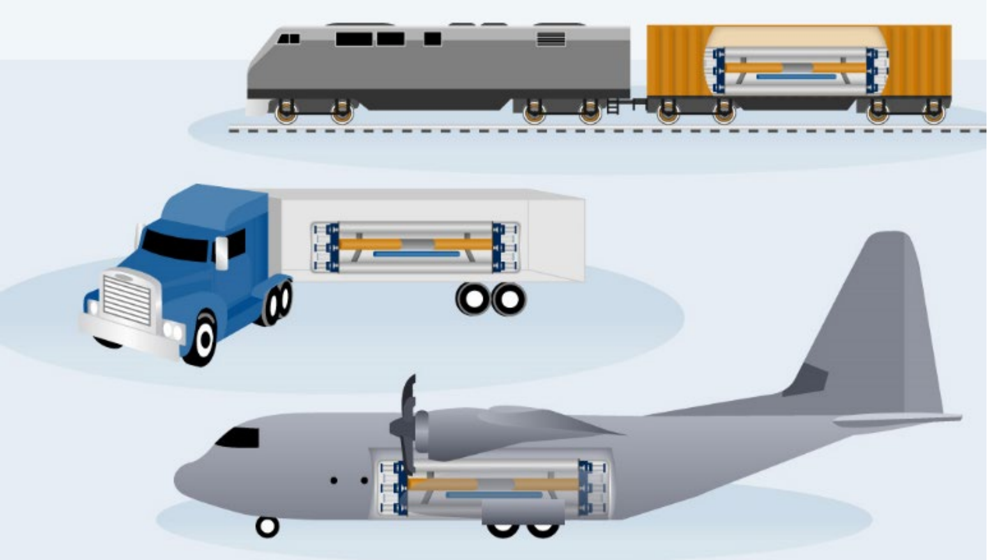

Figure 11. Examples of microreactor transportation options[50]

2.2 Supply Chain Segments

For the purposes of this report, the nuclear supply chain can be divided into two main segments: plant equipment components and the fuel cycle. Other activities, such as decommissioning and decontamination, are relevant over the long term but excluded from this scope to maintain focus on near-term priorities. (These other activities and their supply chain implications could be described in future report versions.) Workforce issues for supply chain segments are discussed in Section 3.1.5.

2.2.1 Nuclear Plant Equipment Components

Current LWRs are a combination of many large components and the systems that connect the plant together. Figure 12 shows the major components in a typical pressurized water reactor (PWR) and the materials that go into each component. The supply chain for boiling water reactors (BWRs) requires similar materials and fabrication processes. This figure does not cover various other items that are generally needed in a plant such as computers, control systems, electronics, concrete, or standard building materials. These other items are not focus areas for this report because they are widely used beyond the nuclear sector, and any supply chain issues

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[49] David Shropshire, Geoffrey Black, and Kathleen Araújo (2021), *Global Market Analysis of Microreactors*, INL/EXT-21-63214, Idaho National Laboratory (link); Timothy R. McJunkin and James T. Reilly (2021), *Net-Zero Carbon Microgrids*, INL/EXT-21-65125, Idaho National Laboratory, November (link); Bikash Poudel, Timothy McJunkin, Ning Kang, and James T. Reilly (2021*), Small Reactors in Microgrids: Technical Studies Guidance*, INL/EXT-21-64616, Idaho National Laboratory, November (link); ANS Nuclear News (2021), "Microreactor planned for U.S. Air Force base in Alaska," October 25 (link); Juan A. Vitali et al. (2018), *Study on the Use of Mobile Nuclear Power Plants for Ground Operations*, report for the U.S. Army Deputy Chief of Staff, October 26 (link).

[50] U.S. Government Accountability Office (2020), *Nuclear Microreactors*, Report No. GAO-20-280SP, February (link).

related to these items would most likely be unrelated to nuclear plant construction or operation. For more on the supply chain for semiconductors, please see the DOE semiconductor supply chain report.

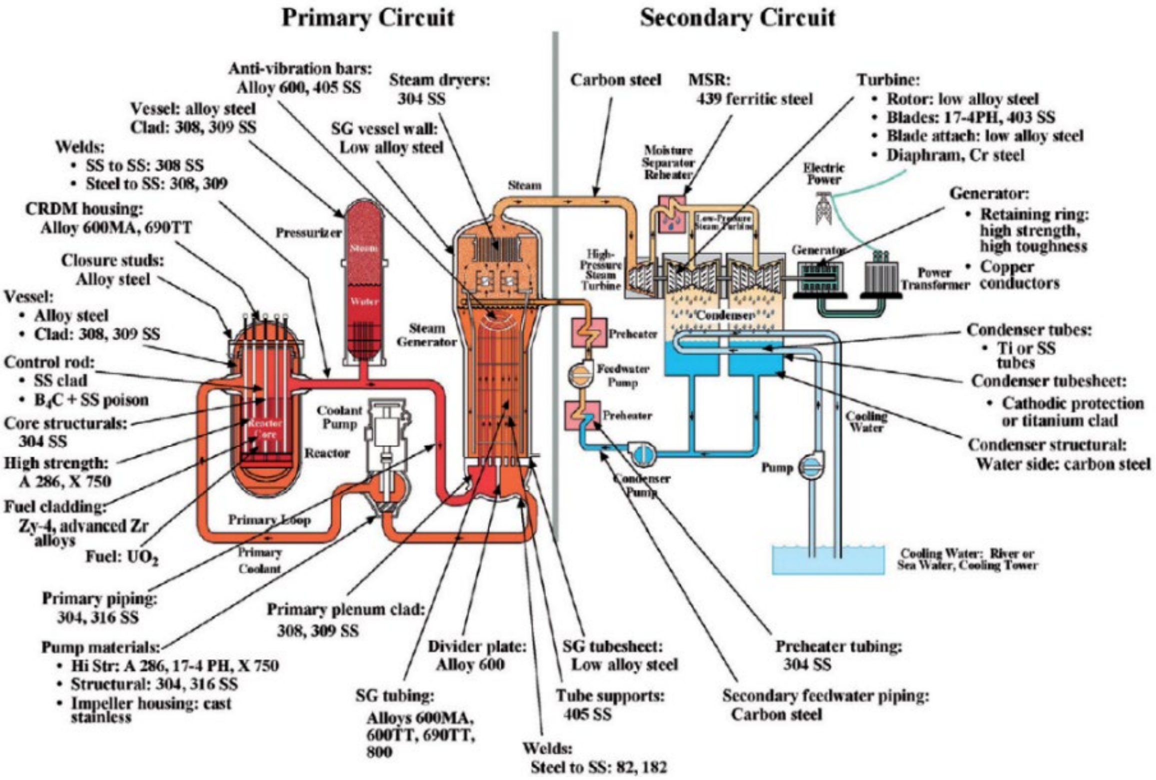

Figure 12. Pressurized Water Reactor Components and Materials[51]

This report addresses the following plant components for large LWRs. These items are required to both maintain the current operating fleet as well as potentially build additional plants.

- Raw material production
- Large component forgings and fabrication
- Other component forging and fabrication
- Enriched lithium
- Structural steel and concrete

Table 4 displays the raw material input requirements for a typical large PWR, normalized to the energy output of the plant. Material inputs for boiling water reactors are similar. Materials of concern include cadmium, chromium, and nickel. Cadmium is used in PWR control rods, but otherwise is not required in vast quantities. Nickel and chromium are used in the stainless steel and nickel alloys throughout the piping systems. Currently, nickel production is limited to the Eagle Mine in Michigan, and the United States imports approximately 50 percent of total domestic demand.[52] Chromium production is also limited in the United States, and almost 70 percent of chromium is imported.[53] Other potential minerals of concern include hafnium, indium, and niobium, which lack domestic sources.

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[51] Todd Allen, Jeremy Busby, Mitch Meyer, and David Petti (2010), "Materials Challenges for Nuclear Systems," *Materials Today* 13:14-23 (link).
[52] MPR Associates (2018), *United States Nuclear Manufacturing Infrastructure Assessment*, Report No. 1660-0001-RPT-001, Rev. 1 (link).
[53] Ibid.

Table 4. PWR material input requirements per kW[54]

Material	kg / kW
Concrete	180 – 560
Carbon steel	10 – 65
Wood	4.7 – 5.6
Stainless steel	1.56 – 2.10
Galvanized iron	1.26
PVC	0.80 – 1.27
Insulation	0.70 – 0.92
Copper	0.69 – 2.00
Uranium	0.40 – 0.62
Manganese	0.33 – 0.70
Zirconium	0.20 – 0.40
Chromium	0.15 – 0.55
Nickel	0.10 – 0.50
Inconel	0.10 – 0.12
Brass / bronze	0.04
Lead	0.03 – 0.05
Aluminum	0.02 – 0.24
Silver	0.01
Cadmium	0.01
Boron	0.01
Indium	0.01
Total	**195 - 635**

The current fleet of reactors relies on forgings and vessels that require very large forging and fabrication facilities. Currently, all these large forging facilities are outside of the United States and are mainly located in South Korea and Japan.[55] For the current fleet, these capabilities are not needed to build new plants and would most likely only be utilized for large component replacement like a steam generator or pressurizer replacement.

Outside of the large forgings, the remaining components would fall under small forgings or general piping and equipment needs. The United States has capabilities to support smaller forgings, piping, and other components. For many of the nuclear components, these suppliers will need to acquire and maintain their certifications to fabricate nuclear grade components (e.g., ASME N Stamp, discussed in Section 3.1.6). Obtaining the certifications takes time and money which could cause issues in ramping up suppliers or limit the available suppliers if the market does not develop as intended. Additionally, there is a risk of counterfeit parts that do not meet the requirements stated in their material certifications.

For the current fleet, PWRs continually add lithium-7 (Li-7) for pH control throughout the plant lifetime. The amount of Li-7 needed annually in total for the current fleet is estimated at 300 kg/yr.[56] The enrichment of Li-7 is only performed in China and Russia, and the dependability of this supply chain is uncertain, especially as more PWRs come online in other countries that could increase demand for Li-7. Due to these potential issues, EPRI is in the process of researching whether potassium hydroxide could be utilized as an alternative to lithium-7 for PWR pH control.[57]

The exact set of advanced reactors that will be deployed in the United States is not currently known. Therefore, the exact materials that will need to be supplied to establish the supply chain is unknown until a later stage of demonstration and commercial deployment. However, based on the various designs under development, there are common materials that will be required. Table 5 outlines the various fuel, claddings, and structural

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[54] Michael F. Ashby (2013), Materials for low-carbon power, Chapter 12 in *Materials and the Environment* (2nd ed., pp. 349–413) (link).
[55] MPR Associates (2018), *United States Nuclear Manufacturing Infrastructure Assessment*, Report No. 1660-0001-RPT-001, Rev. 1 (link).
[56] Government Accountability Office (2013), *Stewardship of Lithium-7 Is Needed to Ensure a Critical Supply*, Report No. GAO-13-716, September (link).
[57] Electric Power Research Institute (2017), *Potassium Hydroxide (KOH) Qualification Program*, presentation by Keith Fruzzetti, October 20 (link).

materials that will be required for different reactor types. For this report the following items are considered for advanced reactors:

- Various raw materials for component fabrication
- Component fabrication (large and small)
- Nuclear graphite
- Helium
- Sodium
- Molten Salts (minerals, enrichment, and synthesis)

Table 5. Reactor types, coolants, fuels, claddings, and structural materials[58]

Type	Coolant	Fuel	Cladding	In-core Structural Materials	Out-of-core Structural Materials
PWR	Water – single phase	UO_2 or MOX	Zirconium alloy	Stainless steels, nickel-based alloys	Stainless steels, nickel-based alloys
BWR	Water – two phase	UO_2 or MOX	Zirconium alloy	Stainless steels, nickel-based alloys	Stainless steels, nickel-based alloys
SCWR	Supercritical water	UO_2	F-M, Incaloy, ODS, Inconel	Same as cladding options, as well as low-swelling SS	F-M, low-alloy steels
VHTR	Helium	UO_2 or UCO	SiC or ZrC coating and surrounding graphite	Graphites, PyC, SiC, ZrC; vessel: F-M	Ni-based superalloys, F-M with thermal barriers, low-alloy steels
GFR	Helium or supercritical CO_2	MC, UO_2	Ceramic	Refractory metals and alloys, ceramics, ODS; vessel: F-M	Ni-based superalloys, F-M with thermal barriers
SFR	Sodium	MOX, U-Pu-Zr, MC, or MN	F-M or F-M ODS	F-M ducts, 316 SS grid plate	Ferritics, austenitics
LFR	Lead or lead-bismuth	MN	High-Si F-M or ODS, ceramics, or refractory alloys	*Not applicable*	High-Si austenitics, ceramics, or refractory alloys
MSR	Molten salt, e.g. FLiNaK	Salt, TRISO	*Not applicable*	Ceramics, refractory metals, Mo, Ni-based alloys, graphite, Hastelloy N	High-Mo, Ni-based alloys

PWR: Pressurized Water Reactor, BWR: Boiling Water Reactor, SCWR: Supercritical Water Reactor, VHTR: Very High Temperature Reactor, GFR: Gas Fast Reactor, SFR: Sodium Fast Reactor, LFR: Lead Fast Reactor, MSR: Molten Salt Reactor, MOX: Mixed Oxide $(U,Pu)O_2$, F-M: Ferritic-Martensitic stainless steels (typically 9-12 wt% Cr), ODS: Oxide Dispersion-Strengthened Steels (typically ferritic martensitic), MC: mixed carbide (U,Pu)C, MN: Mixed Nitride (U,Pu)N; TRISO: TRi-structural ISOtropic

As with the existing LWRs, advanced reactors will require both chromium and nickel to support vessels and piping as piping systems will be stainless or nickel alloys. The same issues for chromium and nickel will remain for advanced nuclear plants. There are limited U.S. sources for yttrium, which is being evaluated for use as a moderator in advanced reactors.

Large forgings are not as critical for the advanced reactor designs because the vessels are smaller than large LWR vessels. Some of the design types will require large forgings, but most will rely on smaller vessel designs as the goal is to move fabrication to a factory to reduce construction costs.

New reactor designs that rely on TRi-structural ISOtropic (TRISO) fuels need structural graphite in the core. Natural graphite is currently not produced in the Unites States. Graphite is imported into the United States with

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[58] S.J. Zinkle and G.S. Was (2013), "Materials challenges in nuclear energy," *Acta Materialia* 61(3):735-758 (link).

most of the imports coming from China.[59] Additionally, this graphite will need to be manufactured as nuclear grade graphite for which there are limited U.S. suppliers.

Many advanced reactors will not utilize water as a coolant. Gas reactors will be operated with helium. The supply of helium could be an issue as supply has been limited in the recent past.[60] While that could be an issue, the expectation is that the advanced nuclear fleet will rely on the current helium supply chain. Another coolant that will be utilized is sodium in sodium fast reactors. There currently is an abundance of sodium production in the United States in the form of sodium chloride (NaCl – salt) and reserves are considered inexhaustible, but there is not currently a producer of large quantities of nuclear grade sodium and that will need to be established to support commercial deployment of SFRs.[61]

Molten salt reactors require high purity salts to use as the coolant and fuel (unless fueled with TRISO). Either lithium or chlorine-based salts will be required. For lithium, this will add to the requirement for additional lithium production as was noted for PWRs. For both lithium and chlorine, enrichment will be required. Currently there are limited enrichment capabilities for both lithium and chlorine. Additionally, the fuel salt will require synthesis. Currently, this has been limited to laboratory small scale production for research, and full-scale commercial capabilities will need to be deployed. Some advanced reactor fuels also require beryllium, which is discussed later in the report.

2.2.2 Nuclear Fuel Cycle

A depiction of the nuclear fuel cycle is contained in Figure 13. Note that this figure refers to "permanent storage," but the terms "disposal" or "repository" more accurately express the preferred approach, as discussed below. This report focuses on five sections of the nuclear fuel cycle:

1. Mining and Milling
2. Conversion
3. Enrichment (both LEU and HALEU)
4. Fabrication (LWR fuel and advanced fuel forms)
5. Used fuel management

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[59] MPR Associates (2018), *United States Nuclear Manufacturing Infrastructure Assessment*, Report No. 1660-0001-RPT-001, Rev. 1 (link).
[60] Ibid.
[61] Ibid.

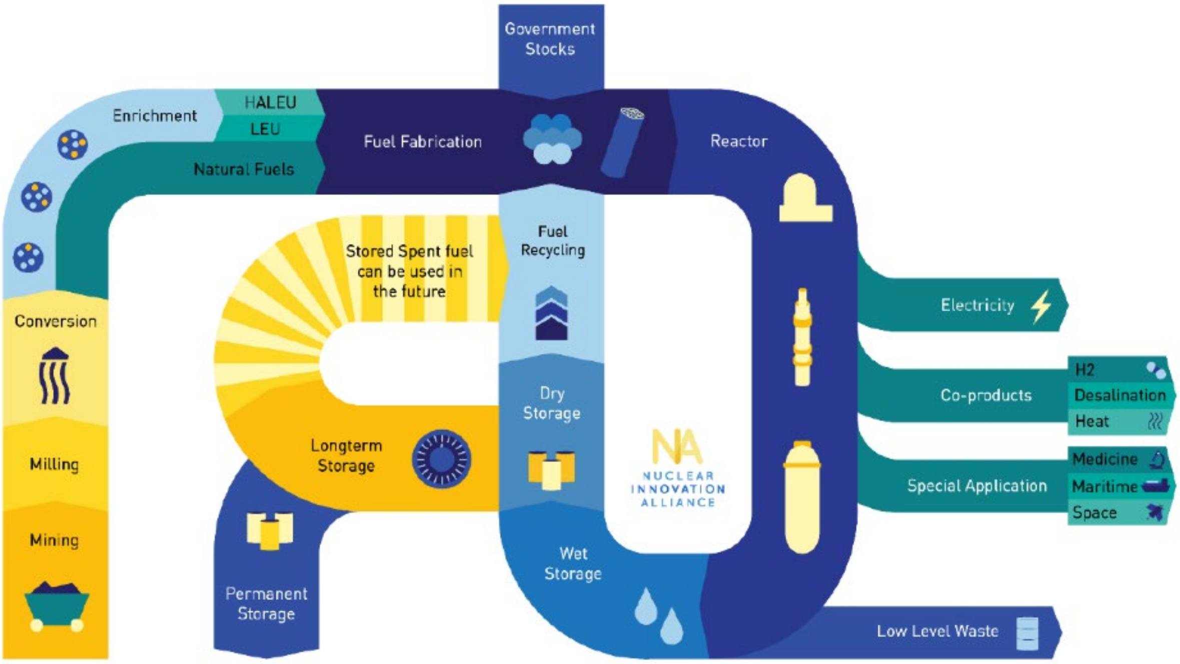

Figure 13. Nuclear Fuel Cycle[62]

Most uranium is imported into the United States from other countries. Figure 14 shows where most uranium reserves are located that can be extracted for less than $130/kg.

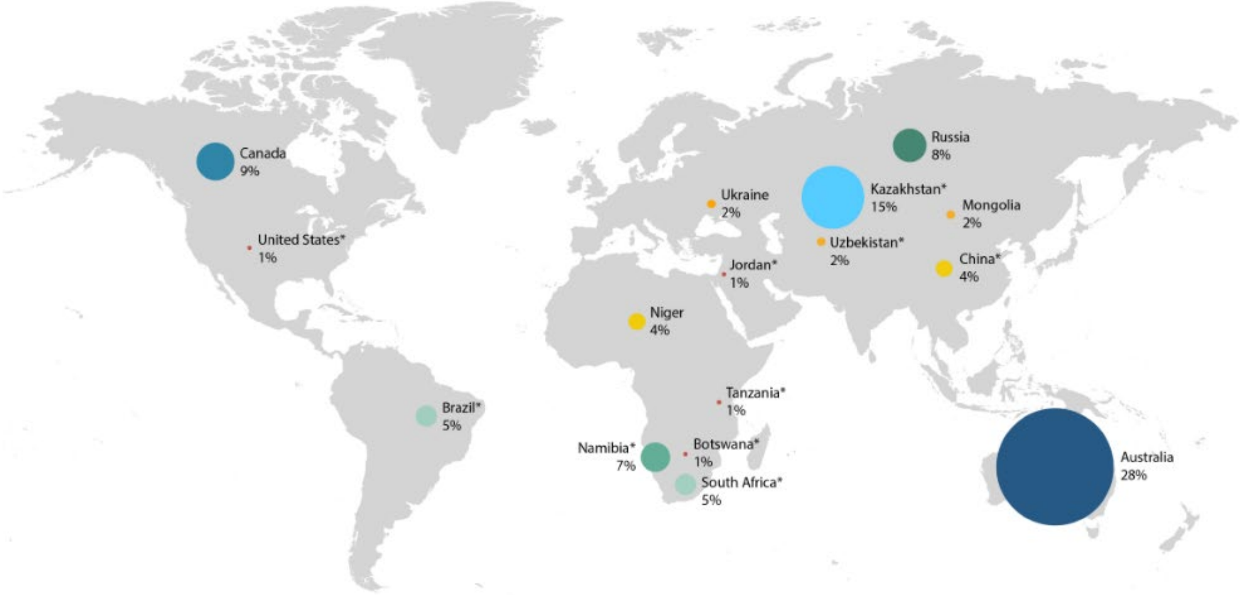

Figure 14. Global distribution of uranium resources[63]

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[62] Nuclear Innovation Alliance (2021), *U.S. Advanced Nuclear Energy Strategy for Domestic Prosperity, Climate Protection, National Security, and Global Leadership*, February, p. 3 (link).

[63] Nuclear Energy Agency (2020), *Uranium 2020: Resources, Production, and Demand*, NEA Report No. 7551 (link).

Although the United States has uranium deposits and mining capacity, domestic uranium production is low because it is less expensive to import uranium based on current supply and demand dynamics.[64] Figure 15 shows the production of uranium in the United States from 1949 through 2019. As shown in the figure, uranium production is at an all-time low. The United States is reliant on imports primarily from Canada, Australia, Russia, Kazakhstan, and Uzbekistan.

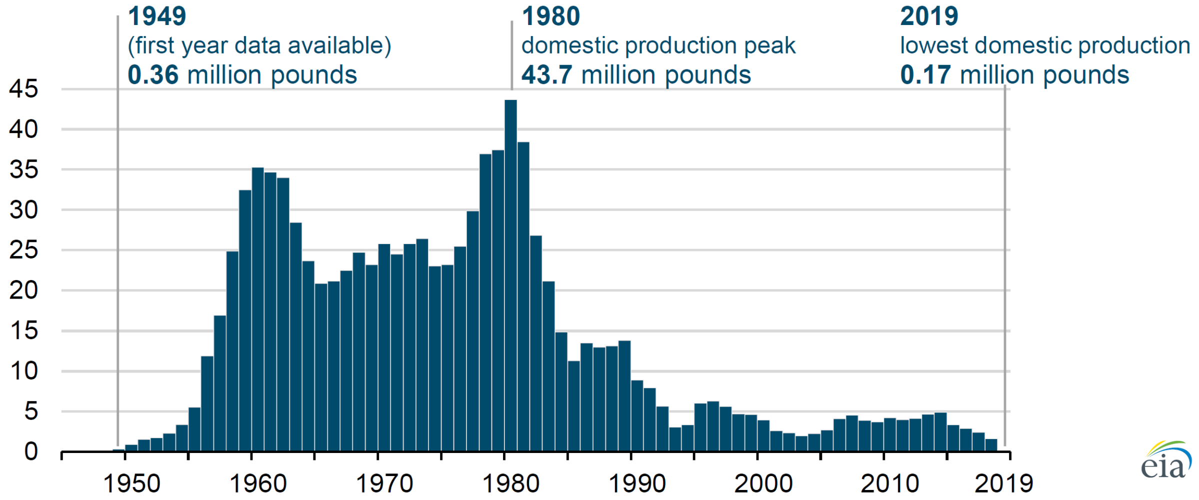

Figure 15. U.S. Uranium Concentrate (U_3O_8) production (million pounds)[65]

Currently, all conversion of uranium occurs outside the United States after the only U.S. supplier (ConverDyn/Honeywell Metropolis Works) idled its plant in 2017.[66] In April of 2021, the plant is in the process of restarting and will come online in 2023.[67] So, until the unit is restarted or another unit is built, the United States is relying on foreign conversion capabilities.

The current fleet of LWRs and some of the advanced reactors utilize low enriched uranium (LEU). Current LWRs use LEU which is enriched to less than 5 percent. Many advanced reactor concepts will utilize high assay LEU (HALEU) which is enriched to between 5 percent and 20 percent, and some advanced fuels for LWRs may also employ HALEU. There are currently six primary suppliers of LEU (<5 percent) and one of those is based in the United States. Currently the United States does not have HALEU enrichment capabilities, and the only countries with such capabilities currently are Russia and China.

LWR fuel for the commercial fleet is fabricated in U.S. facilities. There are currently three suppliers that supply the United States and international nuclear fleet: Global Nuclear Fuel Americas (Wilmington, NC), Westinghouse Columbia Fuel Fabrication Facility (owned by Westinghouse Electric Company in Columbia, SC), and Framatome (Richland, WA).[68] There are companies pursuing commercial facilities to supply fuel for the advanced rectors. BWXT restarted its TRISO fuel manufacturing facility in 2020.[69] The DOE ARDP awards to X-energy and TerraPower include funding to stand up commercial scale fuel fabrication for their specific fuel types (TRISO for X-energy and metal fuel for TerraPower).[70] For molten salt reactors, facilities

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[64] U.S. Department of Commerce Bureau of Industry and Security Office of Technology Evaluation (2019), *The Effect of Imports of Uranium on the National Security*, April 14 (link).

[65] U.S. Energy Information Administration (2020), "U.S. uranium production fell to an all-time annual low in 2019," July 17 (link).

[66] MPR Associates (2018), *United States Nuclear Manufacturing Infrastructure Assessment*, Report No. 1660-0001-RPT-001, Rev. 1 (link).

[67] World Nuclear News (2021), "U.S. conversion plant gears up for next 40 years, April 14 (link).

[68] MPR Associates (2018), *United States Nuclear Manufacturing Infrastructure Assessment*, Report No. 1660-0001-RPT-001, Rev. 1 (link).

[69] BWXT (2020), "BWXT Accomplishes Restart of TRISO Nuclear Fuel Manufacturing," November 10 (link).

[70] U.S. Department of Energy (2020), "U.S. Department of Energy Announces $160 Million in First Awards under Advanced Reactor Demonstration Program," October 13 (link).

will need to be established to create commercial scale levels of molten salt fuels. Other fuel forms will also need commercial facilities for full production.

Commercial transport of HALEU and molten salt fuels will need to be addressed. Currently, there are shipping cylinders that are designed to transport HALEU UF_6, but they can only transport limited quantities. Shipping cylinders will need to be developed that can support industrial scale shipping that would support commercial deployment. Molten salt fuels currently have no approved shipping containers.

The final step in the nuclear fuel cycle is long-term disposition of used nuclear fuel. The technical and societal aspects of nuclear fuel cycle and waste management options have been evaluated extensively since the early days of nuclear energy, and other countries have addressed the "back end" of the fuel cycle in various ways. The United States has not yet implemented an integrated long-term strategy.[71]

The United States currently uses a once-through (open) nuclear fuel cycle, shown in the upper panel of Figure 16. A fully closed cycle with separation facility for fuel reprocessing, shown in the lower panel, or another variation between open and fully closed cycles, could utilize more of the available energy from the uranium in the fuel, reduce the amounts of waste requiring long-term disposal, and remove the most long-lived radioactive isotopes from the disposed waste. Alternative fuel cycles could consume used nuclear fuel from nuclear reactors, thereby reducing future capacity needs for final disposal of discharged fuel. Alternative fuel cycles operate or have been planned in several countries, including France, Japan, India, Russia, and China, but they are not considered economically viable in the United States under current market conditions.[72]

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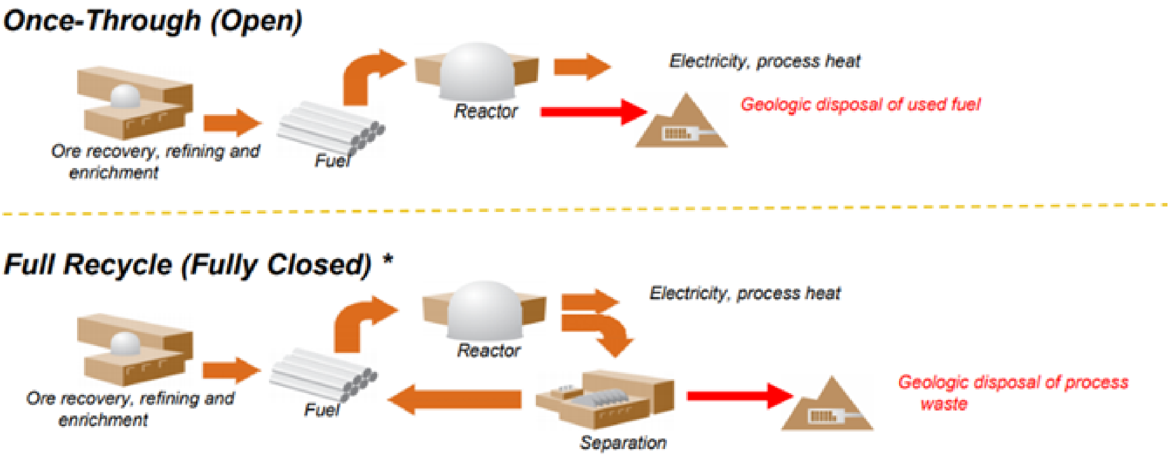
[71] National Research Council (1957), *The Disposal of Radioactive Waste on Land* (link); National Research Council (2001), *Disposition of High-Level Waste and Spent Nuclear Fuel: The Continuing Societal and Technical Challenges* (link); MIT Interdisciplinary Study (2011), *The Future of the Nuclear Fuel Cycle* (link); Blue Ribbon Commission on America's Nuclear Future (2012), *Report to the Secretary of Energy*, January (link); U.S. Department of Energy (2013*), Strategy for the Management and Disposal of Used Nuclear Fuel and High-Level Radioactive Waste*, January (link); Nuclear Energy Agency (2021), *Strategies and Considerations for the Back End of the Fuel Cycle*, NEA Report No. 7469, February (link); U.S. Nuclear Waste Technical Review Board (2021), *Six Overarching Recommendations for How to Move the Nation's Nuclear Waste Management Program Forward - A Report to the U.S. Congress and the Secretary of Energy*, April (link); Congressional Research Service (2021), *Civilian Nuclear Waste Disposal*, Report No. RL33461, September 17 (link); U.S. Government Accountability Office (2021), *Commercial Spent Nuclear Fuel: Congressional Action Needed to Break Impasse and Develop a Permanent Disposal Solution*, Report No. GAO-21-603, September 23 (link).

[72] Matthew Bunn et al. (2003), *The Economics of Reprocessing vs. Direct Disposal of Spent Nuclear Fuel* (link); Guillaume De Roo and John E. Parsons (2009), *Nuclear Fuel Recycling, the Value of Separated Transuranics, and the Levelized Cost of Electricity* (link); Francesco Ganda, Brent Dixon, Edward Hoffman, Taek K. Kim, Temitope Taiwo, and Roald Wigeland (2017), "Economic Analysis of Complex Nuclear Fuel Cycles with NE-COST," *Nuclear Technology* 193(2):219-233 (link); Idaho National Laboratory (2021), "Advanced Fuel Cycle Cost Basis Report" (link).



*A specific fuel cycle strategy may include more than one fuel design, reactor design, or fuel treatment process.

Figure 16. Nuclear Fuel Cycle Alternatives[73]

Approximately 86,000 metric tons of used nuclear fuel are being stored at U.S. nuclear plant sites on a temporary *ad hoc* basis, and 2,000 metric tons are added each year.[74] Geologic repositories are the internationally accepted approach for long-term disposition and are technically feasible. Finland is currently constructing a geological repository, and Sweden is planning one as well.[75] In the United States, DOE operates the Waste Isolation Pilot Plant (WIPP) in New Mexico, a deep geological repository for defense-related transuranic waste.[76] The proposed geological repository at Yucca Mountain has been determined not to be a workable option.[77] In April 2021, the U.S. Nuclear Waste Technical Review Board outlined possible steps toward the goal of "creat[ing] a robust, safe, and effective nuclear waste management capability that can successfully implement a geologic repository."[78] In a report published in September 2021 summarizing the results of expert interviews, the U.S. Government Accountability Office states that "most experts said Congress should … amend the Nuclear Waste Policy Act of 1982 (NWPA) to authorize the Department of Energy (DOE) to implement a new consent-based process for siting consolidated interim storage and permanent geological repository facilities."[79]

2.3 Global Competitiveness and Foreign Government Policies

The United States has built more nuclear reactors than any other country, and U.S. designs for light-water reactors have been adopted around the world. Figure 17 shows the relationships among global nuclear reactor

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[73] Adapted from Robert Hill (2010), "Transmutation," Argonne National Laboratory (link).

[74] U.S. Government Accountability Office (2021), *Commercial Spent Nuclear Fuel: Congressional Action Needed to Break Impasse and Develop a Permanent Disposal Solution*, Report No. GAO-21-603, September 23, p. 1 (link).

[75] Nuclear Energy Agency (2021), *Strategies and Considerations for the Back End of the Fuel Cycle*, NEA Report No. 7469, February, p. 19 (link); Matthew Larson et al. (2020), *Geology and Design of Major Spent Fuel Repositories*, ORNL/SPR-2020/1804, Oak Ridge National Laboratory, November (link).

[76] WIPP is the only deep geological repository in the world for nuclear waste. There are operating geologic repositories in Canada and Germany for toxic elemental and chemical wastes (mercury, arsenic, cyanide).

[77] U.S. Government Accountability Office (2011), *Commercial Nuclear Waste: Effects of a Termination of the Yucca Mountain Repository Program and Lessons Learned*, Report No. GAO-11-229, April (link); U.S. Government Accountability Office (2011), *Yucca Mountain: Information on Alternative Uses of the Site and Related Challenges*, Report No. GAO-11-847, September (link); U.S. Government Accountability Office (2017), *Commercial Nuclear Waste: Resuming Licensing of the Yucca Mountain Repository Would Require Rebuilding Capacity at DOE and NRC, Among Other Key Steps*, Report No. GAO-17-340, April 26 (link).

[78] U.S. Nuclear Waste Technical Review Board (2021), Six Overarching Recommendations for How to Move the Nation's Nuclear Waste Management Program Forward - A Report to the U.S. Congress and the Secretary of Energy, April (link).

[79] U.S. Government Accountability Office (2021), *Commercial Spent Nuclear Fuel: Congressional Action Needed to Break Impasse and Develop a Permanent Disposal Solution*, Report No. GAO-21-603, September 23, Highlights (link).

vendors and utility customers since 1950. The U.S. cluster lies at the center of the figure, anchored by the three main U.S. vendors: Westinghouse (with pressurized water reactors), Combustion Engineering (also with pressurized water reactors; acquired by Westinghouse in 2000), and General Electric (with boiling water reactors). These three U.S. vendors supplied reactors not only to domestic utilities, but also to customers abroad, and they have collaborated with designers in other countries in compliance with U.S. nuclear export controls, particularly Japan, Germany, France, South Korea, and China. The most recent exports of U.S. nuclear reactor designs (excluding plant order announcements in 2021 discussed below) are Westinghouse's AP1000 units at China's Sanmen and Haiyang sites, which began operating in 2018 and 2019.[80]

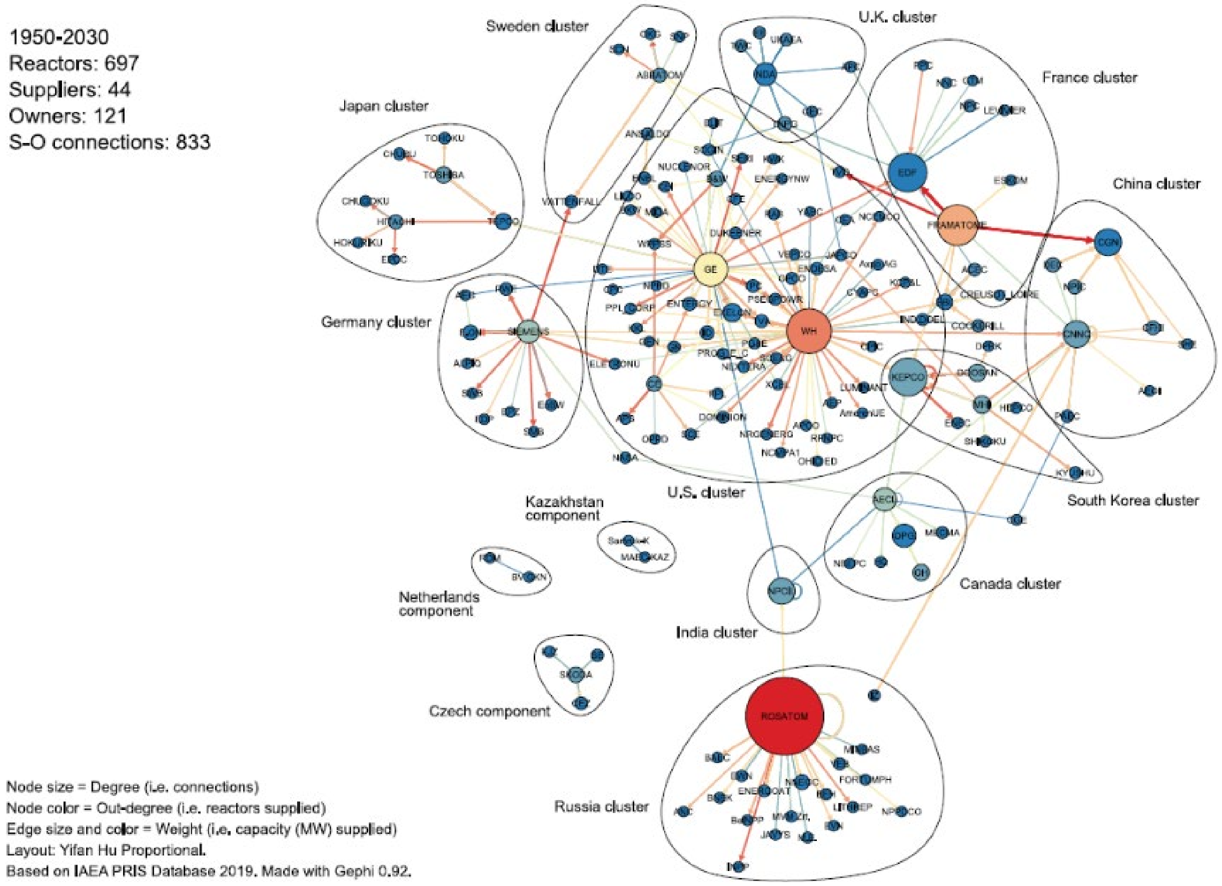

Figure 17. Historical Global Relationships Among Nuclear Vendors and Utility Customers[81]

Figure 18 illustrates the two waves of global nuclear reactor construction and the shrinking role of U.S. vendors. During the first wave of construction from the 1960's to the 1980's (which ramped down rapidly after the Chernobyl accident in 1986), many reactors were built by Westinghouse, Combustion Engineering, and General Electric, as well as Framatome (based in France), Siemens (based in Germany), and Rosatom (based in Russia). The U.S. vendors have built few reactors at home or abroad during the second construction wave, which began in the early 2000's. Instead, most reactors in the second wave were built by Rosatom, Framatome, Toshiba (based in Japan), KEPCO (based in South Korea), and Chinese state-owned enterprises.

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[80] International Atomic Energy Agency (2021), "Power Reactor Information System: China" (link).

[81] Jochen Markard, Nuno Bento, Noah Kittner, and Alejandro Nuñez-Jimenez (2020), "Destined for decline? Examining nuclear energy from a technological innovation systems perspective," *Energy Research & Social Science* 67:101512 (link).

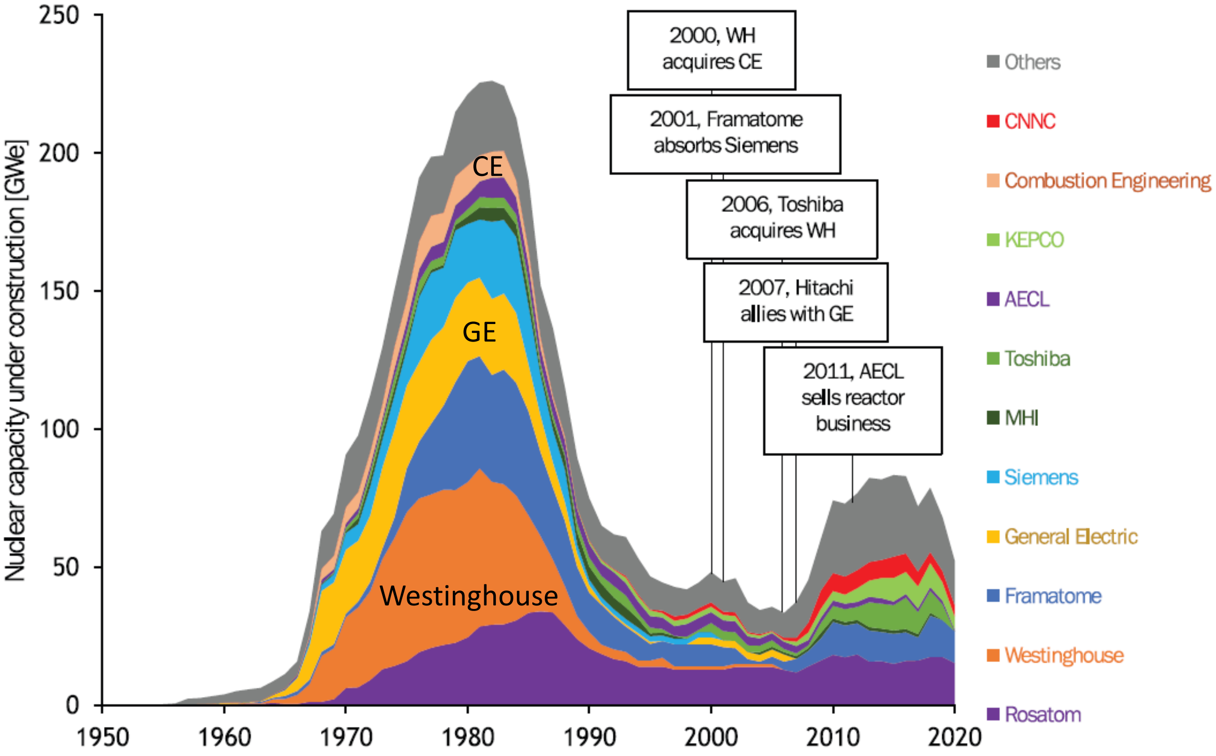

Figure 18. Global Nuclear Plant Construction by Reactor Vendor[82]

Figure 19 provides more detail on global nuclear additions from 2010 to 2019. The single U.S. addition represents completion of the Tennessee Valley Authority's Watts Bar Unit 2 in 2016. The majority of new nuclear reactors over the last decade have been built in China. In the nuclear industry, the same vendor and national affiliates that supplied the reactor also often provide operations and maintenance (O&M) services during the reactor's lifetime. The U.S. O&M supply chain has atrophied as U.S. reactor exports have declined. The U.S. O&M supply chain would benefit both from growth in the domestic nuclear fleet and from growth in U.S. reactors exports.

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[82] Jochen Markard, Nuno Bento, Noah Kittner, and Alejandro Nuñez-Jimenez (2020), "Destined for decline? Examining nuclear energy from a technological innovation systems perspective," *Energy Research & Social Science* 67:101512 (link).

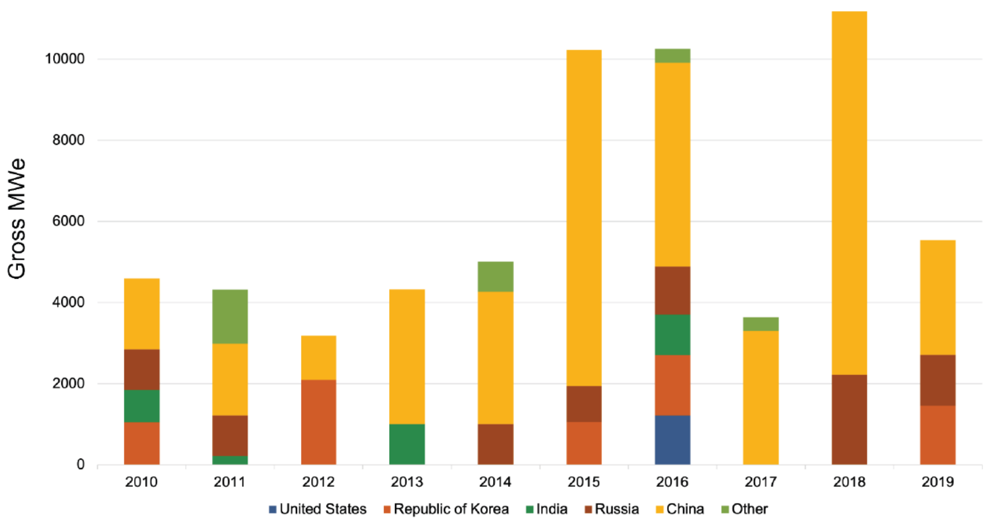

Figure 19. Global Nuclear Additions, 2010-2019[83]

Deciding whether to build nuclear reactors in a certain country, and which domestic or foreign vendors should build them, involves many issues beyond pure economics. The reduced role of U.S. vendors in global nuclear construction does not imply that they face insurmountable challenges from lower-cost competitors in the global reactor market. In fact, nuclear construction costs depend more on overall project management, experience accumulated over multiple units, regulatory interactions, contracting approaches, and local prices for labor and commodity inputs than on the direct costs of the reactor or any other equipment.[84] U.S. reactor designs could therefore be constructed at similar cost to foreign reactor designs if project management and other indirect factors were effectively controlled. Nuclear energy decisions, especially in an international trade context, always extend beyond economics to questions of national energy strategy, environmental goals (particularly CO_2 emission reductions), non-proliferation, technological readiness, regulatory infrastructure, geopolitical relationships, and local public acceptance.

Table 6 summarizes the strengths, weaknesses, opportunities, and threats for U.S. nuclear exports amid global competition. The table notes that the U.S. government contributes to various strengths, such as the Nuclear Regulatory Commission's "gold standard" of safety evaluations and the government's extensive international collaborations on nuclear issues since the mid twentieth century. The figure also notes weaknesses, such as long timelines for export applications and domestic R&D programs. Additional weaknesses and threats include the financial challenges of the U.S. nuclear industry (discussed below), government-backed financing by foreign competitors and a long-term, unwavering commitment by foreign governments to develop and export nuclear reactors.

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[83] American Nuclear Society (2021), *The U.S. Nuclear R&D Imperative*, February (link).
[84] LucidCatalyst for the UK Energy Technologies Institute (2018), *The ETI Nuclear Cost Drivers Project* (link).

Table 6. U.S. Nuclear Sector's Strengths, Opportunities, Weaknesses, and Threats[85]

Strengths	Weaknesses
U.S. Nuclear Companies	**U.S. Nuclear Companies**
Established knowledge and expertise in nuclear energy	Cost and schedule overruns for recent U.S. nuclear projects
Strong technical innovation culture	Limited attention to balance of plant and construction strategies
High-quality manufacturing capabilities	Limited attention to business models beyond electric grid units
High safety standards in nuclear construction and operation	
U.S. Government	**U.S. Government**
"Gold standard" of nuclear regulation (NRC)	Long leadtimes for nuclear R&D, programs, demonstrations
Strong international relationships for investment, R&D, fuel	Many stringent requirements on U.S. companies, int'l customers
Support from International Development Finance Corporation and Export-Import Bank	
World-leading research at the national laboratories	
Funding for nuclear R&D, programs, demonstrations	
Opportunities	**Threats**
Future global clean energy growth, especially in non-OECD	Competition from other clean energy sources with falling costs
Potential cost reductions with advanced nuclear innovations	Competition from state-owned enterprises, esp. China, Russia
New energy products and addressable markets	Increased influence of other countries through infrastructure inv.
Long-term relationships with nuclear newcomer countries	Possible shifts in policies and programs, disrupting progress

A precondition for U.S. nuclear technology exports is an agreement for peaceful nuclear collaboration under Section 123 of the Atomic Energy Act. These agreements are negotiated by the U.S. Department of State in consultation with the DOE, National Nuclear Security Administration, and Nuclear Regulatory Commission. The 48 countries with which the United States has established Section 123 agreements are displayed in Figure 20.

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[85] Adapted from American Council for Capital Formation (2021), *Transition from Traditional Nuclear Energy to Functional Nuclear Energy in the Global Energy Market*, report by Efe Kurt of Idaho National Laboratory (link); see also Pillsbury Winthrop Shaw Pittman LLP (2012), *Nuclear Export Controls: A Comparative Analysis of National Regimes for the Control of Nuclear Materials, Components and Technology*, October (link).

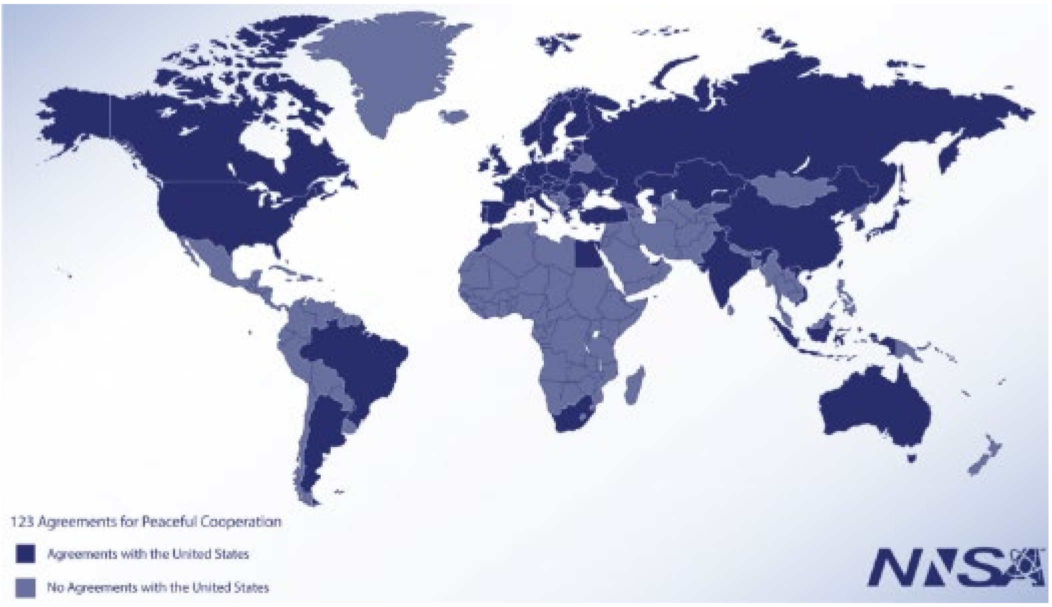

Figure 20. U.S. International Nuclear Agreements under Section 123 of the Atomic Energy Act[86]

Adequately addressing the risk of nuclear liability for nuclear damage is essential for participation by U.S. firms in nuclear energy projects outside the United States. The Convention on Supplementary Compensation for Nuclear Damage (CSC) was adopted under the auspices of the IAEA to assure the availability of prompt, meaningful and equitable compensation for nuclear damage and to provide legal certainty concerning liability for nuclear damage.[87] The United States is a member of the CSC and encourages other countries to join the CSC as the best way to address concerns about nuclear liability.

Westinghouse, General Electric, and other U.S. nuclear developers have executed memoranda of understanding with several countries for SMRs and microreactors. The U.S. government has launched the Foundational Infrastructure for Responsible Use of Small Modular Reactor Technology (FIRST) program to support capacity-building in partner countries.[88] Another U.S. government initiative that supports SMRs is ITA's SMR Public-Private Program (SMR PPP), an interagency initiative to promote the deployment of SMRs, with an initial focus on Europe and Eurasia. In July 2020, the U.S. International Development Finance Corporation announced changes in its policies to enable support for nuclear energy projects.[89] At the 26th UN Climate Change Conference in Glasgow in November 2021, the U.S. Department of Energy and the Romanian utility Nuclearelectrica announced a partnership on deploying the NuScale SMR for a retiring coal plant in Romania.[90] Later in November 2021, Westinghouse signed a contract with Ukrainian nuclear operator Energoatom to build AP1000 reactors.[91] In December 2021, the Ontario utility OPG selected the GE-Hitachi BWRX-300 SMR for new reactor construction at the Darlington nuclear site.[92]

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[86] National Nuclear Security Administration (2022), "123 Agreements for Peaceful Cooperation" (link).

[87] International Atomic Energy Agency (2022), "Convention on Supplementary Compensation for Nuclear Damage" (link).

[88] U.S. Department of State (2021), "Program To Create Pathways to Safe and Secure Nuclear Energy Included in Biden-Harris Administration's Bold Plans To Address the Climate Crisis," April 27 (link); World Nuclear News (2022), "USA to assist Estonia in nuclear capacity building," January 25 (link).

[89] U.S. International Development Finance Corporation (2020), "DFC Modernizing Nuclear Energy Policy," July 23 (link).

[90] U.S. Department of Energy (2021), "U.S. Secretary of Energy Jennifer Granholm and Romanian Minister of Energy Virgil Popescu Highlight New Partnership on SMRs," November 4 (link).

[91] World Nuclear News (2021), "Westinghouse signs initial contract for Ukrainian AP1000s," November 22 (link).

[92] World Nuclear News (2021), "OPG chooses BWRX-300 SMR for Darlington new build," December 2 (link).

The remainder of this section focuses on the two principal foreign competitors for future U.S. nuclear exports: China and Russia.[93]

2.3.1 China

China built its first nuclear power plants around 1990 and has expanded its fleet significantly since 2010, with further growth planned in the next decade and beyond. Figure 21 shows nuclear power plants in China, with reactors in operation denoted by orange circles, reactors under construction by blue circles, and planned reactors by yellow circles. China has completed 40 reactors since 2010 and is currently constructing 15 more.[94] Most of the reactors have taken approximately five years to build; the minimum construction duration among recent completed projects is 49 months (4.1 years) for Yangjiang 4.

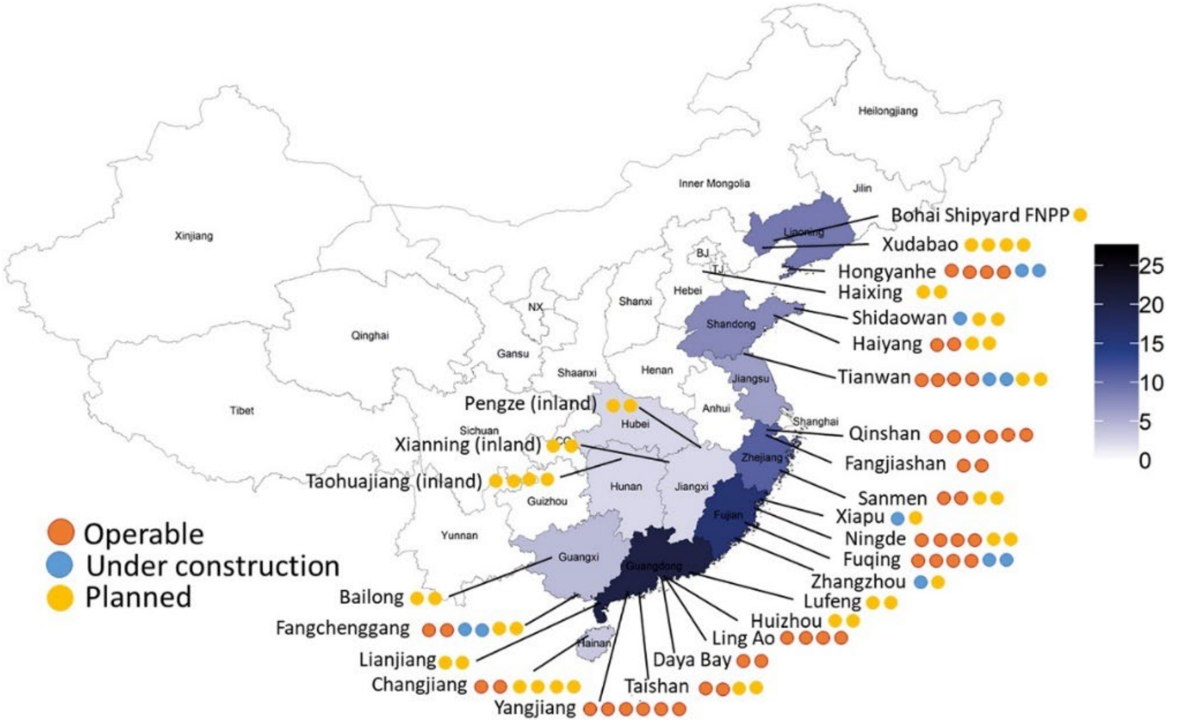

Figure 21. Nuclear reactors in China and total capacity by province in GW by 2030[95]

The Chinese central government has prioritized nuclear in its long-term industrial and energy strategies since the early 2000's. As shown in Figure 22, China began by procuring nuclear reactor designs from the United States and other vendor countries. Collaboration with Westinghouse on AP1000 construction at the Sanmen and Haiyang sites has enabled China to develop the CAP1400 as an indigenous adaptation for future domestic projects and exports. China has created several state-owned companies to design, construct, and operate nuclear plants, such as China National Nuclear Corporation, China General Nuclear Power Group, and State Power Investment Corporation, with subsidiaries for design, engineering, procurement, construction, and fuel. In 2016, the U.S. Department of Justice indicted China General Nuclear Power Group, along with a

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[93] For background information on both countries, see Atlantic Council Global Energy Center (2018), *U.S. Nuclear Power Leadership and the Chinese and Russian Challenge*, issue brief by Robert F. Ichord, March (link); Atlantic Council Global Energy Center (2019), *U.S. Nuclear Energy Leadership: Innovation and the Strategic Global Challenge*, May (link); Center for Strategic and International Studies (2020), *The Changing Geopolitics of Nuclear Energy: A Look at the United States, Russia, and China*, report by Jane Nakano, March (link).

[94] International Atomic Energy Agency (2022), "Power Reactor Information System: China" (link); see also UN Economic Commission for Europe (2021), *Technology Brief: Nuclear Power*, August (link).

[95] Sha Yu, Brinda Yarlaggada, Jonas Elliott Siegel, Sheng Zhou, and Sonny Kim (2020), "The role of nuclear in China's energy future: Insights from integrated assessment," *Energy Policy* 139:111344 (link).

Taiwanese-American citizen and his business, for "conspiracy to unlawfully engage and participate in the production and development of special nuclear material outside the United States." This incident led the U.S. government to tighten restrictions against nuclear exports to China in 2018.[96]

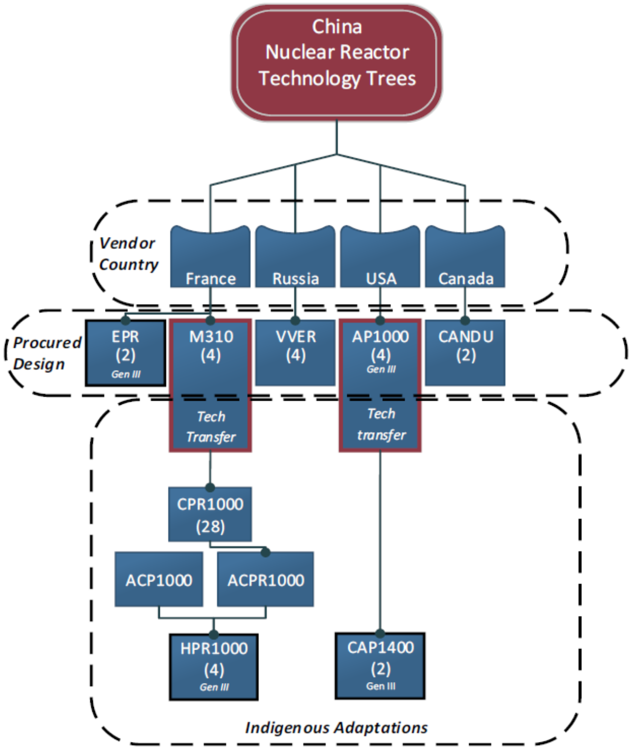

Figure 22. Chinese adaptations of U.S. and other foreign nuclear reactor technologies[97]

As China has expanded its nuclear power plant fleet and developed its own reactor designs, it has also increased the share of nuclear plant components supplied by Chinese vendors, as shown in Figure 23. For example, the Korean industrial conglomerate Doosan manufactured the reactor pressure vessels and steam generators for the first two reactors at both Sanmen and Haiyang, but Chinese vendors wholly or partly owned by the government manufactured these components for the third and fourth reactors at both plants.[98] Through this localization strategy, Chinese companies have developed sufficient capability to pursue nuclear projects as fully integrated consortia around the world. Localization efforts by China and other countries also limit potential export opportunities for U.S. vendors.

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[96] U.S. District Court, Eastern District of Tennessee, Knoxville (2016), *United States of America v. Szuhsiung Ho a/k/a Allen Ho, China General Nuclear Power Company a/k/a China Guangdong Nuclear Power Company, and Energy Technology Int.*, April 5 (link); Congressional Research Service (2018), *New U.S. Policy Regarding Nuclear Exports to China*, December 17 (link).

[97] Nicobar Group (2017), *China's Nuclear Industry 2017-2018: A Tightly Coiled Spring*, December, p. 1.

[98] Ibid., p. 14.

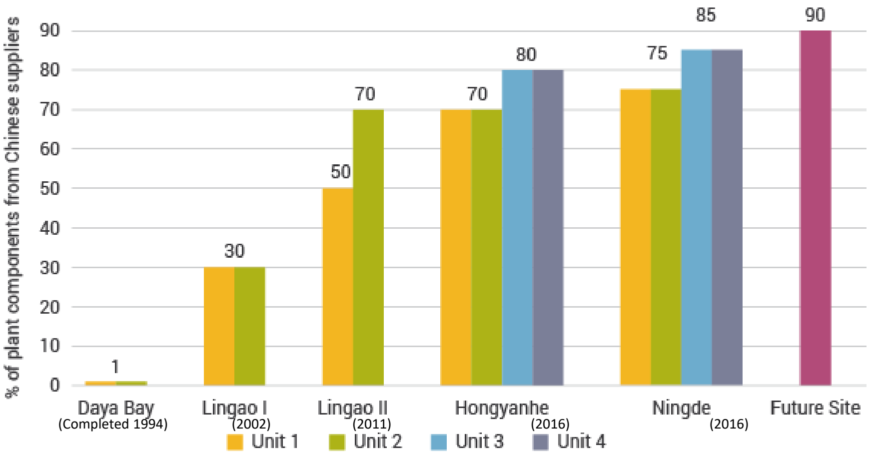

Figure 23. Progressive localization of M310 and CPR1000 components in China[99]

Figure 24 depicts China's efforts to participate in nuclear construction projects in other countries, whether as an exporter of Chinese reactor designs (adapted from foreign templates) or financial partner. Nuclear expansion is an integral part of China's Belt and Road Initiative, with a total target value of $145 billion by 2030.[100]

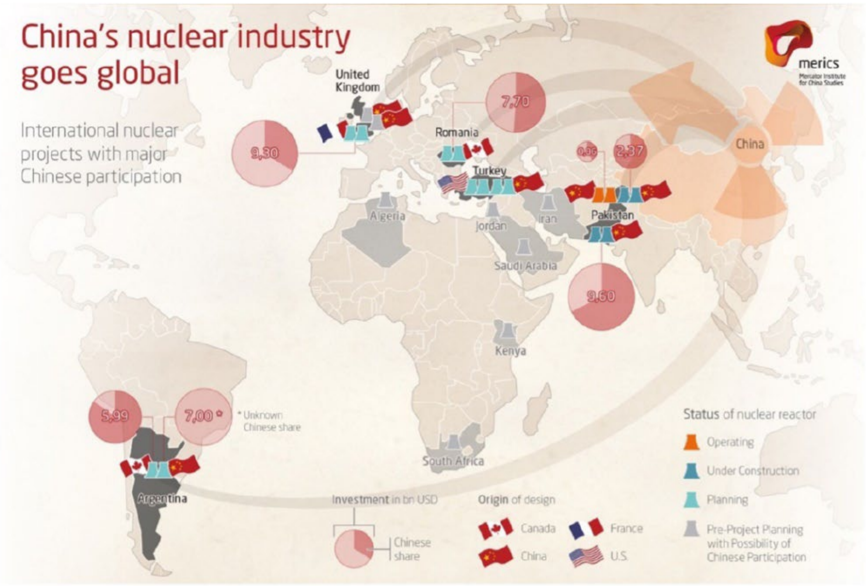

Figure 24. China's Global Nuclear Projects (note: the projects in Turkey no longer have Chinese or U.S. participation)[101]

China is also making progress on non-LWR (Gen IV) nuclear plants. It activated two 250 MWt high-temperature gas-cooled reactors at Shidaowan in 2021 and has designed larger units for subsequent

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[99] World Nuclear Association (2022), "Nuclear Power in China," January (link). The Daya Bay and Lingao I plants have French M310 reactors. All subsequent plants in the figure (Lingao II, Hongyanhe, and Ningde) have CPR1000 reactors, a Chinese adaptation of the French M310 reactor (as shown in the previous figure).

[100] Reuters (2019), "China could build 30 'Belt and Road' nuclear reactors by 2030: official," June 20 (link).

[101] Merics (2016), "China Goes Global" (link); see also American Council for Capital Formation (2017), *The Rise Of China's Civil Nuclear Program and Its Impact on U.S. National Interests*, report by George David Banks, January (link); Carnegie Endowment for International Peace (2018), *The Future of Nuclear Power in China*, report by Mark Hibbs (link).

commercial deployment.[102] China began constructing a pilot 600 MWe sodium-cooled fast reactor at Xiapu in 2017 and plans to connect it to the grid in 2023.[103]

2.3.2 Russia

Russia's state-owned nuclear company, Rosatom, is exporting its reactors through projects in Turkey, Bangladesh, Egypt, Hungary, and other countries.[104] Rosatom organized an online media event titled "Atoms for Humanity" in April 2021 to highlight the need for low-carbon energy in developing countries and potential roles for nuclear plants.[105] Russia is also pioneering floating nuclear power plants with an SMR on a barge (Figure 25), which began supplying power to coastal communities along the Arctic Ocean in 2019. Similar to China's nuclear expansion, state support and financing are key elements of Russia's global nuclear growth strategy. Russia is constructing a BREST-300 lead-cooled fast reactor in Seversk and an SVBR-100 lead-bismuth fast reactor in Dimitrovgrad.[106]

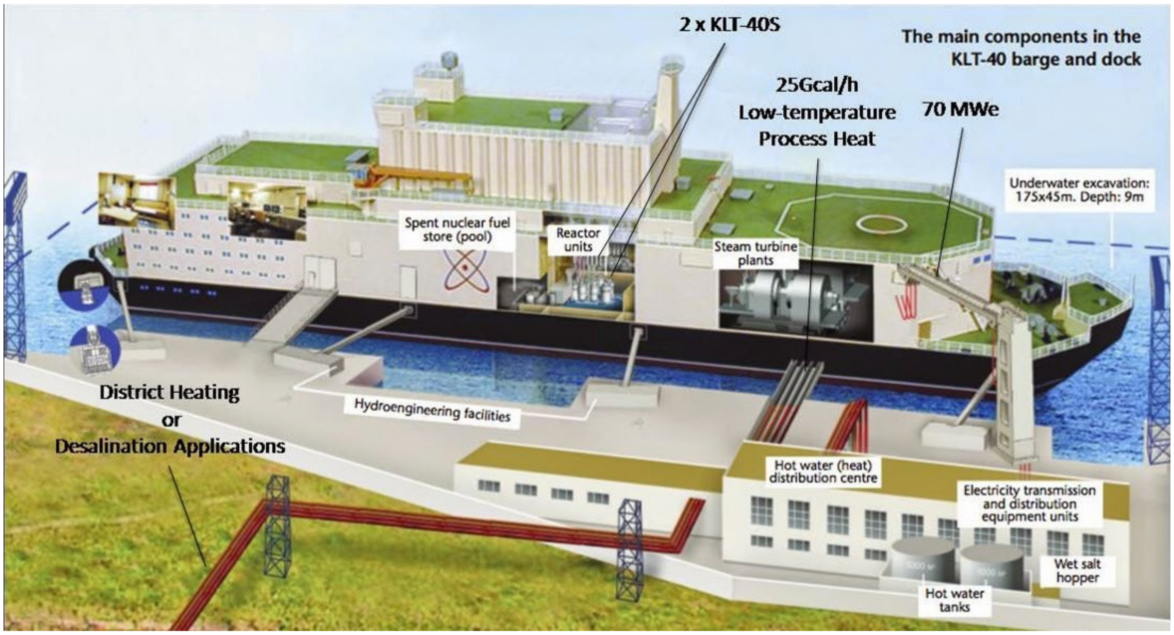

Figure 25. Russian KLT-40 Nuclear Barge[107]

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[102] World Nuclear News (2021), "Dual criticality for Chinese demonstration HTR-PM," November 12 (link).
[103] World Nuclear News (2020), "China starts building second CFR-600 fast reactor," December 29 (link).
[104] Center for Strategic and International Studies (2020), *The Changing Geopolitics of Nuclear Energy: A Look at the United States, Russia, and China*, report by Jane Nakano, March (link).
[105] Rosatom (2022), "Atoms for Humanity" (link).
[106] World Nuclear Association (2021), "Nuclear Power in Russia," December (link); BREST is an acronym for Bystryi Reaktor so Svintsovym Teplonositelem (fast reactor with lead coolant); SVBR is an acronym for Svintsovo-Vismutovyi Bystryi Reaktor (lead-bismuth fast reactor).
[107] UN Economic Commission for Europe, *Technology Brief: Nuclear Power*, August 2021.

3 Supply Chain Risk Assessment

Table 7 lists the most important fuels and materials for risk assessment of the nuclear energy supply chain. These are listed in order of importance for both the current fleet and the advanced reactors.

Table 7. Key Supply Chain Issues for Current Large Reactors and Advanced Reactors

Component / Product	Description
Current Large Reactors	
Uranium mining, milling, and conversion	Most uranium is imported and conversion is performed by foreign suppliers
Enriched lithium	Most lithium is imported and there is increased demand from other industries. EPRI is studying potential substitutions.
Chromium and nickel	Current plants will replace various high alloy steel components, thus some level of steel components will be needed.
Advanced Reactors	
HALEU	Most advanced reactors will require HALEU for fuel
Fuel fabrication	There are limited fuel fabrication facilities in the United States for advanced nuclear fuel
Nuclear graphite	All graphite is imported and there are no suppliers of nuclear graphite in the United States
Lithium	Some molten salt reactors will need lithium. It is imported and will have increased demand from other industries.
Lithium and chlorine enrichment	Lithium and chlorine will require enrichment to high purity levels to be utilized in reactors.

3.1 U.S. Vulnerabilities

3.1.1 Financial Viability of Existing U.S. Nuclear Power Plants

As capital-intensive infrastructure, nuclear power plants must generate sufficient quantities of electricity each year, and sell their electricity at sufficiently high prices, to recover their capital investments and operating costs. Annual capacity factors are high across the U.S. nuclear fleet because of carefully designed programs for asset utilization based on decades of plant experience, and operating costs per MWh decreased by 24 percent between 2012 and 2019.[108] The financial viability of many existing plants is threatened, however, by low electricity prices caused primarily by low natural gas prices, thermal plant additions (typically natural gas plants with high efficiency), and increasing market penetration of subsidized renewables.[109] An analysis from 2017 found that nearly all U.S. nuclear units had lower revenues than costs (Figure 26).

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[108] Nuclear Energy Institute (2020), *Nuclear Costs in Context*, October (link).

[109] Geoffrey Haratyk (2017), "Early nuclear retirements in deregulated U.S. markets: Causes, implications and policy options," *Energy Policy* 110:150-166 (link); Andrew Mills, Ryan Wiser, Dev Millstein, Juan Pablo Carvallo, Will Gorman, Joachim Seel, and Seongeun Jeong (2021), "The impact of wind, solar, and other factors on the decline in wholesale power prices in the United States," *Applied Energy* 283:116266 (link).

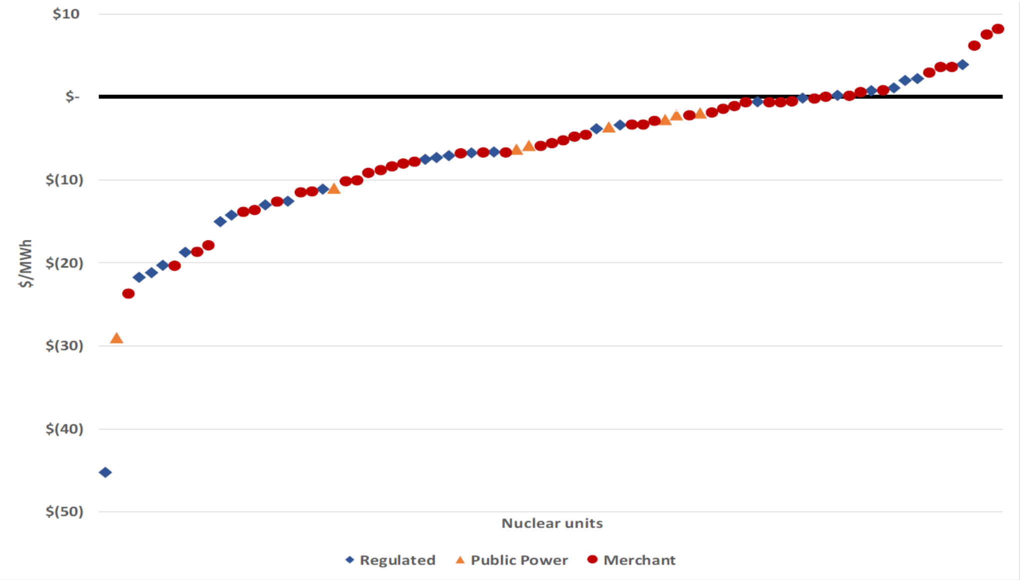

Figure 26. Revenue Gap of Existing U.S. Nuclear Power Plants[110]

Low electricity prices, in combination with maintenance requirements for aging equipment and policy issues such as the ecological impacts of cooling water intake, have led to the retirement of twelve U.S. nuclear reactors since 2012, and three additional retirements are planned (excluding four units in Illinois that will receive state assistance from legislation passed in September 2021).[111] Figure 27 shows the number and causes of nuclear unit retirements in OECD countries from 2011 to 2025. Most of the U.S. retirements are attributed to market pressure.

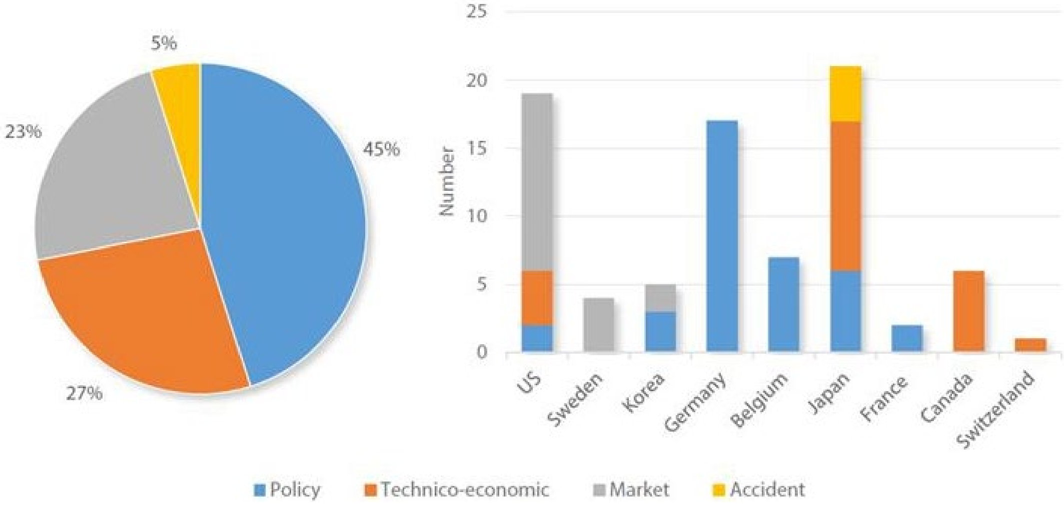

Figure 27. Nuclear plant closures in OECD countries, 2011-2025[112]

Ex ante and *ex post* empirical modeling studies indicate that nuclear retirements may lead to higher CO_2 emissions because of replacement power from natural gas or other fossil units, higher electricity prices, and higher likelihood of

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[110] Ronaldo Szilard, Phil Sharpe, Edward Kee, Edward Davis, and Eugene Grecheck (2017), *Economic and Market Challenges Facing the U.S. Nuclear Commercial Fleet – Cost and Revenue Study*, INL/EXT-17-42944 (link).

[111] Congressional Research Service (2021), *Nuclear Energy: Overview of Congressional Issues*, October 20, Report R42853, pp. 9-10 (link); see also Congressional Research Service (2021), *U.S. Nuclear Plant Shutdowns, State Interventions, and Policy Concerns*, June 10, Report R46820 (link); U.S. Department of Energy (2017), *Staff Report to the Secretary on Electricity Markets and Reliability*, August, pp. 27-34 (link).

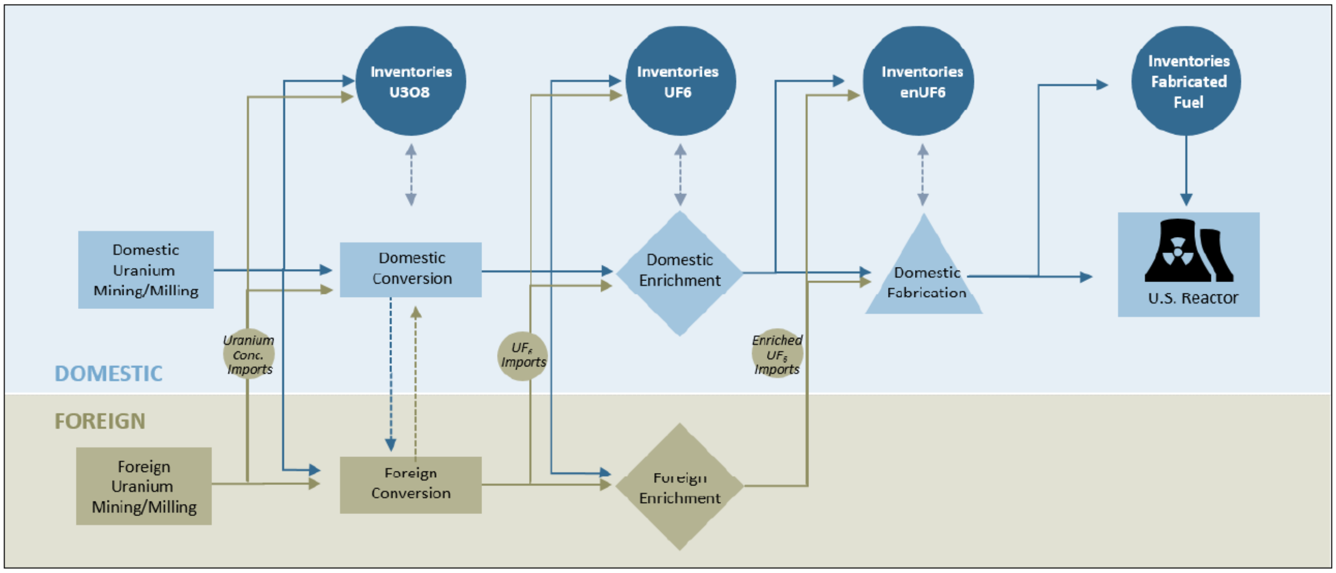
[112] Nuclear Energy Agency (2021), *Long-Term Operation of Nuclear Power Plants and Decarbonisation Strategies*, NEA Report No. 7524 (link).

blackouts or other service disruptions.[113] Several states have introduced non-market financial supplements to nuclear power plants with negative net revenues, and the Infrastructure Investment and Jobs Act of 2021 (Public Law 117-58) authorizes $6 billion in total funding from Fiscal Years 2022 to 2026 for a civil nuclear credit program to support the financial viability of eligible nuclear power plants.[114]

3.1.2 Uranium

The current uranium supply chain is developed to support the U.S. LWRs with LEU enriched to less than 5 percent. As previously discussed, most advanced reactors will require the use of LEU enriched to no more than 20 percent (HALEU). This section covers the current LEU supply chain (< 5 percent enrichment) and the associated risks, as well as projections of HALEU that would be needed to support advanced reactors.

Figure 28 shows the intersections between the foreign and domestic fuel supply chain supporting the U.S. LWR fleet (LEU supply chain). This figure shows how the current LWR fuel supply chain works. This figure does not show how much capacity is available in the United States versus the foreign entities.



Source: CRS generated a conceptual diagram depicting uranium material flows at the front-end of the nuclear fuel cycle.

Notes: The figure shows a simplified version of the nuclear fuel supply chain for domestic nuclear power reactors.

"Domestic" and "Foreign" are used here consistent with DOE's interpretations of the terms. *Domestic* refers to physical facilities operating within the United States, regardless of a foreign corporation ownership. In some instances, domestic uranium producers, suppliers, enrichers, and utilities operating in the United States have foreign ownership or are subsidiaries of foreign corporations. The term *foreign* is used to describe any non-U.S. based facility or material origin. Foreign inventories may exist in other countries, but are not shown here.

Figure 28. Domestic and Foreign Low Enriched Uranium (< 5 percent) Supply[115]

Figure 29 shows the current breakdown of global uranium production. The United States produces only 0.2 percent of global supply. The largest supplier of uranium is Kazakhstan with close to half of production, with Australia second at

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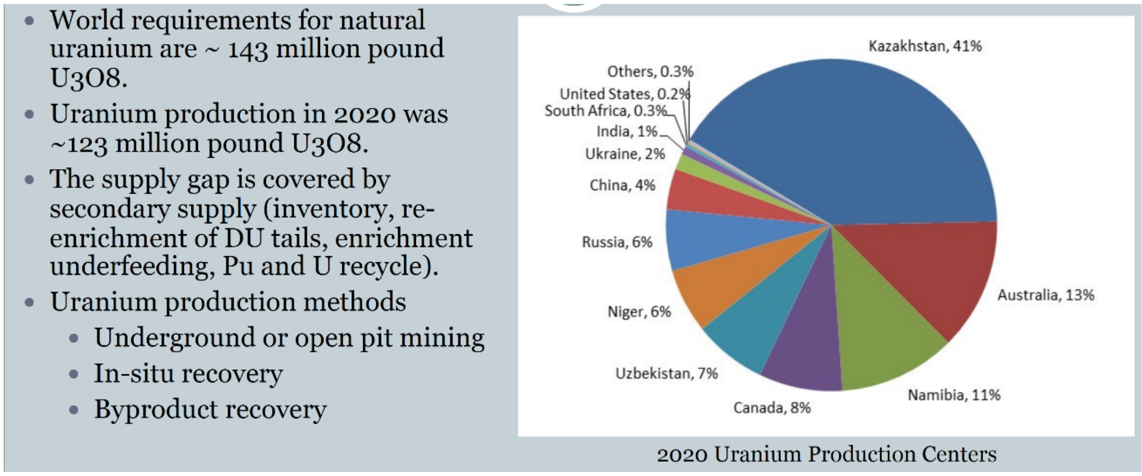
[113] NERA Economic Consulting (2012), *Potential Energy and Environmental Impacts of Denying Indian Point's License Renewal Applications*, March (link); California Air Resources Board (2015), *California Greenhouse Gas Emissions for 2000 to 2013 – Trends of Emissions and Other Indicators*, June 16, p. 4 (link); Energy Information Administration (2016), "Fort Calhoun becomes fifth U.S. nuclear plant to retire in past five years," October 31 (link); Luca Davis and Catherine Hausman (2016), "Market Impacts of a Nuclear Plant Closure," *American Economic Journal: Applied Economics* 8(2): 92–122 (link); James Richards and Wesley J. Cole (2017), "Assessing the impact of nuclear retirements on the U.S. power sector," *Electricity Journal* 30:14-21 (link); Kathryn D. Huff et al. (2021), *Economic and Carbon Impacts of Potential Illinois Nuclear Plant Closures*, University of Illinois at Urbana-Champaign, *Advanced Reactors and Fuel Cycles*, Report No. UIUC-ARFC-2021-02, May 6 (link); Justin Aborn et al. (2021), *An Assessment of the Diablo Canyon Nuclear Plant for Zero-Carbon Electricity, Desalination, and Hydrogen Production*, November (link).

[114] Center for Climate and Energy Solutions (2018), *Solutions for Maintaining the Existing Nuclear Fleet*, report by Doug Vine, May (link); Manhattan Institute (2019), *Is There a Future for Nuclear Power in the United States?*, report by Jonathan A. Lesser, July (link); U.S. Congress (2021), *Infrastructure Investment and Jobs Act of 2021*, enacted November 15, Section 40323 (link).

[115] Congressional Research Service (2019), *The Front End of the Nuclear Fuel Cycle: Current Issues*, Report No. 45753, July 29 (link).

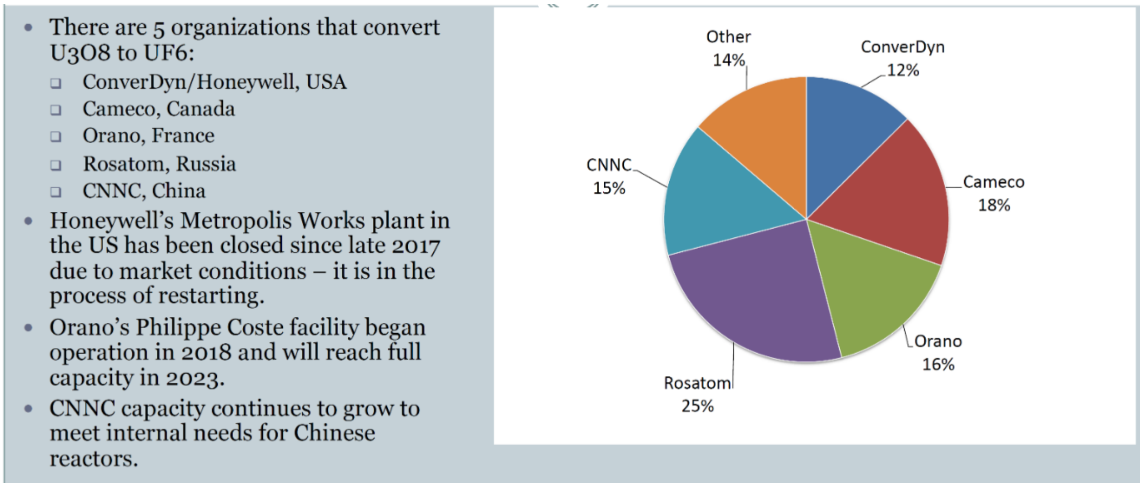
13 percent. The risk for the United States is a disruption to the global uranium supply where U.S. capacity cannot come up to speed fast enough to counter the disruption.



- World requirements for natural uranium are ~ 143 million pound U3O8.
- Uranium production in 2020 was ~123 million pound U3O8.
- The supply gap is covered by secondary supply (inventory, re-enrichment of DU tails, enrichment underfeeding, Pu and U recycle).
- Uranium production methods
  - Underground or open pit mining
  - In-situ recovery
  - Byproduct recovery

Figure 29. Global uranium production in 2020[116]

After uranium mining and milling, it must go to a conversion facility to be converted to uranium hexafluoride (UF_6). Figure 30 shows the global conversion capacity by company. Chinese and Russian state-owned enterprises control 40 percent of the world's conversion capacity.[117] The United States does not currently have operating conversion capacity and must rely on foreign suppliers. However, the ConverDyn/Honeywell Metropolis Works plant located in Illinois is in the process of restarting and will come online in 2023. In 2020, it was estimated that the world is currently using about 50 percent of its capacity for conversion.[118] After conversion to UF_6, the uranium must be enriched to the required level. Enrichment is dominated by four major suppliers: URENCO (United States, UK, Germany, and Netherlands), ORANO in France, Rosatom in Russia, and CNNC in China. There are many other smaller facilities in other countries.



- There are 5 organizations that convert U3O8 to UF6:
  - ❑ ConverDyn/Honeywell, USA
  - ❑ Cameco, Canada
  - ❑ Orano, France
  - ❑ Rosatom, Russia
  - ❑ CNNC, China
- Honeywell's Metropolis Works plant in the US has been closed since late 2017 due to market conditions – it is in the process of restarting.
- Orano's Philippe Coste facility began operation in 2018 and will reach full capacity in 2023.
- CNNC capacity continues to grow to meet internal needs for Chinese reactors.

Figure 30. Global uranium conversion organizations[119]

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[116] Eileen M. Supko (2021), "The Front End of the Nuclear Fuel Cycle," ANS FCWMD Nuclear Fuel Cycle Webinar, October.

[117] See also U.S. Department of Commerce Bureau of Industry and Security Office of Technology Evaluation (2019), *The Effect of Imports of Uranium on the National Security*, Subsection VI.D. "The Effect of State-Owned Enterprises on Global Uranium Supply" and Appendix I, April 14 (link).

[118] World Nuclear Association (2021), "Conversion and Deconversion," September (link).

[119] Eileen M. Supko (2021), "The Front End of the Nuclear Fuel Cycle," ANS FCWMD Nuclear Fuel Cycle Webinar, October.

3.1.3 HALEU Supply Chain for Advanced Reactors

Many advanced reactor designs require HALEU fuel. The United States does not currently have any commercial capacity to supply HALEU enrichment. The only supplier of HALEU right now is Tenex in Russia.[120] The Energy Act of 2020 (part of the Consolidated Appropriations Act of 2021, Public Law 116-260), Section 2001 "Advanced Nuclear Fuel Availability," requires DOE to establish a program to support the availability of HALEU. DOE is working to implement this act and is currently supporting a cost-shared demonstration project to produce a small quantity of HALEU using domestic technology.[121]

Studies have been performed to evaluate the expected HALEU demand. INL performed a study to evaluate HALEU needs through 2030. This study combined both the near term known high-fidelity demand and the potential commercial demand. High-fidelity demand, including the U.S. Department of Defense microreactor program,[122] DOE advanced reactor demonstration, medical isotopes, and other DOE needs, is approximately 8 to 12 metric tons of uranium (MTU) per year through 2030.[123] The report also includes a potential commercial demand that could exceed 100 MTU by 2030.[124] However, it should be noted that these are based on an assumption of commercial deployment which could end up being delayed. For example, both the X-energy and TerraPower reactors will require HALEU with the X-energy design estimated to require 1.6 MTU and the TerraPower design requiring 13 MTU in a core load.

The INL study discussed above does not look at HALEU needs after 2030 where deployment of advanced nuclear reactors would be expected except for some early commercial demand projections. The amount of HALEU required will depend on the speed and scale of commercial advanced reactors. Dixon et al. (2021) evaluated a potential decarbonization scenario that showed total nuclear capacity increasing to 250 GW in the United States by 2050, which would more than double the current capacity of ~95 GW.[125] As discussed in Section 1.2.1, nuclear capacity expansion in the *Long-Term Strategy* is within the level modeled in Dixon et al. (2021); the sources are consistent in that they both consider substantial increases from current capacity. Under the 250 GW scenario in Dixon et al. (2021), a mix of advanced reactors was assumed for the deployment. Figure 31 shows the yearly HALEU requirements for the advanced reactor mix used in that study. Under this scenario, the HALEU need ramps from demonstration needs of near zero in 2030 to 520 MTU/yr in 2050. Based on the ramp up, this is a total cumulative HALEU need of 5,350 MTU. Note that there is a range on this number from 3,450 MTU up to 7,175 MTU depending on the mix of advanced reactors deployed. The increase to 250 GW through the deployment of additional nuclear capacity is within reason given the full decarbonization scenarios presented earlier in the report. If nuclear deployment costs see significant decreases, deployment could increase further which would drive additional HALEU demand.

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[120] American Nuclear Society (2021), "Hot U market and simmering interest in HALEU: It boils down to demand," *Nuclear Newswire*, September 22 (link); Third Way (2021), "Background and Policy Issues – HALEU Fuel Supply," by Alan Ahn and Josh Freed, August 12 (link).

[121] World Nuclear News (2019), "Centrus signs HALEU contract with Department of Energy," November 6 (link); World Nuclear News (2021), "Centrus receives licence for HALEU production," June 15 (link).

[122] U.S. Department of Defense (2021), "Strategic Capabilities Office Selects Two Mobile Microreactor Concepts to Proceed to Final Design," March 22 (link).

[123] Monica C. Regalbuto (2020), *High-Assay Low Enriched Uranium Demand and Deployment Options* (summary presentation), INL/EXT-21-61768, Idaho National Laboratory, June (link).

[124] See also Nuclear Energy Institute (2022), *Establishing a High Assay Low Enriched Uranium Infrastructure for Advanced Reactors*, January (link); Nuclear Energy Institute (2021), *Letter to Secretary of Energy Jennifer Granholm on Updated Need for High-Assay Low Enriched Uranium*, December 20 (link).

[125] Brent Dixon, Son H. Kim, Bo Feng, Taek Kim, Scott Richards, and Jin Whan Bae (2021), *Estimated HALEU Requirements for Advanced Reactors to Support a Net-Zero Emissions Economy by 2050*, INL/EXT-21-64913, December (link).

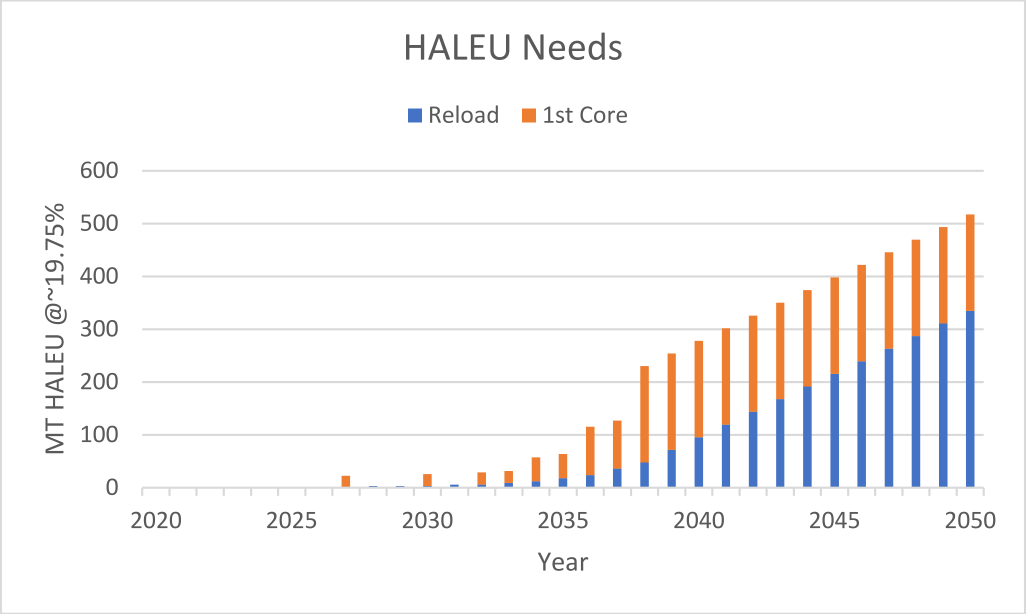

Figure 31. Projected HALEU Needs for Advanced Non-LWRs to 2050[126]

The final need in the fuel supply is fuel fabrication. As previously discussed, companies have started to move forward with fuel fabrication facilities for advanced reactor fuel forms. X-energy is working with the DOE to establish a commercial scale TRISO fuel fabrication facility as part of their ARDP award and BWXT has some existing TRISO commercial capacity (capable of producing 100s of kilograms of TRISO fuel per year) that recently restarted in Lynchburg, Virginia. TerraPower is standing up a commercial production capability for its metal fuel to support their Natrium reactor. Additional advanced reactor fuel form fabrication is expected to be required.

3.1.4 Critical Minerals[127]

Fabrication of parts and components for nuclear plants requires various critical minerals. Figure 32 shows the amount of critical minerals required per megawatt of electricity generated for various power generation types. For nuclear, this chart refers to the current nuclear fleet of LWRs as the materials are known well. Consistent with earlier discussions, chromium and nickel are two of the largest required minerals for construction of LWRs as well as the new advanced reactors. Lithium and graphite are not listed as materials for nuclear power plants as this chart does not refer to the advanced reactors. However, as previously discussed, lithium is important to maintain operation of PWRs and will also be required in molten salt reactors. Other advanced reactors will also require the use of graphite as a moderator.

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[126] Ibid.

[127] Background sources for this section include: Michael F. Ashby (2013), Materials for low-carbon power, Chapter 12 in *Materials and the Environment* (2nd ed., pp. 349–413) (link); Nedal T. Nasser (2020), “Evaluating the mineral commodity supply risk of the U.S. manufacturing sector,” *Science Advances* (link); Jordy Lee et al. (2020), “Responsible or reckless? A critical review of the environmental and climate assessments of mineral supply chains,” *Environmental Research Letters* 15(10): 103009 (link); J. Lee et al. (2020), “Reviewing the material and metal security of low-carbon energy transitions,” *Renewable and Sustainable Energy Reviews* 124:109789 (link); U.S. Department of Energy (2011), *Critical Materials Strategy*, December (link); U.S. Geological Survey (2020), *Investigation of Foreign Reliance on Critical Minerals—U.S. Geological Survey Technical Input Document in Response to Executive Order No. 13953 Signed September 30, 2020*, Open-File Report 2020–1127, Version 1.1, December 7 (link); U.S. Geological Survey (2021), *Mineral Commodity Summaries 2021*, January (link); World Bank (2017), *The Growing Role of Minerals and Metals for a Low Carbon Future*, June (link); The White House (2021), *Building Resilient Supply Chains, Revitalizing American Manufacturing, and Fostering Broad-Based Growth: 100-Day Reviews Under Executive Order 14007*, June (link).

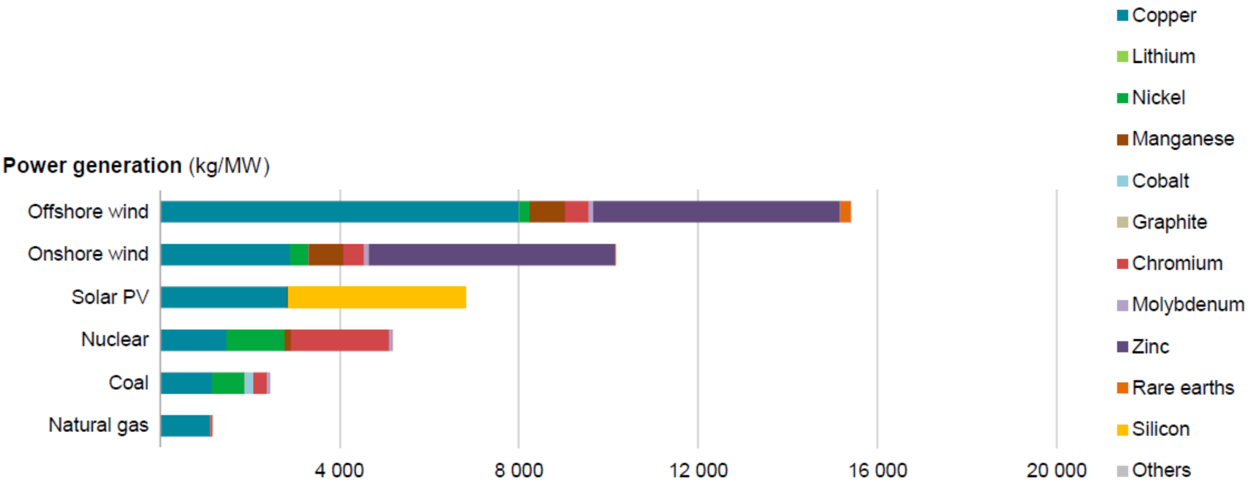

Figure 32. Critical Minerals per MW of Power Generation Sources[128]

Figure 33 shows the top three producing countries for selected minerals. For nickel, graphite, and lithium, most of these minerals are produced outside of the United States. This means that the United States will most likely rely on imports to support construction of these reactors with some of these coming from countries such as China.

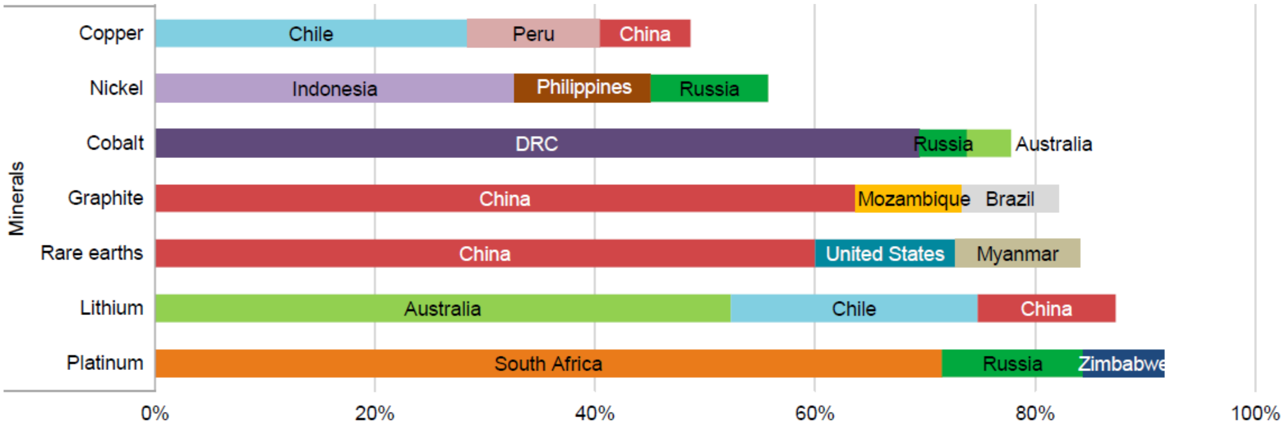

Figure 33. Share of Top Three Producing Countries in Total Production for Selected Minerals, 2019[129]

Some of the most relevant minerals were determined as outlined in the beginning of the section. These minerals are required in large quantities or are critical for certain components. Table 8 shows the U.S. net import reliance of these minerals based on information from the U.S. Geological Survey.[130] The table also includes the countries that produce these materials to enable comparison with U.S. import reliance and source-specific risk assessments.

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[128] International Energy Agency (2021), *The Role of Critical Minerals in Clean Energy Transitions*, World Energy Outlook Special Report, May, p. 26 (link).
[129] Ibid., p. 30.
[130] U.S. Geological Survey (2021), *Mineral Commodity Summaries 2021*, January (link).

Table 8. Critical Minerals Most Relevant to the Nuclear Energy Supply Chain with High U.S. Import Reliance

Mineral	U.S. Net Import Reliance	Countries of Production
Graphite	100%	75% in China
Yttrium	100%	99% in China[131]
Indium	100%	40% in China, 31% in South Korea
Niobium	100%	88% in Brazil
Chromium	75%	Over 50% in South Africa and Kazakhstan
Lithium	>50%	58% in Australia
Nickel	50%	Most production in Indonesia, Philippines, and Russia

Based on this review, graphite is considered a mineral at risk because the United States is 100 percent reliant on imports and 75 percent of global production occurs in China. Yttrium, which could be used as a moderator material for advanced reactors, could also become a mineral at risk because the United States relies entirely on imports and China accounts for 99 percent of global yttrium production. Other critical minerals in Table 8 have more diversified production sources and (in most cases) lower U.S. import reliance.

3.1.5 Workforce and Education

The nuclear supply chain relies on a wide array of workers for initial design and licensing, project planning, construction, operation, and decommissioning. Many members of the current U.S. nuclear workforce are nearing retirement age, and younger replacements will be needed. A large nuclear construction project creates jobs for several thousand workers, including siting and design teams, welders, pipefitters, electricians, civil engineers, safety managers, radiation technicians, health physicists, quality assurance inspectors, and commissioning crews. A study by the Organisation for Economic Co-Operation and Development (OECD) Nuclear Energy Agency and the International Atomic Energy Agency projects that 200,000 labor-years of employment are generated for a new 1 GWe nuclear reactor.[132] An extensive multi-unit nuclear build program in the United States would require a pipeline approach beginning with students in relevant fields, followed by apprenticeships and other entry-level positions, ultimately leading to ample numbers of highly experienced master tradespeople, engineers, and other workers (many of whom are or would be union members).[133] Figure 34 illustrates one such pipeline that combines workers with and without postsecondary study from initial jobs toward technical expertise.

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[131] Congressional Research Service (2019), *Critical Minerals and U.S. Public Policy*, Report No. R45810, June 28, p. 12 (link).

132 Organisation for Economic Co-operation and Development Nuclear Energy Agency and the International Atomic Energy Agency (2018), *Measuring Employment Generated by the Nuclear Power Sector*, Report NEA No. 7204, pp. 30-35 (link). The total employment estimate includes direct, indirect, and induced job impacts for construction, operation and maintenance (assuming a plant lifetime of 50 years), fuel production, decommissioning, and waste management.

[133] European Commission Joint Research Centre (2018), *Nuclear Job Taxonomy*, Report No. 110868 (link); C.R. Kenley et al. (2009), "Job creation due to nuclear power resurgence in the United States," *Energy Policy* 37:4894-4900 (link); European Commission Joint Research Centre (2019), *Results of Surveys of the Supply of and Demand for Nuclear Experts Within the EU-28 Civil Nuclear Energy Sector*, Report No. 117806 (link).

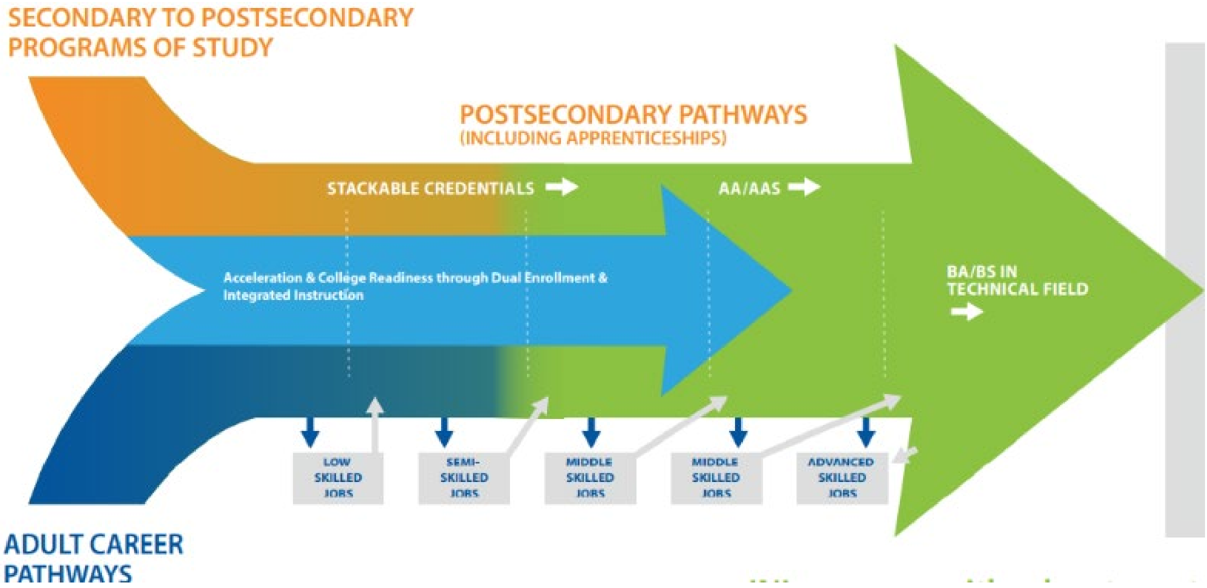

Figure 34. Workforce Development for Nuclear Plants[134]

The United States is currently facing a broader shortage of skilled tradespeople for the same reasons as stated above for the nuclear industry in particular: many workers in these fields are approaching retirement age, and fewer people are replacing them. The American Welding Society indicates that almost half of U.S. welders are over 45 years old, and it predicts that over 300,000 new welders will be needed by 2024.[135] According to a survey by the Nuclear Fabrication Consortium in 2010, 67 percent of welding companies said they would not have enough welders for a resurgence in U.S. nuclear construction.[136] Shortages of skilled labor would increase the schedule and costs of future plants.[137]

3.1.6 Certifications

Many components and processes for nuclear construction and operation require vendor certification. The American Society of Mechanical Engineers (ASME) sets standards and conducts rigorous audits of organizations under its Nuclear Quality Assurance (NQA) program.[138] Figure 35 shows the geographic distribution of nuclear (N)-stamp holders in the United States. A shortage of certified vendors relative to potential future demand for nuclear components and services could hinder deployment of new reactors, raise their costs, and lengthen their construction periods. Some assessments of the NQA program suggest that the administrative burden could be lessened without any decrease in quality assurance, and harmonizing the program with Nuclear Regulatory Commission requirements could enhance both the effectiveness and efficiency of quality assurance in future nuclear projects.[139]

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[134] Amy Rene Lientz (2021), *Energy Supply Chain Strategic Plan*, INL/MIS-21-61259, Idaho National Laboratory, January (link).

[135] American Welding Society (2022), "Demand for welders in the upcoming years" (link).

[136] Nuclear Fabrication Consortium (2010), *Nuclear Fabrication Supply Chain*, p. 12 (link).

[137] Hossein Karimi et al. (2018), "Impact of Skilled Labor Availability on Construction Project Cost Performance," *Journal of Construction Engineering and Management* 144(7) (link).

[138] American Society of Mechanical Engineers (no date), "Nuclear Quality Assurance (NQA-1) Certification" (link).

[139] U.S. Nuclear Industry Council (2021), "U.S. Nuclear Industry Council Comments for NRC ACRS Part 53 Meeting," March 17, slide 28 (link); Robert Patrick White (2019), *Pathways and Frameworks for the Licensing and Regulation of Advanced Nuclear Reactors in the United States*, MIT PhD dissertation, February, pp. 52-54 (link); Jacopo Buongiorno et al. (2018), *The Future of Nuclear Energy in a Carbon-Constrained World*, MIT Interdisciplinary Study, September, pp. 142-144 (link); see also Energy Facilities Contractors Group (2021), *Tailoring of NQA-1 Quality Requirements for Procurement*, June (link); Idaho National Laboratory (2010), *Next Generation Nuclear Plant Quality Assurance Program Description*, PDD-172, October 1 (link); Charles Komanoff (1981), *Power Plant Cost Estimation: Nuclear and Coal Capital Costs, Regulation, and Economics*, pp. 74-78.

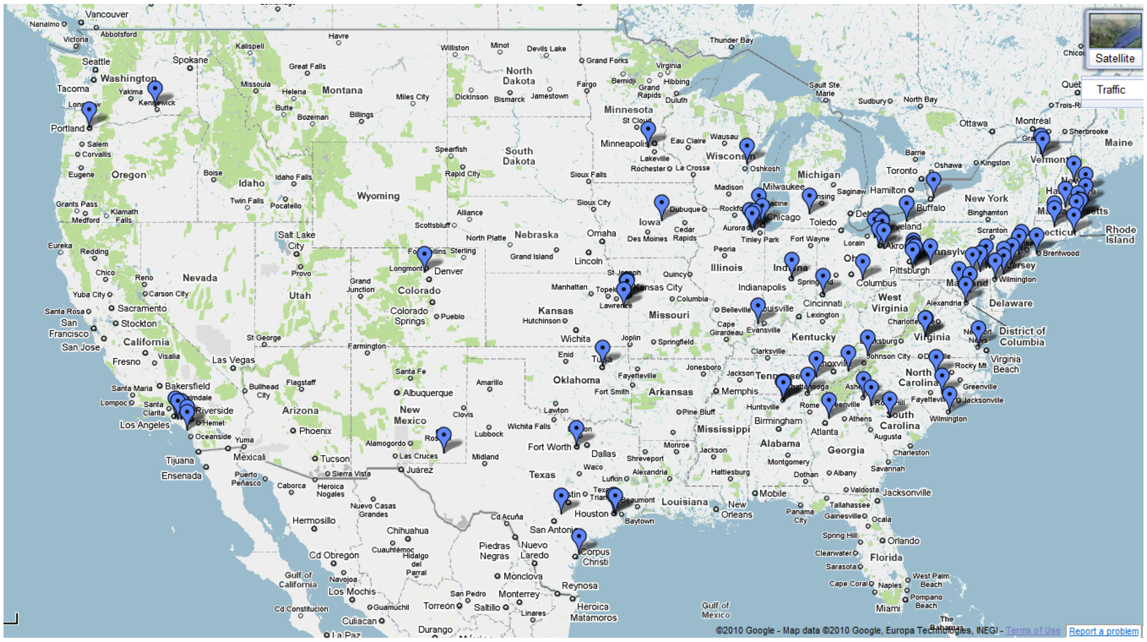

Figure 35. Nuclear Vendors with N-Stamp Certification[140]

3.1.7 Climate Mitigation and Resilience

A resilient energy system relies on the robustness of individual generation technologies, grid infrastructure, and demand side measures. Severe weather events have contributed to a troubling domestic trend where power failures have increased by more than 60 percent since 2015[141]. Generating technologies all respond differently to extreme cold, and although some perform better than others, extreme cold events can cause significant disruptions to all generation technologies. For example, coal piles can freeze, natural gas supply wells and infrastructure can freeze, nuclear reactors can trip offline due to frazil ice buildup, ice buildup on wind turbines can cause them to go offline, snow buildup on solar panels can significantly reduce production, and hydropower can be susceptible to surface and frazil ice buildup.

An extreme winter storm and extended cold weather event hit Texas and the central United States February 8–19, 2021. This led to both exceptional energy demands and issues with electricity and natural gas supplies over several days. Residential space heating drove the increases in demand, with over 60 percent of Texas homes using electric heat pumps and 35 percent using natural gas furnaces. Supply issues were caused by freezing equipment and supply lines, impacting both natural gas supplies and most forms of electricity generation. Natural gas supplies were especially important because natural gas supplied about 50 percent of the electricity generating capacity in ERCOT, the primary grid operator in Texas.

On February 17, 10 GW of capacity was brought back online, and ERCOT ceased load shedding just before midnight. Real time generation by fuel source is shown in Figure 36. Coal, natural gas, and nuclear generators were forced offline to varying degrees due to the freezing weather. A common cause of these outages was frozen plant equipment, since many Texas power plants were not designed to operate in subfreezing conditions and low wind chills for several days.

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[140] Nuclear Fabrication Consortium (2010), *Nuclear Fabrication Supply Chain*, p. 8 (link).
[141] International Atomic Energy Agency (2021), *Nuclear Energy for Net Zero World* (link).

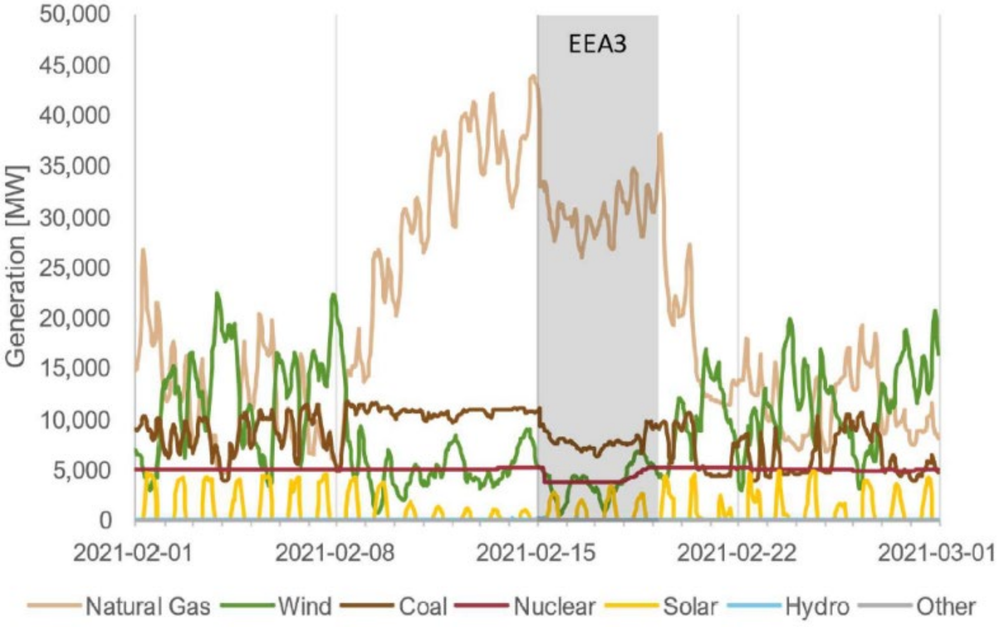

Figure 36. ERCOT Electricity Generation During the Energy Emergency Alert Level 3 in February 2021[142]

The ERCOT grid has very limited interconnections with the Eastern Interconnection (via the Southwest Power Pool) and Mexico (via CENACE). Both adjacent markets were unable to supply emergency power due to their own related operational issues. Even if they had been available to assist, the ties were too small to overcome a 20 GW generating deficit. This event illustrated the intertwined risks of heating and electricity shortages when natural gas supplies are limited. Wind turbines and solar PV panels are also susceptible to derates and outages during cold weather events. If capacity growth continues, their effects on bulk power system reliability will increase. In future decarbonized electricity markets, a variety of zero-carbon energy sources would reduce the impact of a single energy source outage in an extreme weather event.

South Texas Project Unit 1 was forced offline February 15–17, 2021 due to cold weather. The unit had experienced a similar forced outage during a December 1989 cold weather event. The other nuclear power units in ERCOT were unaffected by the weather (South Texas Project Unit 2, Comanche Peak Units 1 and 2). Nuclear power plants are not susceptible to sudden fuel supply interruptions like existing natural gas power plants. New nuclear power plants should be designed for extreme hot and cold weather operations without derating, and the range of future risks due to climate change should be incorporated into the designs. Distributed or portable nuclear power plants currently under development could be useful for emergency power generation in the future.

3.1.8 National Security

The U.S. civil nuclear enterprise makes significant contributions toward national security in the areas of energy, defense, and international cooperation. As sources of reliable baseload electricity, U.S. nuclear plants provide stability and resilience in the energy system. Potential future use of nuclear energy to produce synthetic hydrocarbon fuels would reduce U.S. reliance on oil imports, and transitioning to synthetic fuels produced by nuclear energy could reduce exposure to petroleum supply chain vulnerabilities.[143] Although the United States currently relies on uranium imports

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[142] W. Neal Mann, Katie Biegel, Nicolas E. Stauff, and Brent Dixon (2021), *Feb. 2021 Electricity Blackouts and Natural Gas Shortages in Texas*, ANL 21/29, Argonne National Laboratory, July 30 (link).

[143] Information Technology and Innovation Foundation (2019), *The Clean Energy Dividend: Military Investment in Energy Technology and What It Means for Civilian Energy Innovation*, report by Dorothy Robyn and Jeffrey Marqusee, March (link). Excerpt: "The tether of fuel proved extremely deadly during the conflicts in the Middle East, when resupply convoys carrying fuel and water to U.S. bases there became the most vulnerable targets for insurgent attacks. One oft-cited report calculated that, in 2007 alone, 170 U.S. service members were killed or wounded in fuel-related missions in Iraq and Afghanistan." Many casualties during U.S. military operations in Iraq, Afghanistan, and previous wars occurred during fuel and water supply missions, as reported in Army Environmental Policy Institute (2009), *Sustain the Mission Project: Casualty Factors for Fuel and Water Resupply Convoys*, September (link).

for most of its nuclear fuel needs, several of the countries with large deposits and high production levels are close allies of the United States and could potentially increase their exports to the United States during a supply disruption. As discussed above, the United States has a diverse supply chain capable of providing almost all necessary components for nuclear plants, with the exception of certain critical minerals identified in Section 3.1.4 and large forges for gigawatt-scale reactor pressure vessels (which could be mitigated through advances in additive manufacturing).[144]

Recent reports by the Atlantic Council and the Center for Strategic and International Studies highlight the synergies between civil nuclear energy, naval propulsion, nuclear weapons, and broader aspects of national security.[145] The synergies stem from investment in human capital through broadly applicable university education and scholarship, diverse and robust supply chains, expertise in nuclear safety and non-proliferation, and long-term international relationships for the construction, fueling, operation, and regulation of nuclear facilities.

3.1.9 Cyber Security

Park and Lee (2020) identify five areas of possible cyber attacks on nuclear plants: (1) digitalized protection systems, such as disabling trip signals; (2) digitalized control systems, such as disabling auxiliary feedwater pumps and valves; (3) operator systems, such as disabling alarms or sending wrong information to cause errors of omission or commission; (4) physical components, such as disabling emergency diesel generators; and (5) direct initiation of accident scenarios, such as actuating valves to cause loss of coolant.[146]

Cyber security experts at U.S. utilities, National Laboratories, and other organizations work to prevent such attacks on existing nuclear plants and to design future systems for minimal vulnerability. For example, the Cybercore Integration Center at Idaho National Laboratory "brings together experts in critical infrastructure security assessments, cyber forensic analysis, threat detection and consequence-based targeting to provide real-world technical solutions and innovations that protect operational environments from an ever-evolving threat landscape. Seasoned threat analysts work in concert with experienced power engineers, cyber researchers and control systems experts to develop novel, comprehensive solutions to protect vital control systems from cyberthreats."[147] Researchers are also developing cyber security strategies for remotely operated microreactors.[148] EPRI's Technical Assessment Methodology provides an integrated framework for evaluating cyber security risks across the full array of nuclear plant systems.[149]

Eggers (2021) discusses cyber vulnerabilities across segments of the nuclear supply chain and notes that "supply chain exploits can be introduced early in the product lifecycle such that they remain persistent and undetected until triggered. In addition, the use of commodity hardware and software lowers barriers of entry by enabling the adversary to use publicly available information to gain the knowledge necessary for successful exploits." Figure 37 depicts cyber vulnerabilities in the nuclear supply chain using block figures to represent components and processes, with green figures at the top facing little likelihood of targeted attack, yellow figures in the middle facing moderate likelihood, and peach figures at the bottom facing high likelihood. Smaller shapes on the left of each figure denote stakeholders, such as manufacturers, integrators, and end users. Letters from A to F enclosed in circles denote the six possible types of supply chain attacks.

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[144] Bridget Mintz Testa (2012), "Heavy Duty," *Mechanical Engineering* 134(4):28-32, April (link); Joseph Simpson (2019*), Considerations for Application of Additive Manufacturing to Nuclear Reactor Core Components*, ORNL/TM-2019/1190, Oak Ridge National Laboratory, May 31 (link); Matthew Hiser et al. (2021), "Regulatory Research Perspective on Additive Manufacturing for Nuclear Component Applications," *Journal of Nuclear Materials* 546:152726 (link); EPRI (2021), *Advanced Manufacturing Methods Roadmap for the Nuclear Energy Industry*, Report 3002022978, November (link).

[145] Atlantic Council Global Energy Center (2019), *The Value of the U.S. Nuclear Power Complex to U.S. National Security*, report by Robert F. Ichord and Bart Oosterveld, October (link); Center for Strategic and International Security (2018), *Back from the Brink: A Threatened Nuclear Energy Industry Compromises National Security*, report by Michael Wallace, Amy Roma, and Sachin Desai, July (link).

[146] Jong Woo Park and Seung Jun Lee (2020), "A quantitative assessment framework for cyber-attack scenarios on nuclear power plants using relative difficulty and consequence," *Annals of Nuclear Energy* 142:107432 (link); see also Chatham House: The Royal Institute of International Affairs (2015), *Cyber Security at Civil Nuclear Facilities: Understanding the Risks*, report by Caroline Baylon with Roger Brunt and David Livingstone, September (link). Cybersecurity issues are also addressed in the DOE EO 14017 response report.

[147] Idaho National Laboratory (2022), "Cybercore Integration Center: Enabling Partnerships to Secure Control Systems" (link).

[148] Piyush Sabharwall et al. (2021), "Cyber security for microreactors in advanced energy systems," *Cyber Security* 4(4):345-367 (link).

[149] EPRI Journal (2020), "Toward a New Risk-Informed Approach to Cyber Security," January/February (link); Phillip L. Turner, Timothy A. Wheeler, and Matt Gibson (2017), *Risk Informed Cyber Security for Nuclear Power Plants*, SAND2017-3970C, Sandia National Laboratories and EPRI (link).

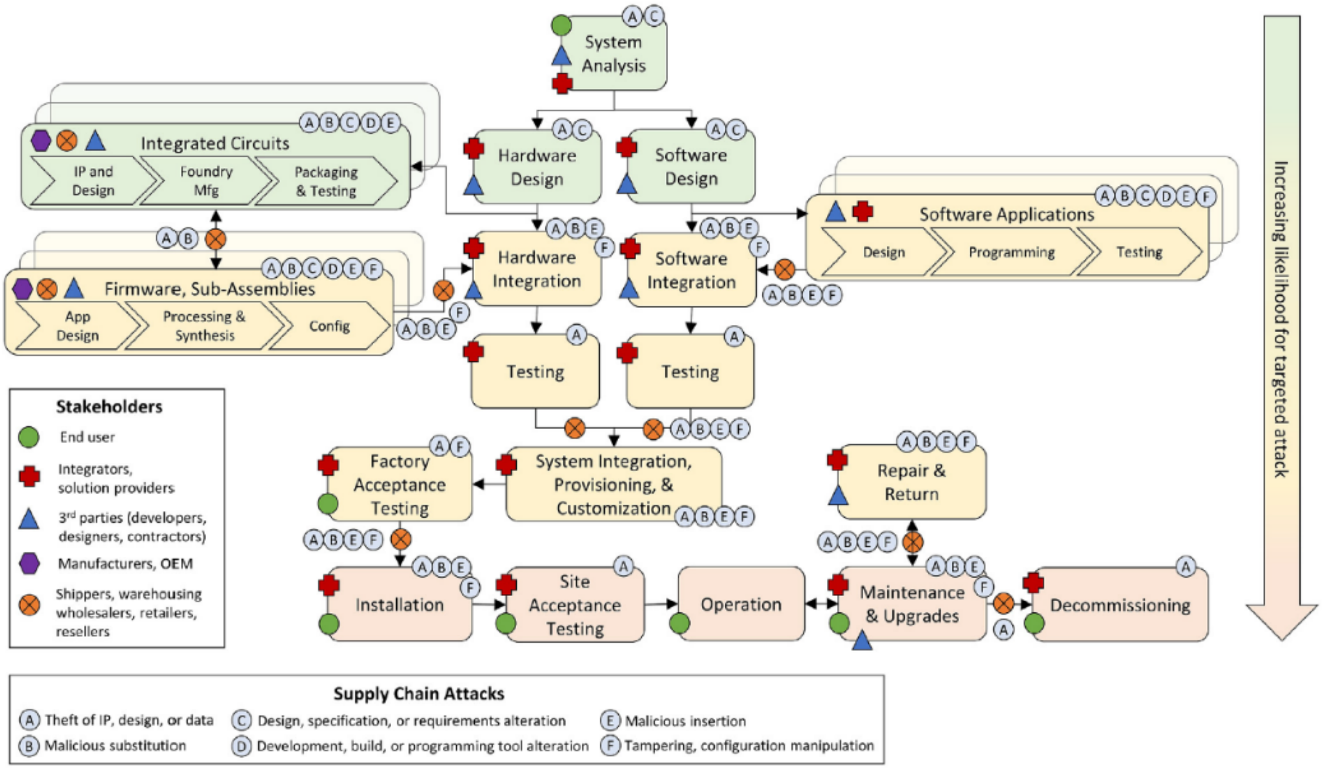

Figure 37. Cyber Security Vulnerabilities in Nuclear Supply Chain[150]

3.2 Future Outlook

The U.S. nuclear sector is poised to diversify in terms of reactor type (based on coolant, fuel, temperature, safety profile, etc.) as well as plant size and energy products. Previous subsections have described the necessary materials to construct non-LWR designs and the need for HALEU to fuel them. Before they can be built and operated, however, further research and analysis must be performed to ensure their technical feasibility and safety and economic competitiveness. Figure 38 illustrates the seven categories of evaluation to demonstrate the safety case for new reactor licensing: accident sequences and initiators, core design and heat removal, fuel qualification, analytical codes and methods, materials analysis, instrumentation and control, and structural analysis. Tobin and Aumeier (2018) provide additional detail on development of materials, fuels, sensors, controls, and advanced manufacturing technologies to enable the next generation of nuclear plants.[151] Progress must continue on non-LWR research, analysis, regulatory framework, and supply chain readiness in this decade so that advanced reactors can enter the U.S. energy system and achieve widespread commercial deployment over the longer term.

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[150] Shannon Eggers (2021), "A novel approach for analyzing the nuclear supply chain cyber-attack surface," *Nuclear Engineering and Technology* 53:879-887 (link).

[151] K. Tobin and S. Aumeier, editors (2018), *Technologies to Reactors: Enabling Accelerated Deployment of Nuclear Energy Systems*, December 12 (link).

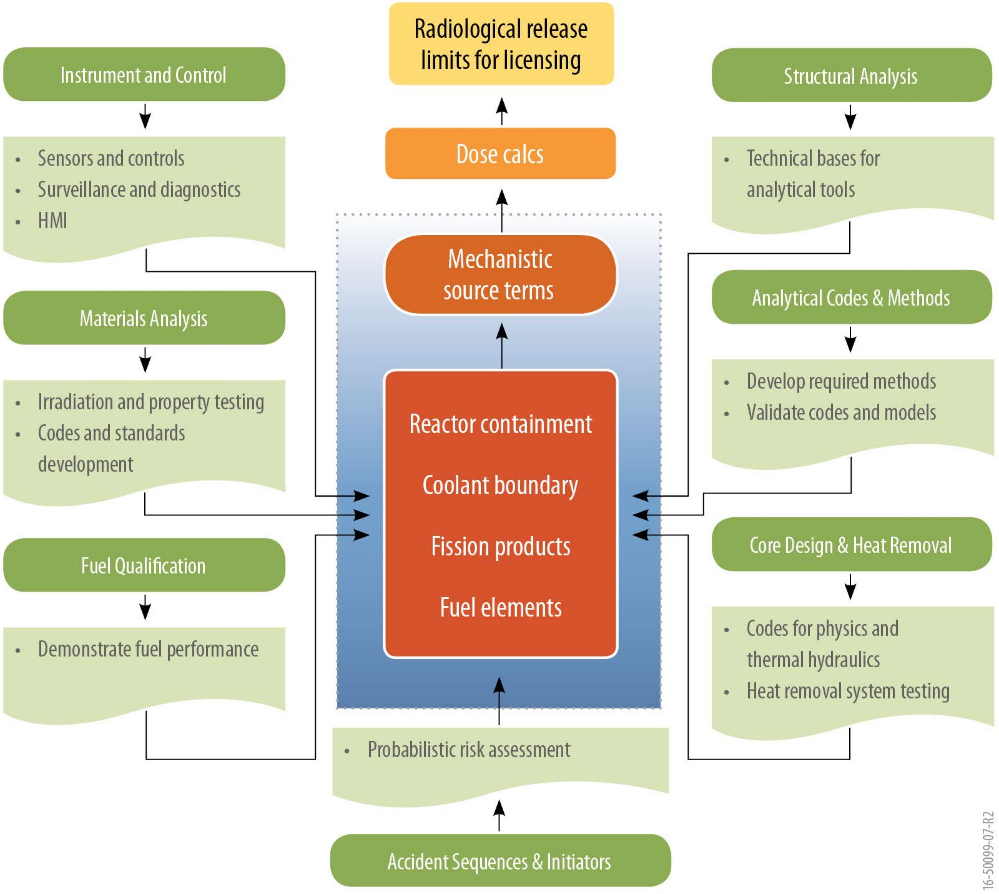

Figure 38. Technology development typically required for licensing[152]

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[152] D. Petti, R. Hill, J. Gehin, et al. (2017), *Advanced Demonstration and Test Reactor Options Study*, INL/EXT-16-37867, Rev. 3, January, p. 64 (link).

4 U.S. Opportunities and Challenges

4.1 Prioritization of Efforts

The appendix presents an evaluation table using the standard template provided by the DOE Office of Policy for prioritizing efforts to support U.S. energy supply chains. The rows of the table show the components and segments of nuclear plants. For example, the nuclear fuel component consists of raw uranium and milling, uranium conversion, enrichment to LEU, enrichment to HALEU, LWR fuel fabrication, and advanced nuclear reactor fabrication. The second set of rows in the table relates to the reactor vessel, piping, and other equipment, with segments for input minerals and fabrication processes. The remaining sets of rows relate to other core components, coolants, molten salts, high-temperature reactors, and nuclear plant construction materials.

The ten columns of the table contain the evaluation criteria for the components and segments: (1) significant domestic suppliers, (2) significant domestic demand, (3) projected significant domestic demand, (4) significant global market, (5) projected significant global demand, (6) cost competitiveness among U.S. suppliers, (7) cost competitiveness between U.S. and global suppliers, (8) security of foreign sources, (9) sufficient effort to address environmental concerns, and (10) sufficient effort to address human rights concerns. Assessment entries in each cell ("Yes," "No," "Maybe," "N/A" if not applicable, or "?" if unclear based on current information) and color coding indicate the evaluation results across components and segments.

4.2 Near-Term and Long-Term Planning

As described in this report, the U.S. nuclear energy industry enables the largest commercial nuclear fleet in the world, generates the largest source of clean power in the country, and supports approximately half a million jobs. Driven by innovation and public-private partnerships, the U.S. nuclear industry is poised to diversify further in coming years as advanced nuclear plants with different coolants, fuels, sizes, and delivery methods are developed, demonstrated, and deployed to provide low-carbon energy for broader applications. Accelerated deployment of these innovative clean technologies provides the United States the opportunity to re-establish international leadership in this critical industrial sector, therefore ensuring that clean nuclear energy is deployed with a high-level of both safety and non-proliferation standards around the world.

Table 9 summarizes the U.S. nuclear energy supply chain's opportunities and challenges for near-term and long-term planning. In the near term (through the mid-2020s), the two main priorities for expansion of U.S. nuclear energy are to establish a secure domestic HALEU supply and to demonstrate innovative designs under ARDP. These actions will enhance U.S. energy security, establish new U.S. export opportunities, and reaffirm U.S. leadership in global nuclear energy, particularly on advanced technologies. Long-term planning revolves around continued operation and license extensions for existing LWRs, construction and operation of new plants (including possible repowering of retiring coal units), and broader application of nuclear energy beyond the power sector (such as heat, hydrogen, ammonia, and synfuels). Seizing these opportunities, however, will require overcoming various technical, economic, and planning challenges.

Table 9. U.S. Nuclear Energy Opportunities and Challenges for Near-Term and Long-Term Planning

Opportunities	Challenges
Near Term (through mid-2020s)	
Production of HALEU and other fuel forms	Aligning investment and production levels with possible future needs (depending on timing, size, and number of new plants)
Demonstration of innovative designs under ARDP	Sustained funding support (authorized in Section 41002 of the Infrastructure Investment and Jobs Act of 2021, Public Law 117-58), successful project implementation and testing outcomes
Long Term (beyond the mid-2020s)	
Continued operation and license extensions for existing LWRs	Possibly adverse future market conditions (lower electricity prices, lower net demand with renewables, lower plant revenue)
Construction and operation of SMRs, microreactors, and possibly new large LWRs	Further R&D and demonstration projects necessary, cost and schedule containment, siting and permitting, production of HALEU and other fuel forms, workforce and regulatory readiness, specialized components (domestic manufacturing or imports), critical mineral supply, national long-term waste disposal plan
Repowering coal plants with nuclear reactors	(similar to challenges listed above)
Carbon conversion (especially coal) with nuclear energy	(similar to challenges listed above)
Nuclear production of heat, hydrogen, ammonia, synfuels	(similar to challenges listed above, as well as integration with the various applications)
Government procurement of SMRs and microreactors for federal facilities, military bases and mobile operations, remote communities and islands (Alaska, Puerto Rico), space missions	(similar to challenges listed above)
Expanded exports of U.S. nuclear innovations	Competition with state-owned enterprises in other countries, especially China and Russia

5 Conclusion

This report responds to Executive Order 14017 by providing information on the current status and future outlook for the U.S. nuclear energy supply chain at home and abroad. DOE's goals are to enable continued operation of existing U.S. nuclear reactors, enable deployment of advanced nuclear reactors, develop advanced nuclear fuel cycles, and maintain U.S. leadership in nuclear energy technology. Although there are challenges and risks in each of these areas, implementation of targeted policies would support achievement of all the goals and would strengthen the U.S. nuclear supply chain to meet the Nation's energy, environmental, and societal needs.

Recommended policy actions to address the vulnerabilities and opportunities covered in this report may be found in the Department of Energy 1-year supply chain review policy strategies report, "America's Strategy to Secure the Supply Chain for a Robust Clean Energy Transition." For more information, visit www.energy.gov/policy/supplychains.

Appendix: Evaluation Table

Component/product	**SC segments to meet the demand of the final product**	**Significant domestic suppliers**	**Significant domestic demand**	**Projected significant domestic demand**	**Significant global market**	**Projected significant global demand**	**Cost competitive among U.S. suppliers**	**Cost competitive between U.S. suppliers vs. global suppliers**	**Is foreign supply source significant secure?**	**Is there sufficient effort to address environ-mental concerns?**	**Is there sufficient effort to address human rights concerns?**	**Does it make sense to build domestic capability for this product/ component?**
Nuclear fuel												
	Raw Uranium and Milling	No [most is imported]	Yes	Yes	Yes	Yes	Yes	No	Maybe	Maybe	?	Yes
	Uranium Conversion	No	Yes	Yes	Yes	Yes	Yes	No	Maybe	Maybe	?	Yes
	Enrichment LEU	Yes	Yes	Yes	Yes	Yes	Yes	Yes	N/A	N/A	N/A	No
	Enrichment HALEU	Not currently, but will ramp up	Not currently	Yes, for advanced reactors	Not currently	Yes, for advanced reactors	N/A currently	N/A	N/A	N/A	N/A	Yes
	LWR Fuel Fabrication	Yes	Yes	Yes	Yes	Yes	Yes	Yes	N/A	N/A	N/A	No
	Advanced Nuclear Fabrication	Not currently, but will ramp up	Not currently	Yes, for advanced reactors	Not currently	Yes, for advanced reactors	N/A currently	N/A	N/A	N/A	N/A	Yes
Reactor vessel, piping, and other equipment												
Minerals of Concern	Hafnium	No	No	Yes	Yes	Yes	N/A	N/A	Maybe	Yes	?	Low/no U.S. deposits

Component/product	**SC segments to meet the demand of the final product**	**Significant domestic suppliers**	**Significant domestic demand**	**Projected significant domestic demand**	**Significant global market**	**Projected significant global demand**	**Cost competitive among U.S. suppliers**	**Cost competitive between U.S. suppliers vs. global suppliers**	**Is foreign supply source significant secure?**	**Is there sufficient effort to address environ-mental concerns?**	**Is there sufficient effort to address human rights concerns?**	**Does it make sense to build domestic capability for this product/ component?**
	Indium	No	No	Yes	Yes	Yes	N/A	N/A	Maybe	Yes	?	Low/no U.S. deposits
	Niobium	No	No	Yes	Yes	Yes	N/A	N/A	Maybe	Yes	?	Low/no U.S. deposits
	Yttrium	No	No	Yes	Yes	Yes	N/A	N/A	Maybe	Yes	?	Low/no U.S. deposits
	Chromium	No	Yes	Yes	Yes	Yes	?	?	Yes	Yes	Yes	No action
	Nickel	No	Yes	Yes	Yes	Yes	?	?	Yes	Yes	Yes	No action
Other Minerals (No Concern)	Cadmium, Cobalt, Copper, Lead, Molybdenum, Silver, Tin, Titanium, Tungsten, Vanadium, Zirconium	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No action
Fabrication	Large Component Forging and Manufacturing	No	No	Yes	Yes	Yes	?	?	Yes	?	?	Maybe (some future reactors may not need capabilities or utilize advanced manufacturing methods)
	Other component Forging and manufacturing	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No action

Component/product	SC segments to meet the demand of the final product	Significant domestic suppliers	Significant domestic demand	Projected significant domestic demand	Significant global market	Projected significant global demand	Cost competitive among U.S. suppliers	Cost competitive between U.S. suppliers vs. global suppliers	Is foreign supply source significant secure?	Is there sufficient effort to address environ-mental concerns?	Is there sufficient effort to address human rights concerns?	Does it make sense to build domestic capability for this product/ component?
Other Core Components												
	Beryllium*	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No action
	Nuclear Graphite	No	No	Yes	No	Yes	Maybe	Maybe	No	No	?	Low/No U.S. deposits, No current fabricators of Nuclear graphite structures/components
Coolant	Helium	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No action
Molten salts												
	Beryllium*	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No action
	Lithium	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Maybe	?	Yes	Lithium is needed for PWR chemistry control as well as next generation molten salt reactors
	Lithium Enrichment	No	Yes	Yes	Yes	Yes	Yes	Yes	Maybe	?	Yes	No action
	Chlorine Enrichment	No	No	Yes	Yes	Yes	Maybe	Maybe	?	?	?	Later
	Salt Fuel Synthesis	No	No	Yes	No	Yes	Maybe	Maybe	?	?	?	Later

Component/product	SC segments to meet the demand of the final product	Significant domestic suppliers	Significant domestic demand	Projected significant domestic demand	Significant global market	Projected significant global demand	Cost competitive among U.S. suppliers	Cost competitive between U.S. suppliers vs. global suppliers	Is foreign supply source significant secure?	Is there sufficient effort to address environ-mental concerns?	Is there sufficient effort to address human rights concerns?	Does it make sense to build domestic capability for this product/ component?
High-temp reactors	Ceramics	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No action
Construction	Steel	Yes	Yes	Yes	Yes	No	Yes	Yes	N/A	Yes	N/A	No action
	Concrete	Yes	Yes	Yes	Yes	Yes	Yes	Yes	N/A	Yes	N/A	No action

For more information, visit:
energy.gov/policy/supplychains

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