Landscape of U.S. Domestic Advanced Nuclear Energy Supply Chain

An overview analysis of bottlenecks, opportunities, and recommendations

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Executive Summary

The United States does not face a nuclear energy technology constraint. It faces an industrial capacity constraint. Advanced reactor designs are progressing, electricity demand is rising, and federal policy support has expanded. If capital is to flow at scale, the domestic supply chain must be able to deliver qualified components, skilled labor, and manufacturing throughput sufficient to support order book deployment.

This report finds that a concentrated set of structural bottlenecks—particularly in downstream fabrication, machining, welding, inspection, and workforce qualification—is limiting that capacity today. Unless these constraints are addressed deliberately and in sequence, renewed nuclear ambition risks reverting to bespoke projects rather than sustained, multi-unit delivery.

Purpose and Scope

This analysis is intended for industry leaders, policymakers, regulators, investors, and other decision-makers whose actions shape supplier investment, workforce development, and fuel availability. Nuclear energy supply chains operate on multiyear timelines, and early decisions are crucial. The report assesses where bottlenecks exist today, why they persist, and what is required to move from episodic projects to sustained deployment.

The analysis focuses on advanced nuclear fission reactors where near-term supply chain pull is most credible, including gigawatt-scale Gen III+ light-water reactors (notably the AP1000) and selected Gen III+ and Gen IV small modular reactor (SMR) designs. Microreactors are examined separately, given their distinct deployment models and supply chain characteristics. Fusion is excluded.

Defining the Nuclear Supply Chain

For the purposes of this report, the nuclear supply chain comprises three interdependent pillars:

- **Fuel Cycle.** The full pathway from uranium mining and conversion through enrichment, deconversion, fuel fabrication, and spent fuel management. This includes conventional low-enriched uranium (LEU) used by Gen III+ reactors, as well as high-assay LEU (HALEU) and advanced fuel forms required by many Gen IV designs.
- **Systems, Structures, and Components (SSCs).** The physical equipment required to build nuclear plants, including heavy components (reactor pressure vessels, steam generators), civil materials (concrete, steel), supporting components (pumps, valves, piping), specialized materials (nuclear-grade graphite, cladding, coolants), and instrumentation and controls.
- **Labor and Services.** The skilled human capital and specialized services required to design, license, manufacture, construct, operate, and maintain nuclear facilities, including craft labor, manufacturing labor, engineers, project managers, quality-assurance professionals, inspectors, and regulators.

Core System Finding: Market Paralysis

At the center of the supply chain challenge is a self-reinforcing market paralysis. Suppliers and manufacturers are unwilling to make long-lead capital investments without credible, multiunit demand signals. At the same time, utilities and other offtakers hesitate to make firm commitments in the absence of cost certainty, schedule confidence, and a proven supply chain. This dynamic suppresses investment in manufacturing capacity, workforce pipelines, qualification infrastructure, and fuel supply—compounding the very risks that deter demand.

The analysis further finds that this paralysis is not merely a market failure but is reinforced by stop-start policy signals, slow deployment of public funding, and a lack of decisive down-selection. Together, these factors extend uncertainty rather than resolving it.

Conditioning Constraints That Govern Scale

The analysis identifies three conditioning constraints that shape whether capital, policy, and technology can translate into delivered capacity.

1. **Lack of credible, durable demand signals**, such as aggregated, multiunit order books sufficient to justify supplier investment
2. **Complex, time-intensive qualification and quality-assurance (QA)** acceptance pathways, which govern who can participate in nuclear supply chains and how quickly capacity can be mobilized

3. **Limited skilled labor and services,** particularly in manufacturing, inspection, QA, and construction execution

Qualification timelines for fuels, materials, and manufacturing methods operate on multi-year, sequential cycles, creating hard industrial pacing constraints that cannot be accelerated through funding alone. Which constraint binds first depends on deployment trajectory and sequencing; near-term Gen III+ scaling and longer-term Gen IV industrialization impose different pacing factors. These constraints are mutually reinforcing and must be addressed as a coupled system.

Labor as a Throughput and Risk Constraint

Contrary to common perception, labor constraints are not limited to construction craft labor. The analysis finds that shortages of nuclear-qualified machinists, welders, inspectors, nondestructive examination specialists, and experienced project managers increasingly govern throughput, schedule, and execution risk. These roles are labor-intensive, slow to train, and subject to intense competition from other industrial projects.

While labor shortages do not initiate market paralysis, they set the achievable slope of deployment once demand materializes and amplify cost and schedule risk if not addressed early.

Fuel Supply: Differentiated and Sequencing-Sensitive Constraints

Fuel supply constraints differ materially by reactor class and must be treated accordingly.

Low-enriched uranium (LEU)
The LEU supply chain is technically mature, with existing conversion, enrichment, and fabrication capacity serving the current fleet. However, the analysis finds that this system operates with limited slack and increasing geopolitical exposure. The impending loss of Russian enrichment supply, reliance on allied state-owned enterprises, single-point domestic conversion risk, and uncertainty around long-term policy durability create structural fragility under fleet-scale expansion.

Further, overfeeding illustrates how operational choices shift dependence across the fuel cycle, increasing demands on mining and conversion while boosting enrichment output in the short term. However, significant reliance on this approach would quickly create conversion bottlenecks and raise feedstock costs, yielding only modest net gains under prevailing economic conditions.

LEU will not constrain initial deployment, but it can become a rate-limiting factor for large Gen III+ build programs if capacity expansion and policy signals are not stabilized early. LEU also serves as the upstream feedstock for HALEU, tightly coupling the two pathways.

High-Assay LEU (HALEU)
HALEU remains a hard bottleneck for Gen IV deployment. The United States lacks commercial-scale domestic enrichment, deconversion, certified transport packages, and fuel fabrication capacity. Fuel qualification timelines are long and sequential, and investment is stalled by the same demand uncertainty affecting the broader supply chain. Without deliberate market-making and careful sequencing, Gen IV reactors cannot scale independently of earlier industrialization steps.

Reprocessed Fuels
Plutonium-bearing fuel, which is the product of spent fuel reprocessing, is not required for Gen III+ or Gen IV deployment. A fuel cycle for plutonium-bearing fuel would require separate, purpose-built supply chains that do not currently exist in the United States. This fuel pathway would have to resolve economic, safeguards, security, and proliferation issues before it could be credibly pursued at scale.

Where Manufacturing Actually Binds

The analysis finds that the most acute manufacturing bottlenecks increasingly lie downstream rather than in first-article heavy forgings alone. Machining, welding, finishing, inspection, and nondestructive examination frequently sit on the critical path. These steps are labor-intensive, qualification-bound, and difficult to parallelize. Expanding supply chain capacity therefore depends less on adding factories than on increasing qualified throughput within existing and new facilities.

In several segments—including specialty alloys, nuclear-grade graphite, large forgings, and other qualified subcomponents—the supplier base is limited and globally concentrated. While not always the first binding constraint, this concentration heightens exposure to geopolitical disruption and execution risk under sustained, multi-unit deployment.

Across multiple supply chain segments, capacity is thin and highly concentrated, though the nature of that concentration differs by segment. In the fuel cycle, one or two qualified suppliers often serve the entire market, creating acute fragility. In heavy manufacturing, capacity is typically limited to a small number of globally qualified firms—often two to five, and in some cases reliant only on allied suppliers. In both cases, constrained supplier bases heighten exposure to disruption and underscore the importance of qualification pathways and targeted capacity expansion, rather than broad diversification alone.

Design Diversity and Temporal Misalignment

The large number of reactor designs, fuel forms, and component specifications fragments supplier investment and workforce development. Parallel qualification pathways and bespoke requirements dilute capital, slow learning curves, and limit economies of series. Absent convergence and disciplined sequencing, technology diversity functions as a structural tax on scale.

Microreactors illustrate a distinct supply chain logic. Their smaller size, higher factory content, and different customer base—including defense and remote applications—make them more amenable to alternative qualification pathways and nontraditional suppliers. While successful microreactor programs could generate substantial volume for specific component classes (such as instrumentation and controls), they do not create the construction cadence, heavy manufacturing demand, or broad workforce pipelines required to anchor large-scale bulk power production at grid scale, and therefore should not be conflated with fleet-scale deployment strategies.

Across reactor classes, a persistent temporal misalignment remains: fuel and materials qualification, workforce development, and manufacturing expansion unfold over multi-year horizons, while demand signals and policy programs often arrive episodically and late. This disconnect risks stranded capital, idle capacity, and missed deployment windows even when financial support is available.

Core Conclusions

This analysis leads to five central conclusions:

1. Order books are a prerequisite, not an outcome, of supply chain scale.
2. Repeatable Gen III+ deployment is industrially foundational for rebuilding manufacturing, workforce, and qualification capacity.
3. Demand certainty, qualification pathways, and labor availability must be treated in an integrated fashion.
4. For the foreseeable future, fuel pathways must be uranium-based and sequenced, with early attention to LEU resilience and deliberate market-making for HALEU.
5. Absent coordination, renewed nuclear energy ambition risks reproducing past failures rather than establishing a durable industrial base.

Calls to Action

Federal Government
The federal government should fix demand uncertainty and fuel deadlock by providing durable policy clarity, accelerating funding deployment, aggregating or backstopping early demand where markets cannot yet form, and acting selectively as a market-maker for HALEU.

Regulators and Standards Organizations
Regulators and standards organizations should fix qualification pacing by expanding and formalizing alternative QA entry pathways, shortening cycle times for code cases, and enabling repeatable approvals for validated manufacturing methods.

EPCs, OEMs, and Suppliers
EPCs, OEMs, and Suppliers should fix downstream throughput constraints by investing in machining, welding, inspection, and nondestructive examination capacity; embedding design-for-manufacturability early; and coordinating on standardization to reduce fragmentation.

Utilities, Offtakers, and Capital Providers
Utilities, offtakers, and capital providers should fix bankability gaps by converting interest into firm, long-duration commitments; supporting fleet-style procurement and standardized commercial structures; and aligning contracting approaches with supply chain and workforce realities.

Workforce and Training Institutions
Workforce and training institutions should avoid timing mismatches by scaling skilled labor pipelines in alignment with realistic deployment sequencing and verified manufacturing demand.

This report examines these constraints in detail, tracing how they manifest across the fuel cycle, manufacturing, labor and services, and the policy and regulatory environment. For each segment, the analysis identifies where capacity exists, where it is thin or missing, and which bottlenecks are likely to bind first under different deployment trajectories. Taken together, this analysis provides a shared factual baseline to inform coordinated action—clarifying not only what must be built, but in what sequence, by whom, and on what timelines.

About This Report

Commissioned by the Nuclear Scaling Initiative and prepared by Solestiss, this report is a first step in gathering and organizing existing knowledge as well as practitioner insights. Its goal is to provide a shared baseline for discussions about how to support and scale the U.S. nuclear supply chain, recognizing that many of these topics are evolving quickly and will benefit from continued input.

Rather than presenting a definitive roadmap, this report aims to surface practical observations and real-world bottlenecks identified by suppliers, labor groups, developers, and public sector actors. To inform this report, its authors reviewed industry reports and analyses, then interviewed more than 40 industry stakeholders to gain firsthand perspectives from across the supply chain. The resulting analysis reflects an evolving field and is intended to complement efforts by the federal government, industry coalitions, and mission-aligned organizations working to ensure that supply and workforce can meet anticipated demand.

The report is intended for use by policymakers, nongovernmental organizations, philanthropic and private investors, suppliers, and developers seeking to better understand the current bottlenecks and opportunities in scaling nuclear deployment. It is not exhaustive but rather serves as a launch point for more focused analysis, strategic interventions, and collaborative planning.

Entities Supporting This Effort

NUCLEAR SCALING INITIATIVE

The Nuclear Scaling Initiative (NSI) is a collaborative effort of the Clean Air Task Force, the EFI Foundation, and the Nuclear Threat Initiative to build a new nuclear energy ecosystem that can quickly and economically scale to 50+ gigawatts of safe and secure nuclear energy globally per year by the 2030s. NSI's plan for revolutionizing how nuclear energy is constructed, financed, and regulated will advance climate goals, spark economic development, expand energy access, and ensure that nuclear technology is used for only peaceful purposes.

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Solestiss is an energy sector advisory services company with a strong focus in nuclear energy markets, products and projects. The Solestiss team combines deep technical and project delivery expertise in nuclear and energy infrastructure with engineering, megaproject execution, strategy, regulatory, and M&A experience. As a lean, nimble partner and a 100% woman-owned business, Solestiss supports clients—suppliers, developers, utilities, and investors—by rapidly mobilizing expert teams to bring immediate value.

Introduction

As the United States seeks to meet rising energy demand, enhance energy security, and decarbonize its electricity and industrial sectors, advanced nuclear reactors (small modular reactor-scale designs and the gigawatt-scale AP1000 design) have emerged as a promising source of reliable, carbon-free baseload heat and power.

A confluence of recent factors, from federal support to the prospects of long-term, surging electricity demand, is creating new momentum for nuclear power. At the same time, the domestic supply chain necessary to design, build, and fuel these reactors is strained. The existing supply chain continues to support the needs of the current reactor fleet—including operations, license extensions, uprates, and participation in global nuclear projects. However, scaling to support a major expansion of domestic nuclear capacity would require a fundamentally different level of industrial readiness.

This report examines the landscape of the U.S. advanced nuclear supply chain, highlighting the forces driving renewed interest as well as the bottlenecks inhibiting readiness. It provides a foundation for understanding the headwinds and tailwinds affecting the industry today, defines the scope of what a nuclear supply chain entails, outlines which reactor technologies are considered (and why), and describes the methodology behind our findings. The goal of this work is to frame the industry's key challenges and opportunities as the nation prepares for a new era of nuclear deployment.

Key Supply Chain Dynamics: Tailwinds vs. Headwinds

Several tailwinds are propelling the advanced nuclear energy sector in the 2020s, even as headwinds pose challenges. The industry benefits from:

1. **Unified government support:** Strong bipartisan commitment has translated into significant funding and incentives for nuclear energy under the current administration. This support includes the clean electricity investment tax credit (26 U.S. Code §48E), which can cut 30% to 50% of a nuclear project's capital cost, and more than $6 billion dedicated to advancing small modular reactor (SMR) designs through demonstration programs led by the U.S. Department of Energy (DOE). The support also includes a statutory ban on the importation of uranium and low-enriched uranium (LEU) produced by Russia, coupled with $3.4 billion to rebuild the domestic enrichment supply chain, as well as access to low-cost public sector financing through DOE's Office of Energy Dominance Financing (formerly the Loan Programs Office).[1] This policy support lowers private sector financial barriers and signals long-term confidence in advanced reactors.
2. **Surging power demand:** The need for 24/7 clean power is growing rapidly, driven by energy-intensive data centers, AI computing hubs, a resurgence of domestic manufacturing, electrification of transportation, and increased HVAC requirements across the building stock. The majority of these loads require reliable, around-the-clock electricity—and in some cases, customers demand low-carbon alternatives—creating a fresh market pull for nuclear energy. Additionally, customer interest is now expanding beyond power purchase agreements (PPAs) for existing reactors and plant restarts. There's growing urgency to move as quickly as possible on new nuclear, even where advanced reactors cannot meet demand timelines of less than five years.
3. **Regulatory modernization:** Nuclear regulators are working to streamline and update licensing processes, supported by recent policy drivers such as the Accelerating Deployment of Versatile, Advanced Nuclear for Clean Energy (ADVANCE) Act and executive orders promoting domestic nuclear deployment. The Nuclear Regulatory Commission (NRC) is actively revising its procedures to enable more efficient licensing of advanced reactors, which could reduce deployment timelines. As of February 2026, the NRC has committed to approximately 18-month reviews of construction permit applications for three active projects. That's a significant improvement from past review cycles, which historically have taken four to six years.
4. **Favorable technology trends:** Today's reactor designs represent a generational shift from earlier builds, spanning both gigawatt-scale Gen III+ plants (e.g., AP1000) and Gen III+ SMR/Gen IV concepts. Key innovations include greater modularity, standardization, and factory fabrication, which enable faster, more predictable construction and deployment. At the same time, advances

[1] EFI Foundation, *Making Small Modular Reactors Bankable Investments*, November 2024.

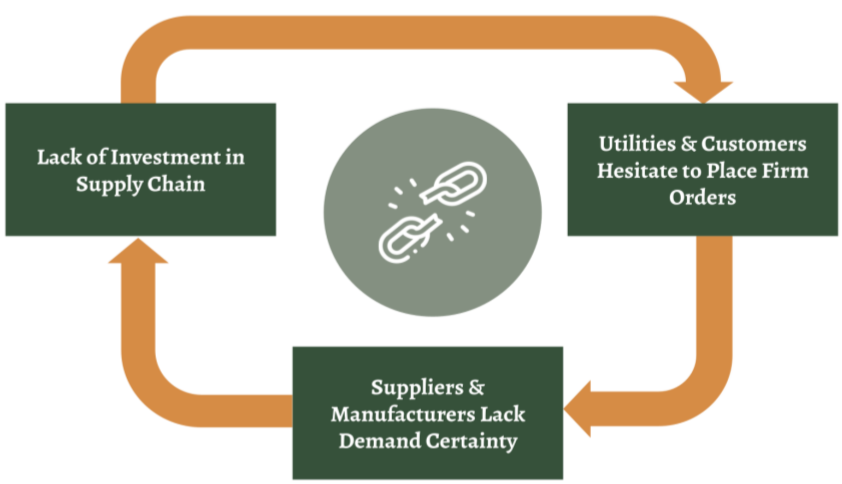
in safety systems and passive design features strengthen the social license to operate and expand the potential use cases for nuclear energy. Together, these innovations promise meaningful improvements in cost, schedule, scalability, and public acceptance compared to prior nuclear builds.

Counterbalancing these tailwinds are formidable headwinds affecting the supply chain sectors:

1. **"Chicken-and-egg" demand deadlock:** A classic chicken-and-egg problem is stalling investment in new reactor builds, resulting in upstream and downstream supply chain effects. Suppliers and manufacturers are reluctant to expand capacity or invest in new fuel production facilities without firm orders, while customers for reactor output (utilities and other buyers) hesitate to place orders without, among other things, an assured supply chain in place. This supply-demand deadlock creates market paralysis that is repeatedly cited as the central challenge across the nuclear energy industry.
2. **Critical workforce gaps:** The nuclear energy sector is facing a looming skills shortage just as it attempts to scale up. An aging workforce is retiring faster than new talent is entering, and the pipeline for skilled trades and, to a lesser extent, engineers is relatively weak. Competition for labor is fierce, and growing demand vectors like advanced manufacturing, data centers, and other industrial-scale construction are drawing from the same pool of welders, electricians, pipefitters, and other specialized trades. Without dramatic investments in training and education, the lack of qualified workers could become a choke point for new projects and drive costs higher as projects attempt to attract existing talent.
3. **Policy uncertainty:** Despite recent supportive legislation, the long-term policy environment for scaling up nuclear energy capacity in the United States is inconsistent. Shifting political priorities and the absence of a long-term, consistent national strategy make it difficult for companies to commit to multi-decade investments. Perceptions of a lack of policy durability dampen private sector confidence. Moreover, incentives have typically focused on offsetting operating costs or supporting plant-level design and construction activities (e.g., production tax credits, investment tax credits, and first-of-a-kind cost-share programs), which improve some project economics but have not adequately addressed broader new-build bankability, weakening supply chain capital investment signals.
4. **FOAK cost trap:** Infrequent construction of reactors coupled with a breadth of designs and fuel types deployed has trapped the industry in a first-of-a-kind (FOAK) cycle. Every project tends to be a one-off with high up-front costs, unproven execution capabilities, and unproven supply chains, rather than benefiting from the economies of scale associated with repeat builds. Lacking opportunities for learning-by-doing and economies of series (or even multiples), vendors struggle to justify investments in cost reduction initiatives. This FOAK trap perpetuates high costs and both perceived and real risk, reinforcing the hesitation of suppliers and customers to be "first movers." The result is a self-reinforcing cycle that the industry must break to realize cost reductions.

These countervailing dynamics set the stage for the analysis in this report. The central premise is that, while conditions are aligning to support a nuclear energy resurgence, strategic and coordinated action is needed to overcome the market deadlock and capacity shortfalls that currently hinder progress.

Figure 1. The chicken-and-egg cycle blocking supply chain investment



Defining the Nuclear Energy Supply Chain Ecosystem

In this report, the nuclear energy supply chain encompasses the full range of materials, components, facilities, and human resources required to deploy advanced reactors. We categorize the supply chain into three broad domains:

1. **Structures, systems, and components (SSCs):** This includes the hardware and materials that go into reactor projects, from heavy structural elements like concrete and steel, to major components such as reactor pressure vessels, steam generators, pumps, valves, piping, and heat exchangers, down to specialized parts and advanced materials (e.g., nuclear-grade graphite, coolants, and instrumentation and control). SSCs cover all the physical equipment and engineered components that must be manufactured or constructed to build a nuclear plant.
2. **Fuel cycle:** The nuclear fuel supply chain begins with uranium mining and milling, followed by conversion and enrichment (for both standard-assay LEU used in Gen III+ reactors and high-assay LEU, or HALEU, used in some Gen IV reactors), then deconversion into the intended uranium form (e.g., uranium oxide for current light-water reactors, or LWRs), followed by fabrication into reactor fuel forms (such as fuel rods or pebbles). It also includes back-end services like spent fuel management, storage, and disposal (as well as reprocessing, if pursued). A resilient fuel cycle supply chain ensures that reactors have a secure, domestic source of fuel and that nuclear material is managed safely from cradle to grave.
3. **Labor and services:** Beyond hardware, deploying reactors depends on skilled people and support services. This category encompasses the workforce and specialized services needed to license, construct, and operate plants. It includes manufacturing labor (machinists, fabricators, inspectors, quality technicians) and craft labor (welders, electricians, pipefitters, ironworkers, etc.); engineering and project management services; construction management and civil contractors; radiation protection and chemistry technicians; as well as quality assurance, inspection, transportation, and other support capabilities unique to nuclear projects. Human capital and know-how are as much a part of the supply chain as any physical component, and shortages in these areas can be as limiting as equipment bottlenecks.

Exploring these three pillars of the supply chain enables us to pinpoint where bottlenecks exist and identify which parts of the ecosystem require strategic investment or policy intervention. In the pages that follow, we systematically assess strengths and weaknesses in each area of the supply chain and recommend strategies to strengthen the domestic nuclear energy industry as a whole.

Scope of Reactors Covered

Not all nuclear energy technologies share the same supply chain needs. This study focuses on advanced reactor designs that are moving toward commercialization or deployment in the next decade, primarily Gen III+ light-water reactors and Gen IV advanced reactor technologies. In particular, this analysis focuses on a set of reactor types and specific designs that are most likely to influence near-term demand for the domestic supply chain. This includes the gigawatt-scale AP1000 design as well as multiple SMR designs, here defined as having outputs around or below 300 megawatts electric (MWe).

Microreactors (typically under 20 MWe in capacity) are addressed in their own section. Microreactors may serve niche markets (such as providing remote power or military use) and have supply chain and regulatory considerations that differ from larger power reactors. Their production volumes, component sizes, and deployment models are sufficiently different and warrant a separate analysis.

Thus, this report's findings and recommendations are organized first by the supply chain needs of SMR and large advanced reactors intended for electricity generation and industrial use, then supplemented by a separate analysis of the differentiated supply chain opportunities and challenges of microreactors.

Table 1. Reactors in scope	
Gen III+ LWR technologies	
Pressurized water reactors (PWR)	▸ **Westinghouse AP1000:** A Gen III+ large-scale reactor with global deployment experience, providing valuable lessons on supply chain gaps and bottlenecks. ▸ **Holtec SMR-300:** A compact PWR targeting modular construction, with manufacturing capabilities closely tied to Holtec's in-house supply chain.
Boiling water reactors (BWR)	▸ **GE Vernova Hitachi BWRX-300:** A simplified, cost-optimized SMR derived from established BWR technology.
Gen IV non-LWR technologies	
High-temperature gas reactors (HTGR)	▸ **X-energy XE-100:** A Gen IV design using tri-structural isotropic (TRISO) fuel and helium cooling, requiring specialized supply chains for graphite and advanced fuel fabrication.
Molten salt reactors (MSR)	▸ **Kairos FHR:** A fluoride salt-cooled high-temperature reactor (FHR) that blends MSR and pebble bed design elements, introducing unique requirements for salt chemistry and structural materials, requiring specialized supply chains for coolant and advanced fuel fabrication. ▸ **Terrestrial Energy IMSR:** An integrated molten salt reactor (IMSR) pursuing a simplified system design with commercially scalable deployment in mind, leveraging existing fuel supply chains.
Sodium fast reactors (SFR)	▸ **TerraPower Natrium:** A sodium-cooled fast reactor design paired with integrated thermal storage, aiming to provide flexible, firm power, with advanced supply chain needs for specialized sodium components and safety systems.

Not all reactor technologies and designs are likely to reach commercialization, and not all bottlenecks identified in this report apply to every design. A key recommendation of this report is to develop technology standardization that moves away from disparate designs and fuel types and toward shared supply chains that can achieve economies of scale. Choosing the right mix of pared-down designs will be a critical task for industry and government.

Gigawatt-scale units drive supply chain demand through their size and volume requirements. Procurement is concentrated in multiunit site programs with large, lumpy orders. Ultra-large forgings and gigawatt-class conventional-island equipment (e.g., reactor pressure vessels, steam generators, main coolant pumps, turbine generators, transformers, condensers, cooling systems) have long lead times and a constrained qualified vendor base.[2] Construction relies on massive civil works and field assembly, and oversize/heavy-haul logistics (clearances, bridge ratings, major lifts) become critical path constraints.

By contrast, the physically smaller SMR/advanced designs shift more scope into factory modules, distribute demand across many sites, reduce heavy-haul complexity, shrink balance-of-plant (BOP, sometimes referred to as conventional island) footprints, ease interconnect upgrades, and flatten labor peaks by emphasizing repeatable factory manufacturing and site assembly over megasite craft surges. This ultimately moves schedule risk from on-site integration toward modular throughput and replication.

Within the gigawatt-class category, this analysis focuses solely on Westinghouse Electric Corp.'s AP1000. It is the only new

[2] The conventional island refers to the non-nuclear part of the plant, where thermal energy is converted to electricity, including all non-safety-related support systems.

large-scale design to complete U.S. licensing and construction and enter operation (Vogtle Units 3 and 4) in recent history. This confers practical advantages: established NRC precedents (design qualification, combined operating license and subsequent amendments), qualified component specifications and code cases, a domestic and allied nuclear certified supplier base with recent AP1000 experience, and validated construction, commissioning, logistics, and workforce profiles.[3] Consequently, the near-term supply chain challenge for AP1000s is less about first-article qualification and more about scaling proven pathways—de-bottlenecking ultra-large forgings and gigawatt-class conventional-island equipment, locking in logistics windows, and smoothing field execution across multiunit programs.

SMRs included in this analysis were selected to represent the reactor designs most likely to create near-term, bankable demand signals for the U.S. supply chain. Specifically, the report focuses on SMR designs that (i) have advanced beyond conceptual design into licensing, demonstration, or early construction; (ii) are backed by credible developers, customers, and financing partners; and (iii) are expected to deploy at commercial scale within the next decade.

The SMRs examined span both Gen III+ LWR technologies and Gen IV non-LWR designs, allowing the analysis to capture meaningful contrasts in fuel requirements, materials, manufacturing complexity, and qualification timelines. While these designs are not exhaustive of all SMR concepts under development, they are representative of the technologies most likely to shape near-term supply chain investment decisions.

We also explore microreactors in a later section to illustrate how their needs diverge from both the AP1000 and SMR set. The focus is on representative designs and their supply chain implications. This includes far higher factory content with containerized auxiliaries, minimal site civil works, and logistics built around certified transportable modules (road/rail/air) instead of super-loads; smaller BOP footprints; and microgrid-oriented interconnects. The customer channels also differ, centering on Department of Defense, remote/industrial sites, and behind-the-meter use. This business model also requires expanded participation from nontraditional vendors under appropriate quality assurance (QA) pathways and distinct fuel/transport requirements (often HALEU/TRISO) that shift bottlenecks relative to larger reactors.

Differentiating Supply Chains for Gen III+ and Gen IV Reactors

Commercial nuclear reactors are often grouped into technology "generations" based on design maturity, safety features, and operational experience. Gen III reactors are advanced versions of the large, gigawatt-scale LWRs currently in operation across the globe. The new Gen III+ designs incorporate evolutionary safety and efficiency improvements. These designs use the same fundamental LWR technology (pressurized water reactors and boiling water reactors) but add new safety enhancements, modular construction techniques, and greater design standardization to improve cost and schedule performance.

Gen IV reactors are advanced non-LWR designs that use alternative coolants, higher operating temperatures, and novel fuels such as HALEU-based TRISO particles or metallic fuel.[4] Examples include high-temperature gas reactors, molten salt reactors, and liquid metal-cooled (e.g., sodium) fast reactors. Many remain in the demonstration or licensing stage and require entirely new industrial capabilities to support commercial deployment.

While both Gen III+ and Gen IV designs represent the future of nuclear deployment, their supply chain needs differ sharply. Gen III+ reactors rely on proven water-cooling technology and conventional LEU fuel, supported by a supply chain that—though diminished—once existed at scale in the U.S. and allied nations. Scaling them would involve reactivating idle capabilities, requalifying vendors, and increasing throughput for well-understood components such as reactor vessels, steam generators, turbines, and other large heat exchangers. With the right market and policy signals, industry leaders view Gen III+ reactors as the fastest path to large-scale deployment because the entire supply chain exists at commercial scale.

Gen IV reactors, by contrast, require FOAK industrialization. No commercial-scale supply chains exist for important needs such as HALEU enrichment and deconversion, fuel production and fabrication, nuclear-grade graphite

[3] ASME Code Cases are non-mandatory, approved exceptions or alternatives to code rules. They include specific requirements that, when fully and correctly implemented, help users achieve continued quality and safety.

[4] TRISO (tri-structural isotropic) fuel consists of microscopic uranium fuel kernels individually encapsulated in multiple ceramic coating layers that act as a self-contained containment system, enabling high-temperature operation with enhanced fission product retention.

manufacturing, and advanced coolant supply. Past prototypes, such as the U.S. Experimental Breeder Reactor (EBR) series and France's Phénix and Superphénix, operated at small scale and never established a sustained manufacturing base. Building these capabilities will require coordinated public-private investment, long-term market commitments, and extensive qualification of new materials, processes, and suppliers. The differences between Gen III+ and Gen IV supply chain pathways are outlined in Figure 2 below.

Given these realities, a likely near-term approach is a dual-track strategy: Accelerate deployment of water-cooled reactors to deliver capacity quickly, while simultaneously investing in the infrastructure and qualification work needed for Gen IV supply chains.

As one industry leader summarized, "Because there is an existing supply chain, we should be building as many water-cooled reactors as we can," ensuring proven technologies meet immediate needs while advanced designs are prepared to scale once critical gaps are closed.

Figure 2. Gen III+ vs. Gen IV supply chain pathways

	Gen III+ LWRs *Reconstituting an existing supply chain*	*vs.*	**Gen IV Non-LWRs** *Creating a novel supply chain*
Starting Point	✔ Mature technology ✔ Familiar and/or proven designs ✔ Existing supplier base (though eroded)		✔ FOAK industrialization ✔ No commercial-scale precedent in U.S. or allied nations
Advantages	✔ Leverages decades of operational data and manufacturing experience ✔ Existing QA processes and regulatory precedents ✔ Faster path to capacity growth		✔ Potential for higher efficiency, flexible output, and unique applications (e.g., industrial heat, remote power)
Constraints	✔ Supply chain attrition (fewer N-stamp suppliers) ✔ Limited current throughput for heavy components ✔ Skilled labor availability		*All of the Gen III+ constraints and..* ✔ HALEU and fuel fabrication at scale ✔ Lack of qualified supply base for specialized materials ✔ Long material and process qualification timelines

Approach and Methodology

To develop a holistic view of the advanced nuclear supply chain, a three-pronged research approach was used: stakeholder interviews, literature review, and practitioner experience.

First, we conducted 42 in-depth interviews with a cross-section of supply chain stakeholders. These interviews gathered insights from across the ecosystem, including:

1. Reactor technology developers (established incumbents and first time reactor developers).
2. Equipment suppliers and fabricators (manufacturers of nuclear components, materials, and the fuel cycle).
3. Engineering, procurement, and construction (EPC) firms and constructors (responsible for building plants).
4. Federal and state agencies (government bodies supporting nuclear initiatives or regulating the industry).
5. Industry organizations and consultants providing both niche and sector-wide perspectives.

6. Workforce development groups (nonprofits and unions focused on skilled labor and training for nuclear projects).

Interviewees provided candid assessments of current bottlenecks and ideas for solutions. These on-the-ground perspectives from experts were invaluable in identifying real-world pain points not evident in published data alone. To encourage unfiltered insights, interviewees are not individually cited in this report and results are aggregated. This approach allowed participants to speak freely about organizational challenges, internal capabilities, and perspectives on the nuclear ecosystem.

In parallel, a comprehensive review of recent studies, reports, and data on the nuclear supply chain was conducted. This literature review spanned government and industry analyses, academic studies, and technical reports covering topics such as manufacturing capacity for reactor components, the status of the domestic fuel cycle, nuclear workforce trends, and policy measures to support advanced nuclear deployment.

By synthesizing key findings from sources like DOE reports, Nuclear Energy Institute (NEI) workforce studies, supply chain assessments, and others, this effort built upon the knowledge base already established in the field.

Finally, the analysis is grounded in the deep practitioner expertise of the Solestiss team, drawing on decades of collective, hands-on experience designing, building, delivering, and operating nuclear projects. This internal know-how, which spans engineering, project development, strategy, and regulatory compliance, provided a critical real-world filter to assess the viability of proposed solutions, validate the bottlenecks identified by stakeholders, and ensure the report's findings are rooted in the practical realities of project execution.

Combining firsthand stakeholder input, secondary research, and deep practitioner experience allows this report to present a well-rounded assessment of the U.S. advanced nuclear supply chain.

In this introduction, we have outlined the high-level landscape. With this framing in place, the subsequent sections examine each segment of the supply chain. We explore the current state of the fuel cycle (uranium supply and fuel fabrication); the status of heavy component manufacturing and availability of critical systems and components; the supporting components and advanced technologies that enable reactor construction; the workforce and human capital pipeline; and the overarching policy, investment, and regulatory environment. In each area, we identify key players, major bottlenecks, and opportunities or strategic pathways to strengthen the domestic supply chain. The report concludes with concrete recommendations that would enable the U.S. to surmount the supply chain challenges and unlock the full potential of advanced nuclear energy.

The Fuel Cycle

The nuclear fuel cycle encompasses the full pathway from uranium mining through reactor fuel fabrication and, ultimately, spent fuel management. On the "front end," uranium ore is mined, milled into yellowcake (U_3O_8), converted into uranium hexafluoride (UF_6) gas, enriched to the desired uranium-235 (U-235) content from its natural state (about 99.3% U-238 and 0.7% U-235), deconverted into a solid fuel form, and fabricated into the specific assemblies, pellets, or particles used in a reactor.

In the United States, most of the current and near-term fleet will operate on LEU, typically enriched to 3%-5% U-235 . A smaller but growing segment of advanced designs—particularly many Gen IV concepts—require HALEU, enriched to between 5% and less than 20% U-235. Some of these designs, such as high-temperature gas reactors, use TRISO fuel, which consists of microscopic uranium kernels (often HALEU) encased in multiple ceramic and carbon layers, embedded in pebbles or compacts for high-temperature performance. Some Gen IV designs are also considering the use of reprocessed, plutonium-bearing fuel in their reactors.

Figure 3. Nuclear fuel cycle

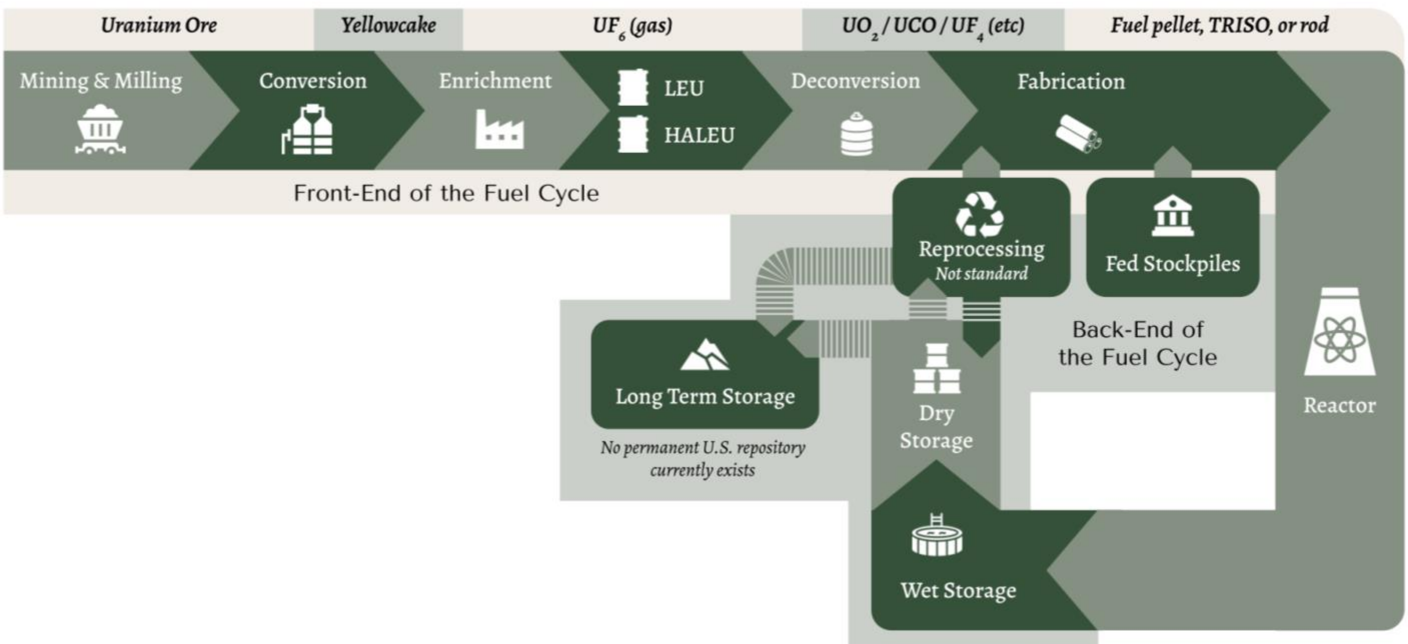


Table 2 summarizes the primary fuel types required by a representative set of advanced reactor designs examined in this study, illustrating the mix of conventional LEU fuels and more specialized HALEU or alternative fuel forms.

Table 2. Fuel requirements for advanced reactor designs

Current fuel types	Reactor
Conventional uranium oxide fuel pellets (LEU ~3%-5%)	**Westinghouse AP1000** (PWR) **Holtec SMR-300** (PWR SMR) **GVH BWRX-300** (BWR SMR)
TRISO fuel particles in graphite pebbles (HALEU)	**X-energy XE-100** (HTGR SMR)

TRISO fuel pebbles (HALEU)	**Kairos KP-FHR** (MSR/HTGR SMR)
Liquid fuel dissolved in molten salt (LEU, UF_4)	**Terrestrial IMSR** (MSR SMR)
Metal fuel assemblies (HALEU)	**TerraPower Natrium** (SFR SMR)

Several of the advanced reactor designs explored in this study—including the AP1000, Holtec SMR-300, and GVH BWRX-300—will operate on conventional LEU fuel, typically enriched to 3%-5% U-235 (some may use slightly higher enrichments at 5%-10%, referred to as LEU+, as recently demonstrated in the existing fleet at Vogtle Unit 2). The supply chain for LEU/LEU+ is significantly more mature and globally diversified than for HALEU, supported by existing infrastructure and decades of commercial reactor operation. However, even the LEU supply chain has vulnerabilities, which are discussed below. Therefore, while reactors using standard LEU fuel face fewer immediate supply hurdles compared to HALEU or reprocessed fuel-dependent designs, ensuring a secure, affordable, and resilient LEU supply remains a critical element of sustaining both current and future nuclear deployments.

Unlike LEU, where most steps of the supply chain exist at commercial scale, HALEU production capacity is still emerging and lacks reliable cost data. Current U.S. HALEU output is limited to a demonstration-scale Centrus Energy Corp. facility, with no large-scale enrichment or deconversion yet in operation, as discussed in more detail in the bottlenecks outlined below.

Thus, scaling LEU supply requires incremental growth with existing players that, according to experts, can scale alongside demand growth. HALEU supply, however, would require a step-order change in capacity, all-new facilities, and coordinated investment across enrichment, deconversion, and specialized fuel fabrication to establish an end-to-end commercial pathway. It is important to note that HALEU is often enriched from existing LEU feed, thus an increase in HALEU demand would further contract LEU supply for the Gen III+ market.

In the United States, the supply chain for reprocessed nuclear fuel that includes separated plutonium—including mixed-oxide fuel, as well as metallic fuels blending plutonium and transuranics—is not commercially established and would require dedicated infrastructure. This includes reprocessing facilities, fuel fabrication lines capable of handling plutonium-bearing fuel (which are more complex than conventional uranium-fuel fabrication), and in some cases dedicated processing or enrichment lines to handle reprocessed uranium. The U.S. does not currently have any of this dedicated infrastructure. For material that cannot readily be recycled—including highly radioactive fission products and uranium and plutonium without viable fuel pathways—extended on-site storage remains necessary until a permanent geological repository is implemented.

Tripling domestic nuclear capacity to 300 gigawatts (GW) by 2050 will require dramatic expansions across every phase of the once-through fuel cycle. Table 3 summarizes key gaps between current U.S. capabilities and the future demand implied by this ambition. Note, however, that this capacity gap assumes a need to scale up all parts of the supply chain domestically, versus relying on allies to help meet capacity needs.

Table 3. Domestic fuel supply chain capacity (as of September 2024)

Fuel supply chain step	Required capacity to triple nuclear capacity	Current domestic capacity	Domestic capacity gap
Mining and milling	55,000-75,000 metric tons (MT) U_3O_8/year	~2,000 MT/year	~33x
Conversion	70,000-95,000 MT UF_6/year	~10,400 MT/year	~8x
Enrichment	45 million-55 million separative work units (SWU)/year	~4.4 million SWU/year	~11x
Fuel fabrication	6,000-8,000 metric tons of uranium (MTU)/year	~3,700 MTU/year	~2x

Data from: U.S. Department of Energy, Pathways to Commercial Liftoff: Advanced Nuclear, September 2024.

Key Players

The advanced nuclear fuel cycle comprises a small number of players with outsized influence on supply availability.

Uranium Mining

At the front end of the fuel cycle, U.S. uranium production has dwindled to nearly zero, handled by only a few small operators and unable to compete with cheaper imports. Domestic uranium mining and milling currently provides only a token amount of feedstock—down over 99.6% from its 1980 peak—with most uranium concentrate now sourced from allies such as Canada and Australia or other foreign suppliers.

Conversion

Converting yellowcake to UF_6 is similarly strained: The U.S. has a single conversion plant (the Honeywell-owned Metropolis Works facility in Illinois), which only recently restarted operations in 2023 with a capacity of 7,000 metric tons of uranium (tU) per year and cannot yet meet national demand. The global market for conversion services is highly concentrated, as shown in Table 4, highlighting the scale at which international competitors operate.

Table 4. World uranium conversion facilities

Company	Country	Location(s)	Capacity (tU/yr)
Cameco	Canada	Port Hope, Ontario	12,500
Orano	France	Malvési / Tricastin	15,000
Rosatom	Russia	Seversk (Tomsk)	12,500
CNNC	China	Lanzhou & Hengyang	15,000
ConverDyn	USA	Metropolis, Illinois	7,000

Data from: World Nuclear Association, "Conversion and Deconversion," updated November 2024.

This concentration means that the U.S. relies on foreign (though allied) companies like Cameco Corp. (Canada) and Orano SA (France) to perform conversion services for nuclear fuel.

Enrichment

Most reactor fuel requires enriching UF_6 to increase its fissile U-235 content. Globally, the vast majority of enrichment capacity exists outside of the United States and through foreign-owned entities, as shown in Figure 4.[5]

For LEU, U.S. utilities depend on a mix of domestic capacity and imports to fuel the existing fleet. The only commercial enrichment plant operating on U.S. soil is run by Urenco USA in New Mexico, supporting about one-third of domestic enrichment needs.[6] Urenco is owned by a European consortium, and its technology and output are controlled from abroad. Domestic enrichment capacity is supplemented by imports from Urenco and Orano facilities in Europe, in addition to imports from Russia (until 2028, per the passage of the Prohibiting Russian Uranium Imports Act in 2024).

LEU supply is available but tight. As utilities pivot off Russian volumes—which account for 24% of required supply at current consumption rates—those needs must be re-contracted into a finite allied separative work unit (SWU) enrichment capacity (Urenco/Orano) that is already running near full utilization.[7]

Enrichers also can increase enriched uranium production by "overfeeding" uranium feedstock within existing enrichment capacity. This decreases the SWU required per unit of enriched product. However, it increases both the concentration of U-235 in the residual "tails" (depleted UF_6 left after enrichment, low in U-235) and the amount of UF_6 used as input material.

While overfeeding can be used to boost output, significant reliance on this approach would rapidly create a bottleneck in UF_6 conversion capacity and increase feedstock costs, yielding only modest net gains. As a result, overfeeding is best understood as an economically constrained, short-term buffer against SWU shortfalls rather than a durable substitute for new enrichment capacity.

For HALEU-level enrichment (between 5% and less than 20% U-235), the United States only has the demonstration-scale Centrus Energy facility, which uses operating centrifuge cascades to enrich uranium and represents a pathway to

[5] World Nuclear Association, "Uranium Conversion and Deconversion," updated November 2024.

[6] World Nuclear Association, *US Nuclear Fuel Cycle*.

[7] Separative work unit: the standard measure of enrichment services

scalable, repeatable domestic HALEU production. While this facility remains demonstration-scale, however, American reactor developers must look to foreign enrichers for any sizable, commercial HALEU supply.

In the near term, limited quantities of HALEU are being supplied through down-blending of government-owned highly enriched uranium (HEU). BWX Technologies Inc. (BWXT) is supporting select early reactor demonstrations by converting finite federal HEU stockpiles into HALEU, providing a critical bridge for FOAK projects. While down-blending can enable demonstrations, it does not create a commercial enrichment capability and cannot resolve the long-term HALEU supply bottleneck.

Russia's state-owned TENEX has been the dominant global source of HALEU, but this supplier is unavailable for domestic entities given the Russian fuel ban. The ban, which will remain in effect through 2040, is paired with roughly $2.7 billion in new federal funding to expand domestic uranium conversion, enrichment, and fuel fabrication capacity. These policy changes are already influencing industry investment decisions: Orano has announced plans for an enrichment facility in the U.S., while Centrus is pursuing an expansion at its manufacturing facility to scale HALEU production.

Allied suppliers are also accelerating HALEU initiatives to create capacity. Urenco's Advanced Fuels Facility in Capenhurst, UK, aims to begin HALEU deliveries to customers by the early 2030s, with a planned annual output of up to 27 tons.[8]

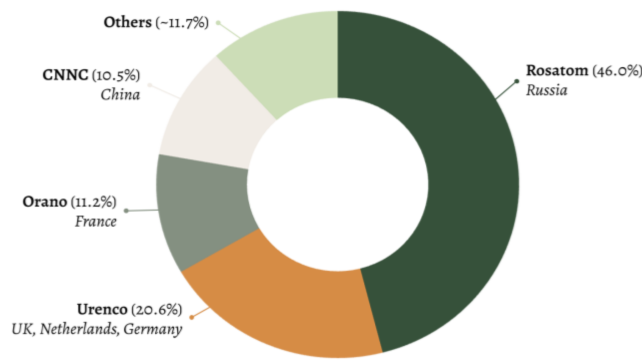
One emerging domestic player is Global Laser Enrichment (GLE), a Wilmington, North Carolina-based company developing a laser enrichment facility in Paducah, Kentucky. GLE is currently focused on the LEU market, with plans to re-enrich DOE-owned depleted uranium tails and a proposed 6 million-SWU-capacity plant scheduled to come online by 2030. While GLE is monitoring the HALEU market and has reserved space at its Paducah site for future HALEU capability, the company has cited major market and policy failures as barriers to investing in advanced fuel production. Its partial ownership by Cameco—the world's second-largest uranium miner—gives GLE a unique position in the broader supply chain, but its ability to scale will depend on clearer federal signals and market commitments.

Centrus Energy is the only U.S. company deploying American-developed centrifuge technology. Centrus manufactures its own centrifuges in Oak Ridge, Tennessee, and ships them to its Ohio enrichment facility—free from foreign components or intellectual property. This makes Centrus uniquely positioned to support U.S. national security missions and to serve as a sovereign provider of enrichment services.

The company is also pursuing entry into the domestic LEU market, with ambitions to build a multimillion-SWU commercial plant and reach production rates of up to 200 centrifuges per month. Centrus has committed $60 million in at-risk capital to build out its centrifuge manufacturing supply chain and recently raised $400 million in convertible debt to support growth.

Regulation is not viewed as a major limiting factor. One interviewee active in the enrichment space noted that the NRC "is not a barrier here," citing a clear and predictable licensing process. For companies pursuing LEU capacity, the current regulatory framework has been described as workable, with no expectation of significant hurdles should they later pursue HALEU licensing as well.

Figure 4. Global uranium enrichment market share (by SWU capacity)



Data from: The World Nuclear Industry Status Report 2023.

Deconversion

For conventional LEU fuel, UF_6 from enrichers is routinely deconverted to uranium oxide for pellet fabrication. In the U.S., this step is integrated at fuel fabrication plants—Westinghouse (Columbia, South Carolina), Framatome (Richland, Washington), and Global Nuclear Fuel-Americas (Wilmington, North Carolina)—and is not viewed as a capacity constraint. Separately, DOE's Mid-America Conversion facilities at Paducah, Kentucky, and Portsmouth (Piketon), Ohio, deconvert depleted UF_6 ("tails") to stable U_3O_8 for long-term storage, with allied deconversion capacity at Orano's Tricastin site in France.

By contrast, the U.S. has no commercial-scale deconversion line for HALEU.

[8] Urenco, *Taking Advanced Fuels Forward,* accessed February, 2026.

Table 5. World uranium deconversion facilities

Company	Country	Capacity (tU/yr)
Orano	France (Tricastin)	20,000
Urenco	UK (Capenhurst)	10,000
Rosatom	Russia (Zelenogorsk)	10,000
Mid-America Conversion	USA (Paducah, Kentucky)	18,000
Mid-America Conversion	USA (Portsmouth, Ohio)	13,500

Data from: World Nuclear Association, "Conversion and Deconversion," updated November 2024.

In the past, deconversion of HALEU has effectively been handled by the enriching country (for example, Russia would enrich and then deconvert material to oxides for fuel fabrication). With no domestic plant, even the small quantity of HALEU that Centrus produces for DOE is being stored as UF_6 gas, awaiting deconversion. Several U.S. companies (including Centrus) have received DOE grants to begin designing a domestic HALEU deconversion facility, and industry strongly favors co-locating any new deconversion unit at the enrichment site to minimize transportation and security costs.[9] Until such a plant is built, however, it will be a struggle to convert any HALEU that's produced into usable fuel.

Several advanced reactor designs, including TerraPower LLC's Natrium and Oklo Inc.'s Aurora, plan to use metallic HALEU fuel, which will require deconversion pathways capable of producing metal rather than oxide. Interviewees noted that metallic HALEU production involves added nonproliferation considerations, which are manageable but expected to add time and complexity to establishing a commercial metal-fuel deconversion capability.

Fuel Fabrication

The final step is turning enriched material into finished fuel—such as uranium oxide pellets, TRISO particles and pebbles, or metal fuel assemblies—and assemblies ready for reactor use.

For LWRs, there is an established, competitive domestic fuel fabrication market in place. Each of the three domestic participants (Framatome North America, Global Nuclear Fuel-Americas, and Westinghouse) have capacity to support additional LWR fuel and could scale their processes if given a clear demand signal (projects under construction). That said, one major fabricator emphasized that interrupting existing lines to automate or expand would temporarily reduce output, potentially affecting the operating fleet, thus careful planning for expansion will be required.

For Gen IV designs, several domestic players are attempting to stand up specialty fuel fabrication capabilities. Global Nuclear Fuel-Americas (GNF) is developing the metallic fuel form to be used in the Natrium reactor design in a new facility on its Wilmington, North Carolina, campus. Metallic fuel fabrication is technically complex and not currently produced at scale in the U.S., but the Natrium program is serving as the anchor project for establishing this capability.

BWXT operates a TRISO particle production line in Lynchburg, Virginia, and is exploring an additional TRISO fuel facility in Wyoming. X-energy LLC, another reactor developer, is building a dedicated TRISO fuel fabrication plant in Oak Ridge, Tennessee, slated to come online by the end of 2027 with an initial capacity of roughly 8 metric tons of fuel per year. Similarly, Kairos Power LLC is developing its own fuel supply for its fluoride salt reactor: Its Hermes test reactor will use HALEU TRISO pebbles fabricated in collaboration with national labs, and the company plans to establish a fuel fabrication facility in Oak Ridge for future production.[10]

Each of these efforts is tied to a specific reactor design, meaning the TRISO specifications are bespoke and not yet standardized across the industry.

Terrestrial Energy Inc. is taking a different approach, by extracting uranium tetrafluoride (UF_4) in the middle of the LEU deconversion process. This approach utilizes facilities (with process modifications) like those at Westinghouse's Springfields in the U.K. and is supported by the deconversion supply chain.

Companies with an interest in incorporating reprocessed spent fuel would require new fuel fabrication infrastructure not supported by existing supply chains, as discussed in the next section.

The challenge for advanced reactor fuel is whether these new domestic initiatives can scale up in time to meet demand, or whether developers will need to rely on allied partners abroad for fuel fabrication expertise and capacity.

[9] World Nuclear Association, "Uranium Conversion and Deconversion," updated November 2024.

[10] Nuclear Innovation Alliance, *A Company Compendium,* 2025.

Reprocessing

Some companies are exploring fuel forms that will require reprocessing, meaning the chemical separation of spent reactor fuel into uranium, plutonium, and residual waste (in contrast to recycling fuel in place without separation). The United States currently has no commercial civilian spent-fuel reprocessing facility and has generally avoided the practice because of economic, policy, and proliferation-risk concerns. Because such a path would introduce new infrastructure, additional security and safeguards requirements (given the presence of separated plutonium, which is considered a direct-use weapons-usable material), and high capital and operational costs, it would add layers of complexity to the fuel supply chain.

Commercial spent nuclear fuel assemblies typically contain roughly 95%-96% uranium, about 1% plutonium, and the remaining approximately 3%-4% fission products and actinides.[11] Although many of these uranium and plutonium fractions could be recovered for further fuel use under ideal reprocessing, current commercial practices recover only a small portion of spent fuel mass—on the order of 1%-2%. While spent fuel is sometimes described as roughly 96% reusable material by mass, that figure refers mostly to uranium that includes impurities that make reuse difficult and costly. In some cases, it also requires re-enrichment to serve as fuel, but because of impurities, dedicated enrichment infrastructure is needed. The fissile material that often provides the most energy benefit in reprocessed fuels is the plutonium.

An analysis from the Belfer Center for Science and International Affairs finds that reprocessing and fabricating new fuel from separated materials remains more costly than direct disposal unless uranium prices exceed $450 per kilogram of uranium (kgU).[12] For context, as of December 2024, uranium was trading at approximately $176/kgU.[13]

Bottlenecks

Structural, geopolitical, and market obstacles continue to hinder the establishment of a secure and sustainable domestic fuel supply chain for advanced nuclear reactors.

Heavy Reliance on Imported Uranium

In 2023, 95% of the uranium used in U.S. reactors came from foreign sources, with major supplies from allies such as Canada, Kazakhstan, Australia, and others.[14] Domestic uranium mining has collapsed from its 1980 peak: By 2020, U.S. production hit record lows (about 0.2% of 1980 output).[15] This decline was driven by sustained low uranium prices, which made U.S. mines uneconomical, and by regulatory and land-access hurdles. The result is only a handful of small ISR (in situ recovery) domestic mining operations exist today. The domestic mining workforce and milling capacity also atrophied during decades of minimal production, creating human capital bottlenecks in restarting operations.

Long Uranium Mining Lead Times and Growing Supply-Demand Gap

New uranium mines typically require 10 to 20 years from discovery to full operation because of complex permitting, financing, and infrastructure demands. Notably, mines operational between 2020 and 2024 had an average lead time of 17.8 years.[16]

This timing risk is worrying given projected uranium demand growth. There were 60,000 tU produced globally in 2024, and the World Nuclear Association projects that global reactor uranium needs will rise from approximately 67,000 tU consumed in 2024[17] to 87,000 tU by 2030 to 150,000 by 2040, while existing mine output is expected to halve between 2030 and 2040 as deposits deplete.[18]

Only One Domestic Facility for UF_6 Conversion

The one domestic conversion facility was idled from 2017 to 2023 because of a global oversupply of conversion services.[19]

[11] U.S. Congressional Research Service, *Considerations for Reprocessing of Spent Nuclear Fuel,* CRS Report R48364, Jan. 23, 2025.
[12] Matthew Bunn, *The Cost of Reprocessing in China*, Belfer Center for Science and International Affairs, Harvard Kennedy School, 2016.
[13] Cameco Corporation, *"Uranium Price."*
[14] World Nuclear Association, *US Nuclear Fuel Cycle*.
[15] Ibid.
[16] S&P Global Market Intelligence, *From 6 Years to 18 Years: The Increasing Trend of Mine Lead Times*, S&P Global, 2023.
[17] Connoting a supply-demand deficit.
[18] World Nuclear Association, *Nuclear Fuel Report: Global Scenarios for Demand and Supply Availability 2025-2040*, September 2025.
[19] World Nuclear Association, *US Nuclear Fuel Cycle*.

During that hiatus, U.S. utilities depended entirely on foreign converters (in Canada, France, and Russia). Even after its 2023 restart, Metropolis Works' capacity is insufficient to convert all uranium needed for U.S. reactors, and the facility's supply is already contracted through 2028.[20] Any unplanned outage or delay there could bottleneck the entire fuel supply chain. Another constraint is the lack of redundancy and flexibility: Without alternative domestic conversion plants, the U.S. is vulnerable to price spikes and supply disruptions. Indeed, conversion prices spiked when Metropolis was offline.

Overreliance on Russia for Enrichment

Simply put, current domestic enrichment capacity (LEU and LEU+) is not sufficient to fuel the existing U.S. reactor fleet, let alone future reactors. Urenco's lone U.S. plant has a capacity of about 4.9 million SWU/year, supplying roughly one-third of the United States' annual enrichment needs.[21]

The remaining demand, about 10-11 million SWU, has been met by foreign enrichers. As of 2023, about 27% of the enriched uranium fueling U.S. reactors came from Russia (through TENEX contracts).[22] Russia's state-owned Rosatom controls 44% of global enrichment capacity,[23] thus the forthcoming U.S. ban on Russian LEU imports has amplified supply risks.

The United States also relies heavily on Europe for the majority of imported LEU. Nearly 70% of U.S. enriched uranium imports in recent years originated from European suppliers (such as France's Orano and the German-Dutch-U.K. consortium Urenco), making European enrichment capacity critical to U.S. civilian nuclear fuel security.[24]

A potential LEU capacity shortfall could also limit HALEU availability. LEU serves as the feedstock for HALEU production, meaning any constraint at the LEU stage directly bottlenecks HALEU fuel supply.

Allied LEU enrichment headroom is limited, and adding new centrifuge cascades is a multiyear buildout. That said, domestic enrichers interviewed cited the three- to four-year lead time for new LEU cascades as shorter than the time frame of any new reactor build. Enrichment capacity can be added faster than new nuclear generation, and thus an LEU bottleneck could be avoided provided properly sequenced demand signals.

Competition With State-Funded Foreign Entities

Domestic fuel suppliers are at a distinct disadvantage when competing against foreign state-owned enterprises (SOEs) such as Orano and Urenco. These SOEs benefit from substantial government financial support, including direct capital injections and state-backed loans, which enable them to shoulder financial risks and make long-term investments that are untenable for private U.S. companies operating on purely commercial terms. Moreover, both Orano and Urenco rely on the same gas-centrifuge technology developed and manufactured by their joint venture, Enrichment Technology Company (ETC), giving them a structural advantage in global enrichment markets. Taken together, these circumstances make it challenging for U.S. suppliers to match the cost structures and investment scales of their foreign counterparts.

The historical context of the nuclear fuel industry further complicates this competition. Globally and within the U.S., the industry was born from significant government involvement and investment; no major enrichment provider emerged solely from private capital. A prime example is Centrus itself, which originated as the government-owned U.S. Enrichment Corporation (USEC), established by the Energy Policy Act of 1992 to privatize the Department of Energy's enrichment operations.[25] Today, a privatized U.S. industry is expected to compete on commercial terms against foreign entities that still receive substantial state support, creating a fundamentally uneven playing field.

HALEU Production Capacity Is Nonexistent at Commercial Scale

The most critical bottleneck in the advanced nuclear fuel cycle is the lack of U.S. commercial-scale capacity to produce the HALEU required by some Gen IV reactor designs. This includes enrichment, deconversion, and transportation.

A fundamental market failure faces HALEU suppliers. As one investor bluntly stated, the primary risk factor for their investment in a reactor technology was the supply chain, with the fuel supply chain being "way behind where the reactors are." From their perspective, there is currently "no market"—only talk—when it comes to Gen IV reactors. The absence of bankable offtake agreements from creditworthy buyers of heat or power produced by Gen IV reactors leaves upstream suppliers without the financial certainty needed to invest.

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[20] Energy Intelligence, "Nuclear Fuel: Metropolis Sold Out Through 2028, Weighing Expansion," April 29, 2024.
[21] World Nuclear Association, *US Nuclear Fuel Cycle*.
[22] Mikael Pir-Budagyan, *Securing Energy Independence: The U.S. Path to Resilient Enriched Uranium Supply Chain*, Atlantic Council, Feb. 11, 2025.
[23] Ibid.
[24] Nuclear Innovation Alliance, *Advanced Nuclear Reactor Technology: A Company Compendium,* November 2024 update.
[25] Nuclear Innovation Alliance, *A Company Compendium,* 2025.

On enrichment, Centrus' small demonstration cascade produces about 900 kilograms (kg) per year,[26] which pales against the multi-ton quantities needed for commercial deployment. Given Russia's position as the only commercial supplier of HALEU, domestic suppliers can only rely on small-scale, near-term, down-blending bridge solutions while waiting for other domestic or allied- HALEU capacity.

Compounding the enrichment challenge is the unaddressed gap in deconversion services. Even if enrichment capacity were expanded, there is no commercial-scale facility in the U.S. to deconvert enriched UF_6 gas into metal or oxide forms suitable for HALEU fuel fabrication. This missing step has been explicitly identified by potential fuel producers as a major concern. Enrichment alone cannot support the production of finished fuel, leaving the supply chain incomplete and further deterring investment.

Market paralysis is further exacerbated by slow deployment of government funding intended to catalyze HALEU production. The Department of Energy's slow approach to awarding funds has created uncertainty and is delaying private investment decisions. Despite Congress appropriating billions for LEU and HALEU infrastructure—including $700 million for HALEU in the Inflation Reduction Act and $2.7 billion for LEU and HALEU enrichment and deconversion capacity— stakeholders reported that the funds have been too slow to deploy.

Perhaps this is beginning to change: In January 2025, DOE announced the allocation of the $2.7 billion enrichment program, awarding $900 million each to General Matter, Centrus, and Orano to provide domestic uranium enrichment services. In parallel, DOE also awarded $28 million to GLE to continue advancing next-generation uranium enrichment technology. For HALEU in particular, this announcement followed years of delay. Prior to these awards, one expert rated the effectiveness of DOE's efforts as "1 or 2 out of 10," arguing the U.S. "had a chance to lead on HALEU, but the DOE has bungled it."

Despite this recent progress, the lack of a clear, long-term federal strategy continues to stall investment. The government has yet to articulate whether it intends to prioritize specific enrichment technologies or companies, leading to a scattered approach and a failure to "down-select winners" (i.e., narrow choices to the most promising options) to build market confidence. Without decisive policy direction and timely funding deployment, suppliers are hesitant to commit capital, and developers remain uncertain about future fuel availability.

Beyond production itself, the logistics of moving HALEU present another unaddressed bottleneck. There are no U.S. Department of Transportation-approved, commercially viable cylinders or packages for transporting UF_6 enriched above 5% U-235 or for deconverted HALEU forms.[27] Designing, testing, and certifying new shipping packages is a complex, multiyear process requiring extensive cooperation between DOE, NRC, and the Department of Transportation (DOT), and its absence creates a tangible barrier to establishing a functional fuel cycle.

Taken together, the absence of a secure HALEU supply chain leaves reactor developers unable to plan deployments with confidence, as fuel supply for even initial cores cannot be guaranteed. Fuel suppliers like Centrus and GLE are unwilling to invest in expensive new enrichment facilities without firm, bankable orders from reactor developers, while those developers cannot secure customer commitments or financing without an assured fuel source. This market deadlock has emerged as a primary obstacle to establishing a domestic HALEU supply chain.

TRISO Fuel Fabrication Constraints

TRISO fuel is a novel (typically) HALEU-based fuel form central to certain Gen IV reactor designs, making it a critical link in the advanced nuclear supply chain. However, production of TRISO fuel in the U.S. remains limited to demonstration-scale capacity, with only a few entities developing fabrication programs, such as BWXT and X-energy, as referenced above.

Each advanced reactor developer using TRISO fuel has unique design specifications, creating a fragmented landscape where multiple types of TRISO fuel are needed, which limits opportunities for economies of scale, shared qualification, and cost reduction. As one industry expert noted, "There is something unique about everyone's TRISO fuel."

This customization increases costs, complicates licensing, and leaves developers dependent on small-scale, vertically integrated production with limited throughput. Furthermore, TRISO production is a batch process that, even with standardization, cannot be easily scaled.

The complex, multistep TRISO manufacturing process also faces significant capacity constraints and is further limited by dependence on scarce HALEU feedstock. Even developers who secure an initial TRISO core load through government stockpiles or pilot programs have no assured fuel supply for

[26] MPR Associates, *United States Nuclear Manufacturing Infrastructure Assessment,* prepared for Department of Energy, Dec. 19, 2018.

[27] Ibid.

subsequent reloads given the absence of a commercial HALEU supply chain.[28]

A further concern raised by multiple stakeholders is sequencing risk. If large-scale TRISO fabrication capacity came online before HALEU enrichment were to be established, facilities would sit idle. As one interviewee at a fuel fabricator warned, “If there’s a massive TRISO facility but no HALEU, somebody like me gets fired.” The interdependence of enrichment and fabrication means that misaligned buildout timelines can strand capital and undermine confidence in the broader supply chain.

Fuel Qualification Timelines Are a Pacing Bottleneck

According to experts interviewed, a single fuel-qualification “try” (i.e., one irradiation campaign to target burnup/damage for a specific fuel/cladding configuration, followed by full post-irradiation examination, or PIE) typically takes two to four years of irradiation and 18-24 months of PIE. Even for established fuel forms such as LWR UO_2 or TRISO, this cycle time establishes a baseline of roughly four to six years before definitive qualification data are available.

Capacity is also constrained at existing U.S. test and examination facilities, which create queues and can extend schedules further. If a first try does not meet qualification requirements, subsequent loops compound the delay by multiple years. The result is that fuel qualification (separate from enrichment or fabrication) emerges as a systemic pacing factor for advanced reactor deployment.

For sodium fast reactors (e.g., Natrium), the U.S. has no domestic capability for fast-spectrum neutron testing, which is needed to develop and qualify fuels and materials for these reactor designs. The most extensive fast-reactor testing capabilities currently reside in Russia.[29]

Lack of Standardization

A growing diversity of reactor designs is driving parallel demand across multiple enrichment bands (LEU, LEU+, and HALEU) and multiple fuel fabrication pathways (e.g., oxide pellets, TRISO particles, metal fuels, and liquid fuels). Each pathway carries its own infrastructure needs, qualification programs, quality requirements, transport configurations, and regulatory approvals.

When potential reprocessing and recycled fuel options are layered on top of this front-end diversity, the scope of the required supply chain expands even further — spanning new chemical separation facilities, specialized fabrication lines, safeguard regimes, and waste form licensing.

Taken together, this results in a highly fragmented and capital-intensive supply chain landscape, where resources, talent, and investment are spread across many bespoke pathways rather than concentrated in a smaller number of scalable, repeatable industrial solutions.

[28] U.S. Department of Energy, *Nuclear Energy Supply Chain Deep Dive Assessment*, Feb. 24, 2022.

[29] Ibid.

Table 6. Status of the U.S. fuel supply chain				
Fuel cycle stage	**Current domestic capability**	**Key domestic players**	**Primary bottleneck**	**Key foreign dependencies**
Uranium mining/ milling	Near-zero commercial production; highly import-reliant	Few small-scale operators	Long lead times for next-gen mines; depleting stockpiles at current mines	Canada, Kazakhstan, Australia, Russia
Conversion	One restarted facility (ConverDyn, 7,000 tU/year)	ConverDyn	Current demand met; greater capacity necessary to support fleet growth	Canada (Cameco), France (Orano), Russia
Enrichment (LEU)	Existing commercial facilities	Urenco USA, Orano Federal Services, General Matter, Centrus	Only one operating domestic commercial enrichment facility, but multiple facilities under development	France, UK, Germany, Netherlands, Russia
Enrichment (HALEU)	Demonstration-scale only (900 kg/year)	Centrus, General Matter	Limited commercial-scale capacity for standard assay LEU and none for HALEU; market deadlock on investment	Russia
Deconversion (HALEU)	No commercial capability	N/A	Total lack of commercial facilities; market deadlock on investment	Russia
LWR deconversion & fabrication (LEU)	Established domestic supply chain	GNF, WEC, Framatome NA	N/A	N/A
TRISO fabrication (HALEU)	Demonstration/ prototype-scale only	BWXT, X-energy, Kairos Power	Lack of standardization; each developer has a unique fuel design	N/A
Liquid fuel fabrication (HALEU)	Early lab-scale only	TerraPower/ Southern Co, Terrestrial Energy	Testing & qualification of new fuel designs; scaling fabrication	N/A
Metal fuel fabrication (HALEU)	Demonstration/ prototype-scale only	Framatome NA, Lightbridge, GNF	Testing & qualification of new fuel designs; scaling fabrication	N/A
Reprocessing	Demonstration/ prototype-scale only	Oklo, SHINE, Curio, Exodys	Testing & qualification of new fuel designs; scaling fabrication; safety, security, and proliferation-risk concerns	N/A

Key:

= High risk, lack of established supply chain, with market deadlock preventing any capacity investments

= Medium risk, established but fragile supply chain, with some constraints regarding ability to scale to support fleet growth

= Low risk, established supply chains, with additional capacity available or readily able to scale to support fleet growth

Opportunities and Strategic Pathways

Accelerating the development of a secure fuel supply chain for advanced reactors requires concrete strategies.

Capitalize on Policy Momentum to Rebuild the U.S. Uranium Supply Chain

Recent market and policy shifts are spurring a modest revival. Uranium output jumped in 2024, reaching about 677,000 pounds U_3O_8 (260 tU) domestically—a thirteenfold increase over 2023's output—as companies restarted idle mines in Wyoming, Texas, and Utah.[30,31] Even so, this represents a mere 0.4% of global uranium mine production.

This domestic uptick was driven by higher uranium prices and strong signals from Washington. The Russian ban on uranium imports created an assured market for domestic supply. On the regulatory side, new measures aim to ease mine development. For example, in 2025 the Federal Permitting Improvement Steering Council (FPISC) added select domestic uranium projects to fast-track permitting initiatives under FAST-41 (the Fixing America's Surface Transportation Act federal permitting framework), as seen with Uranium Energy Corp.'s Sweetwater project designated for accelerated review.[32,33]

These efforts, alongside rising global demand for nuclear fuel, present an opportunity for a domestic mining resurgence. But it's contingent on sustained investment and community engagement to avoid the "boom-bust" cycle that previously plagued the sector. In the near term, rebuilding uranium mining and conversion capacity should remain the priority. Plutonium-bearing fuel cycles would require separate, purpose-built supply chains and must resolve significant safeguards, security, and proliferation issues before they could be credibly pursued at scale.

Scout New Mines Now to Meet Increasing Demand in the Near Future

To mitigate looming supply shortfalls, governments, utilities, and international bodies should start identifying and advancing uranium mining projects now. Given the lengthy development timeline, projects initiated today are crucial to feeding uranium demand in the late 2030s. This includes ramping up geological exploration, expediting permitting for viable deposits, and establishing public-private financing partnerships, especially in allied countries such as Kazakhstan, Canada, and Australia. Even if enrichment and conversion follow more rapidly, the chain breaks if raw uranium is unavailable.

Prioritize Strategic Domestic Capabilities While Leveraging Allied Supply Chains

Before embarking on an effort to replicate the entire nuclear fuel supply chain domestically, it is essential to critically assess which parts truly require sovereign U.S. capability and which can be reliably sourced through partnerships with trusted allies. Given the decision to reduce reliance on major suppliers like Russia, the global nuclear fuel market already includes well-established, technologically advanced providers in allied nations—particularly in Europe—that possess mature enrichment and fabrication infrastructure backed by significant economies of scale and deep institutional expertise. Companies such as Urenco USA and Orano exemplify this advantage. They not only maintain operations with substantial technical capacity but also already have significant facilities in the U.S.

A foundational assumption in current U.S. policy is that achieving an entirely independent domestic nuclear fuel supply chain is necessary for national security and resilience against geopolitical shocks. However, this approach warrants critical examination. It presumes the benefits of sovereign control outweigh the immense costs, time, and complexity of building capabilities that match those of established global suppliers. A more strategic approach would differentiate between elements of the fuel cycle that are critical to national security—such as enrichment and deconversion capacity where there is high Russian dependency—and those where collaboration with allied suppliers can achieve both resilience and cost-effectiveness.

This is not merely a theoretical exercise; it reflects the reality of the industrial landscape. As one interviewee noted, there is a significant difference in the corporate and organizational maturity between established international players like Urenco and emerging domestic ones.

A pragmatic strategy might therefore involve leveraging the mature operational capabilities of an allied-owned firm to

[30] U.S. Energy Information Administration, *Domestic Uranium Production Report,* Aug. 5, 2025.
[31] *World Nuclear News*, "U.S. Uranium Industry Growth Continues," Aug. 7, 2025.
[32] Pooja Menon, "Uranium Energy's Sweetwater Plant on Fast Track for In-Situ Mining Approval," *Reuters*, Aug. 5, 2025.
[33] Federal Permitting Improvement Steering Council (FPISC), "Permitting Council Adds Uranium Energy Corp's Sweetwater Uranium Complex to FAST-41 Dashboard."

accelerate near-term HALEU production, while simultaneously making targeted investments to nurture sovereign capacity in the most critical missing links, like deconversion. This hybrid approach could be faster and more capital-efficient than attempting to replicate from scratch the entire fuel cycle with purely domestic, less mature players.

A promising example of domestic fuel supply chain investment is Uranium Energy Corp.'s recent announcement to build a conversion facility in Texas set to produce 10,000 metric tons of UF_6 per year, more than half of current domestic demand.[34]

Another notable example of this emerging strategy is the recent agreement among the "Sapporo 5"—the United States, Canada, France, Japan, and the United Kingdom. In September 2024, they jointly announced over $5.6 billion in combined public and private investment to secure a reliable, transparent, and geopolitically resilient nuclear fuel supply chain.[35] The coalition's objective is to reduce dependence on Russian materials while reinforcing allied capabilities, illustrating how strategic international collaboration can complement targeted domestic buildout efforts.

Provide Clarity to the Market on Fuel Import Policies to Incentivize Domestic LEU Supply Chain Investment

While the U.S. has codified a ban on Russian nuclear fuel imports, with all waivers expiring in 2028, interviewees emphasized that lingering market uncertainty deters domestic capital commitments. Companies remain wary that the ban could be weakened—either through repeated extensions of "temporary" waivers or shifts in political leadership—creating the risk that Russian supply might re-enter the market before billions of dollars invested in new U.S. enrichment or conversion capacity can be fully recouped.

Because the current import ban sunsets in 2040, a facility that begins operations in 2028 would have only 12 years to recover its capital investment before competing with imported Russian LEU, meaning any policy interruptions or construction delays could have an outsized impact on project economics. This uncertainty undermines the economic case for major facilities by raising doubts about long-term demand and price stability. Stakeholders stressed that policy clarity across administrations is essential. Bipartisan commitment to maintaining the ban, without loopholes or reversals, will provide the stable investment environment needed to catalyze a durable domestic fuel supply chain.

Use DOE as a Market-Maker for HALEU

One of the most promising opportunities to break the current supply-demand deadlock is for DOE to act as a market-maker by serving as a guaranteed buyer for an initial tranche of HALEU. By committing to purchase a defined quantity of HALEU, DOE could create a bankable demand signal that gives private companies like Centrus and GLE the confidence to secure financing and begin construction of new enrichment and deconversion facilities. This approach eliminates the uncertainty around early fuel orders that currently prevents suppliers and developers from moving forward.

This can be achieved through specific financing models proposed by industry and policy analysts. One such model is a material offtake agreement program, where the federal government would provide multiyear contracts to private companies to produce a fixed amount of HALEU annually at a fixed price. A second model is a production services agreement program, where the government would contract for specific services like enrichment (e.g., a set number of SWU per year) at a fixed price. These demand-side contracting mechanisms are distinct from DOE's existing capital support programs, including the HALEU Availability Program (HAP) and recent enrichment awards, which primarily reduce construction and first-mover risk but do not provide binding, long-term offtake commitments.

These programs require significant, guaranteed, long-term federal funding to be credible. Analyses suggest that a material offtake agreement program for HALEU alone could require up-front appropriations of $1.5 billion to $2.9 billion, while a production services agreement program could require $2 billion to successfully catalyze private investment in commercial-scale facilities.[36]

Accelerate and Clarify DOE Funding Deployment

Another opportunity lies in the need to expedite and simplify DOE's process for deploying appropriated funds for HALEU infrastructure. Even with demand-side commitments in place, delays or opacity in DOE's deployment of appropriated funds can materially slow private investment decisions. Clear

[34] *World Nuclear News,* "US Uranium Company Unveils Conversion Facility Plans," Sept. 2, 2025.

[35] Office of Nuclear Energy, "Sapporo 5 Release Joint Statement Calling for Like-Minded Nations to Join Commitment to Secure a Reliable Nuclear Fuel Supply Chain," U.S. Department of Energy, Sept. 18, 2024.

[36] Patrick White and Erik Cothron, *Characterizing an Emerging Market for High-Assay, Low-Enriched Uranium Production: Summary for Policymakers,* Nuclear Innovation Alliance, December 2023.

timelines, milestone-based contracting, and predictable disbursement schedules would reduce execution risk and improve capital planning.

One interviewee noted that even if DOE were to dedicate the full $3.4 billion of available enrichment appropriations to support a new facility, any commercial-scale LEU or HALEU enrichment plant would still require substantial private capital to close the gap, highlighting the need for policy structures that de-risk the market for private capital rather than fully fund it. The interviewee proposed that DOE use its appropriated funds to offer milestone-based contracts rather than direct capital expenditure support, arguing this would better align incentives and reduce risk for both government and private investors.

Fund a Commercial-Scale Deconversion Facility

Although interviewees did not identify LEU deconversion capacity as a bottleneck, a domestic, commercial-scale deconversion facility remains a distinct and critical missing link in the HALEU supply chain. Private industry stakeholders strongly recommend that government funding and incentives prioritize construction of such a facility. A public-private cost-sharing approach is likely necessary, as the economics of building a facility are challenging for any private entity to shoulder alone. Successful international models support this strategy: Although not a deconversion facility, the U.K. government's decision to co-fund Urenco's new enrichment facility covers nearly half of that project's cost, de-risking private investment and recognizing the facility's importance as national infrastructure.[37] A similar decisive action by the U.S. government could remove a critical obstacle and enable the entire HALEU fuel cycle.

Leverage LEU+ to Reduce Near-Term Fuel Cycle Risk

The NRC is actively preparing to license higher enrichment levels for LEU+ fuel. In 2023, the NRC approved Framatome's advanced analysis methods for reactor fuel up to 10% U-235, a key step toward allowing utilities to reload cores with LEU+ fuel by 2027.[38] Such regulatory green lights, alongside new certified transportation packages for enriched UF_6 (Framatome obtained approval to ship fresh fuel at up to 8% U-235 in 2022),[39] are resolving the technical hurdles to deploying LEU+ fuel. Furthermore, in December 2024, the NRC approved a license amendment for the Urenco USA enrichment facility that enables the production of LEU+ fuels of up to 10% U-235, increased from the previous 5.5% ceiling.[40]

For the existing LWR fleet, LEU+ enables longer fuel cycles, higher burnup, and improved operating flexibility without introducing new fuel forms or qualification pathways. For advanced LWRs and select microreactor designs that remain within the thermal-spectrum LWR envelope (e.g., designs such as Aalo Atomics'), LEU+ can support early deployment and demonstration while avoiding dependence on an immature HALEU enrichment, deconversion, and transport infrastructure. In this way, expanded LEU+ availability can relieve near-term fuel bottlenecks, smooth demand on the enrichment supply chain, and accelerate deployment of LWR-based technologies, while HALEU-dependent Gen IV designs proceed on a parallel, longer-lead fuel development track.

Support Standardization of Uranium Fuel Forms

Current proposed reactor designs include a wide variety of fuel types that, in many cases, would require bespoke infrastructure for processing and fabrication. This includes metals, oxides, and molten salt-based fuels. Industry should work to harmonize design requirements and encourage shared infrastructure. Co-locating multiple production lines or developing modular production capabilities could enable economies of scale without forcing every developer to build fully independent supply chains.

Later in this report, we will broaden our scope to include microreactors (SMRs producing less than 50 megawatts). That said, there is one microreactor developer team that is pursuing an approach worth mentioning here. Aalo Atomics initially designed its Aalo-1 reactor to use uranium zirconium hydride (UZrH) fuel, a more novel fuel form.[41] However, recognizing the immense technical, regulatory, and financial hurdles of establishing a new fuel supply chain, the company made a strategic pivot to 8% enriched uranium dioxide (UO_2), a form of LEU+.[42] This decision was a deliberate trade-off, potentially sacrificing some performance characteristics to de-risk its supply chain by leveraging the far more mature and globally diversified infrastructure for LEU.

[37] MPR Associates, United States Nuclear Manufacturing.
[38] World Nuclear News, "NRC Approves Use of Framatome Codes in Advanced Nuclear Fuel Development," April 26, 2023.
[39] "Framatome Receives U.S. NRC Approval to Transport Higher Enriched Fuel," *Framatome*, Feb. 22, 2022.
[40] *ANS Nuclear News,* "Urenco USA Has NRC Approval for Increased Enrichment," Dec. 17, 2024.
[41] Gateway for Accelerated Innovation in Nuclear, "Aalo Prepares for US Licensing of Microreactor," Idaho National Laboratory, Sept. 27, 2023.
[42] Ross Moulton, "Unlocking Hypergrowth: Our Bold Move in Nuclear Fuel," Aalo Atomics, July 26, 2023.

A further example of where this can happen is within the area of TRISO fuels. One interviewee emphasized the value of adhering to DOE's Advanced Gas Reactor (AGR) specification, a reference fuel form developed under the Advanced Gas Reactor Fuel Development and Qualification Program beginning in the mid-2000s. That program produced a common TRISO particle specification and demonstrated its performance through multiple irradiation tests at Idaho National Laboratory (INL), creating a baseline that can simplify qualification and allow multiple suppliers to align under a shared standard. By contrast, if each reactor designer introduces just one change to the baseline design, the benefits of standardization collapse and the supply chain fragments. At the same time, it is important to acknowledge that complete standardization across all reactor designs may not be technically feasible and is likely suboptimal for one or more technologies.

A promising example of a standardized approach is the September 2025 partnership announced between BWXT and Kairos to jointly explore and develop commercial-scale TRISO fuel production. The partnership combines Kairos' pebble-level TRISO development capabilities with BWXT's decades of manufacturing experience and streamlines paths toward a shared fabrication facility.[43]

These examples point to a central lesson for advanced reactors: Scale will depend less on fuel innovation in isolation than on fuel supply chains that can be standardized, licensed, and manufactured repeatably. That implies prioritizing uranium-based pathways where industry can converge on a limited set of fuel forms and build shared infrastructure; Plutonium-bearing fuels, on the other hand, sit outside this near-term standardization logic: they introduce distinct supply-chain, security, and nonproliferation concerns, which would demand dedicated facilities that do not exist today in the United States. Given the urgency of building a robust domestic fuel ecosystem, uranium fuels offer the fastest route to durable scale.

Co-Locate Enrichment and Deconversion

Federal policy and funding mechanisms should explicitly incentivize siting enrichment and deconversion facilities together. Co-location would streamline logistics, lower the costs and complexities of transporting HALEU between sites, and enhance security by reducing the distance enriched material must travel.

Taken together, these measures offer a pragmatic path to rapidly establish a resilient fuel supply chain that balances domestic capability with allied partnerships.

[43] *World Nuclear News,* "Kairos, BWXT Team Up for Commercial TRISO Fuel Production," Sept. 3, 2025.

Heavy Manufacturing and Major Components

The advanced reactor supply chain faces critical constraints in heavy manufacturing capacity, particularly in the fabrication and machining of major components. While interest is growing across the industrial base to support advanced reactor deployments, suppliers interviewed consistently emphasized that meaningful investment will not occur without a predictable, multiunit order pipeline. A single project is not enough to justify capital upgrades, and firms are waiting for sustained demand signals before committing to new capacity.

Compounding this hesitation is the steep decline in the number of U.S.-based suppliers certified to produce nuclear-grade components under American Society of Mechanical Engineers (ASME) N-stamp requirements. In this report, “certification” means an organizational or facility authorization (e.g., an N-stamp), while “qualification” means the demonstrated acceptability of a specific component, process, or individual for a defined nuclear service (e.g., ASME's Nuclear Quality Assurance-1 standard, or NQA-1).

Some manufacturers have indicated that reactivating dormant capabilities would require both reliable demand and long-term partnerships—often backed by public or utility-supported anchor projects. Others noted a broader erosion in industrial capacity, pointing to gaps in domestic production of critical inputs like primary steel and high-purity metal powders—materials essential for both conventional and advanced manufacturing techniques.

Workforce limitations also emerged as a consistent theme across interviews. Suppliers flagged machining and welding expertise as particular pain points, with skilled labor increasingly difficult to secure because of demographic shifts and rising competition from other high-growth sectors. These labor constraints not only limit current throughput but also raise questions about how quickly the industry could scale if demand were to accelerate.

Key Players

The U.S. heavy manufacturing landscape for nuclear components (large-scale forging, machining, welding, and finishing of major reactor parts) is relatively limited and highly concentrated. A small number of domestic firms provide key capabilities, particularly for SMRs and advanced designs that do not require ultra-large forgings.

North American Forgemasters is one of the few U.S.-based forges capable of producing SMR-scale reactor pressure vessels and associated components. BWXT also manufactures nuclear-grade components, including heat exchangers, steam generators, and SMR pressure vessels, supported by experience serving the U.S. naval reactor program.

Ultra-large forgings—such as those required for traditional reactor pressure vessels (RPVs)—are currently being sourced from international firms like Doosan (South Korea), Japan Steel Works, and Ansaldo Energia (Italy). Similarly, domestic capacity for steam turbines and specialized electrical equipment is minimal, with key components typically imported from Siemens (Germany) or GE Vernova facilities in Europe.

The small number of U.S. manufacturers capable of nuclear-qualified machining, welding, and nondestructive examination (NDE) also presents a constraint. This limited supplier base—and the erosion of ASME N-stamp-qualified vendors—highlights the need for strategic investments and policies to stabilize and expand domestic manufacturing capability for next-generation nuclear deployment.

Table 7. Manufacturing readiness for key components		
Major component	**Known U.S. capability**	**Known companies**
Reactor pressure vessel (large scale, e.g., AP1000)	No; reliant on foreign suppliers (e.g., Japan, South Korea, Italy)	Doosan (Korea), Japan Steel Works, Ansaldo Energia (Italy)
Reactor pressure vessel (SMR scale)	Yes; multiple U.S. firms can forge/machine SMR-scale vessels	North American Forgemasters, BWXT (limited)
Steam generators/pressurizers	Partial; some domestic capability, often reliant on foreign vendors	BWXT, Holtec, foreign firms (e.g., Framatome, Doosan)
Steam turbine generators	No; mostly sourced from Germany and France	Siemens Energy (Germany), Framatome (France)
Generator step-up transformers	Yes; significant domestic capability, but also available internationally	GE Vernova, Siemens Energy, ABB Group, et al.
Heat exchangers	Partial; exists but limited to specific facilities	BWXT, SPX Technologies, Thermal Engineering International, et al.
Large bore valves, pumps	Yes; multiple U.S. firms can supply	Crane, Curtiss Wright, Flowserve, et al.

In the face of limited supplier bases, a notable trend is emerging among some reactor developers: vertical integration. Rather than waiting for a fragmented and unreliable external market to mature, several leading companies are choosing to become their own suppliers out of necessity (or, in some cases, as a hallmark of their culture).

Holtec, for instance, reports that it controls 75% of its supply chain and is self-manufacturing major components like reactor vessels and steam generators. Kairos Power is developing its own fuel pebbles and building a dedicated molten salt production facility. X-energy is constructing its own TRISO fuel fabrication plant. This mirrors SpaceX's approach in the launch industry, where bringing engine, avionics, and structural manufacturing in-house transformed cost, schedule, and innovation cycles compared to the legacy contractor-driven model.

While this strategy offers developers greater control over schedule and quality for FOAK projects, it also carries risks for the industry as a whole. This approach is incredibly capital-intensive, duplicative, and prevents the development of a competitive, horizontal supply market that could drive down costs through economies of scale.

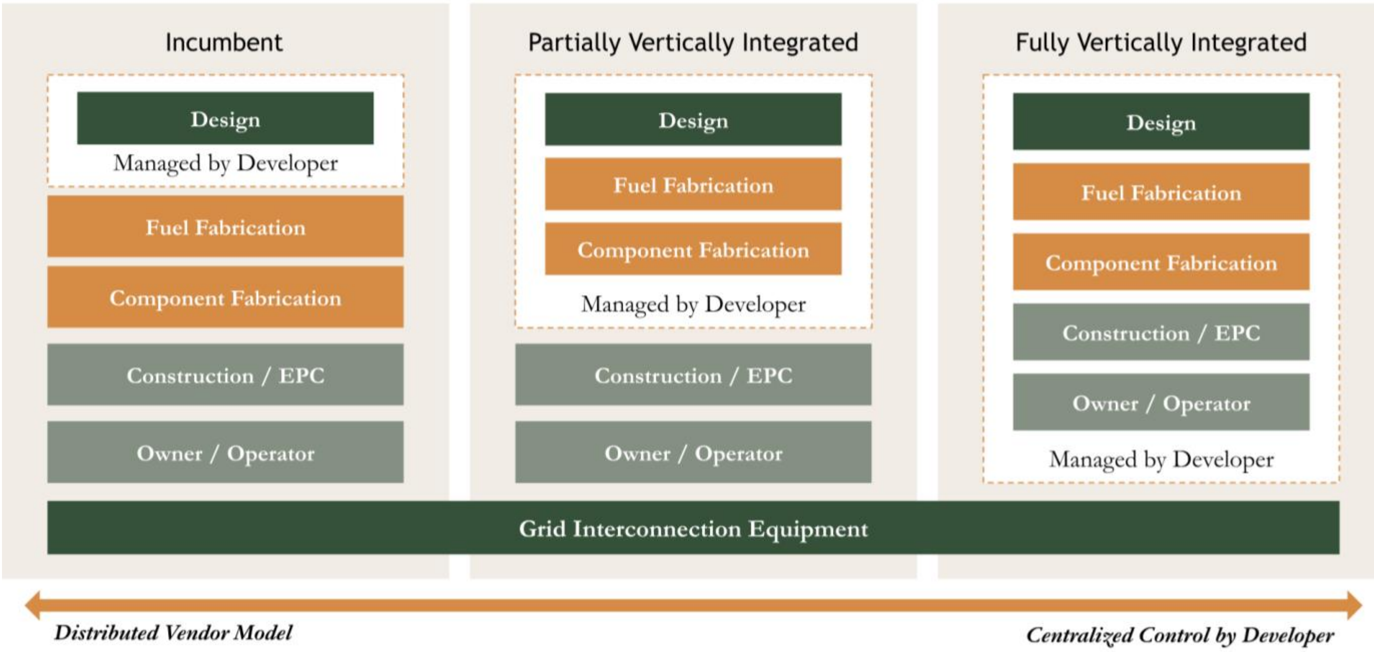
Reactor developers fall along a spectrum of supply chain strategies, from traditional models that rely heavily on external vendors to fully vertically integrated approaches where most capabilities are brought in-house. Incumbents and Gen III+ developers like GE Vernova Hitachi and Westinghouse often operate with a distributed vendor model, partnering with experienced EPC firms and established component suppliers. These companies may lead the design and fuel strategy but outsource fabrication and construction to a broader industrial base. This approach leverages existing supply chains and spreads financial risk but leaves developers exposed to bottlenecks and delays outside their direct control.

In contrast, developers of Gen IV reactors and microreactors are increasingly pursuing vertically integrated models, either partially or fully. For example, Oklo has signaled its intent to build and operate most of its own infrastructure, including fuel production, power plant construction, and long-term waste storage. Radiant Industries Inc. has adopted a similar approach, designing not only its reactor but also key components and modules in-house, while planning to manage its own deployment and servicing. These strategies allow microreactor companies to move quickly, reduce reliance on slow-to-mature supply chains, and tailor their designs to specific use cases such as defense, remote communities, or industrial heat applications.

This developer-led model is particularly prevalent in the microreactor segment because the units are small, factory-fabricated, and targeted at niche markets that may not be large enough to justify the buildout of a conventional supply chain. However, most of these developers are early-stage companies without the capital or capacity to sustain an end-to-end industrial model over the long term without significant orders.

And because many of these designs rely on advanced fuel fabrications like TRISO or metallic HALEU, where no commercial-scale U.S. fabrication capacity exists, developers have been forced to vertically integrate out of necessity.

Figure 5. Spectrum of supply chain models



A Note on Energy Conversion Systems

Some supply chain components, particularly those involved in balance of plant and grid interconnection, are not unique to nuclear energy but affect all major energy projects. While outside the primary scope of this report, persistent challenges in these areas directly constrain the viability of nuclear deployment and therefore warrant attention.

The U.S. lacks domestic manufacturing capacity for steam turbines used in nuclear power plants, resulting in significant international dependencies. According to a 2022 cost analysis of U.S. pressurized water reactors, the turbine generator is the single largest driver of direct costs, accounting for 12.7% of the total.[44] This forces reactor developers to source these high-value components from a small, internationally concentrated set of suppliers, including foreign firms in Germany (e.g., Siemens Energy) and other allied European manufacturing hubs, a reliance several interviewees identified as their most significant foreign supply chain bottleneck.

These conversion system gaps extend beyond the plant boundary to the grid itself. Transformers are foundational to the grid, with over 90% of consumed power in the U.S. passing through large power transformers (LPTs).[45] Their failure or unavailability presents a direct constraint on connecting any new generation source to the grid. The U.S. transformer fleet is dangerously old, with an average age of approximately 40 years, which is near or beyond the transformers' design life. An estimated 70% of all transformers are older than 25 years, creating immense replacement demand that competes directly with new projects.[46]

Current lead times for LPTs and generator step-up (GSU) transformers, which face similar manufacturing, supply chain, and lead-time constraints, now range from one and a half to four years, with some U.S. manufacturers reporting five-year backlogs.[47] Concurrently, the average cost of transformers has doubled or tripled since 2020.[48]

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[44] Benjamin T. Starkey, *Cost Estimation Model for U.S. Pressurized Water Reactor Construction through Multiple Regression,* Doctorate of Engineering praxis, The George Washington University, Aug. 31, 2022.
[45] U.S. Department of Energy, "Electric Grid Supply Chain Review," 2023.
[46] National Infrastructure Advisory Council, *Addressing the Critical Shortage of Power Transformers to Ensure Reliability of the U.S. Grid*," Cybersecurity and Infrastructure Security Agency, June 5, 2024.
[47] National Infrastructure Advisory Council, *Addressing the Critical Shortage of Power Transformers to Ensure Reliability of the U.S. Grid*," Cybersecurity and Infrastructure Security Agency, June 5, 2024.
[48] Niskanen Center, "Powering the Nation: How to Fix the Transformer Shortage," May 20, 2024.

One interviewee shared a particularly stark example from a recent DOE project they had been involved with in east Tennessee that illustrates the new market reality. Even with the full weight of the federal government, the lead time for critical transformers is now 18-24 months—the same as for smaller commercial players. This signals a fundamental erosion of a key strategic advantage that historically underpinned large capital projects: The inability of a government entity with massive buying power to gain preferential treatment shows that the supply for certain long-lead-time components has become nearly inelastic. The direct consequence is a severe loss of project control, where critical path timelines are dictated by suppliers, not the project owner. This removes a primary mechanism for managing project risk and introduces schedule uncertainty and financial risk from the outset.

In response to these shortages, Siemens Energy recently announced a $150 million investment to build a large transformer manufacturing facility in Charlotte, North Carolina, aiming to ease the domestic bottleneck and increase grid resilience, with production scheduled to begin in 2026.[49]

The nation now imports over 80% of its LPTs and relies on foreign sources for most of its distribution transformers, satisfying only about 20% of total demand from domestic production.[50] This reliance potentially exposes U.S. utilities and project developers to global manufacturing capacity constraints and long lead times

The U.S. grid uses tens of thousands of different transformer designs, with most units being highly customized for specific utility needs. This bespoke engineering approach prevents the kind of automated mass production that could increase efficiency and lower costs. It also makes establishing a strategic reserve of interchangeable spare transformers exceptionally difficult. All of this means the U.S. power grid is greatly constrained by a critical transformer shortage.

It is important to note, however, that not all components are a concern. According to an experienced procurement leader, common commercial-off-the-shelf (COTS) electrical and piping components—such as wiring, breakers, and fittings—are widely available through numerous distributors and do not require specialization for nuclear applications.

Bottlenecks

Persistent supply chain constraints hinder domestic manufacturing capacity for key nuclear reactor components, particularly for large-scale and high-precision systems.

Limited Capacity for Ultra-Large Forgings With No Domestic Options

The U.S. has no domestic capability to produce the ultra-large forgings required for traditional large-scale RPVs, such as the AP1000. This creates a near-total reliance on a handful of foreign suppliers.

Given limited capacity and complex global supply chains, the lead time for critical components like large forgings can be several years—significantly impacting project schedules and increasing cost and risk. However, expert interviews indicate that some suppliers have invested in and possess the press capacity sufficient for components required by SMRs, the naval nuclear program and even some (but not all) of the forgings for the AP1000 vessel, suggesting a more favorable near-term outlook for domestic forging capacity for small modular designs. Domestic projects may still elect to source significantly lower-cost forgings from allied partners.

While an ultra-large forge could be built domestically in less than 10 years, a demand signal significantly larger than the 10 AP1000 plants announced by Westinghouse would be necessary to justify the expenditure given that the capability exists and has been utilized in allied nations (Japan, South Korea, and Italy).

Allied sourcing will remain the near-term solution for ultra-large forgings. Interviews and secondary sources indicate AP1000-scale RPV forgings will continue to be sourced from allied nations, and stakeholders expressed no reluctance with this dependency given the strength of these alliances.

Even in this SMR-focused space, domestic forgers face mounting competitive pressure from foreign state-owned entities receiving investment to upgrade their facilities. According to one interviewee, these government-backed firms may reduce or eliminate margins during downturns in order to keep their workforces employed—placing further strain on U.S. forgers operating in a purely commercial environment.

[49] Linda Leung, "Siemens Energy to Build Large Power Transformer Facility in Charlotte, North Carolina," *Manufacturing Dive*, May 2, 2024.

[50] National Infrastructure Advisory Council, "Addressing the Critical Shortage of Power Transformers."

Machining Is a Primary Constraint, Even for SMRs

For every one minute of forge press time, 10 to 30 times that is required in machining time. This ratio reveals that while forging capacity for SMRs may exist, it is the downstream processes of machining, finishing, welding, heat treatment, and nondestructive examination that are an even more significant bottleneck. Suppliers consistently identify this phase as the primary constraint on throughput.

For example, while North American Forgemasters (NAF) can forge components for SMRs, a surge in orders would quickly exceed domestic machining and finishing throughput, creating choke points that would limit overall production capacity. One interviewee noted that even with available floor space, expanding machining capacity would take approximately two years because of the long lead times associated with procuring specialized equipment.

The same interviewee also highlighted a critical downstream bottleneck in final fabrication and welding, stating that current domestic capacity is fully committed to existing contracts for defense work and reactor builds abroad, leaving no availability for additional domestic commercial advanced reactor components.

Heavy-Lift Availability and Booking Delays

Cranes and specialist heavy-lift systems are emerging as a schedule bottleneck for new nuclear construction, driven less by technical feasibility than by global availability and long-forward booking cycles.

A leader at a global heavy-lift contractor said that the same ring cranes, large crawler cranes (greater than 500 tons), and self-propelled modular transporters (SPMTs) used for nuclear are increasingly committed to other capital-intensive markets (offshore wind, large gas turbine programs, international megaprojects, and space launch infrastructure), which is tightening supply and extending lead times.

While assembly of a large ring crane can be completed in under three months, securing the equipment is the gating constraint. Repurposed or shared fleets often require getting in line roughly two years in advance, and in tight markets heavy-lift assets may be booked three to five years out. The same interviewee noted that major component-replacement work at operating nuclear plants is consuming specialist lift capacity, further reducing near-term availability for new builds. These dynamics create the risk that even projects with mature designs and ready sites can be delayed by the inability to secure the right heavy-lift equipment and qualified operators in the required window.

High Capital Costs and Lack of Order Certainty

Manufacturers are reluctant to invest the substantial—often nine-figure—capital required to expand or establish new production lines without a clear, bankable multiunit order book, typically in the range of 10 to 30 reactors. The scale of this challenge is illustrated by NAF, which noted that its recent $340 million investment in a new press has an estimated 40-year return (without a significant additional order book). This long-term financial horizon makes suppliers extremely cautious and highlights why a small number of orders is insufficient to trigger new capacity. A history of "boom and bust" cycles, in which anticipated resurgences in nuclear energy builds failed to materialize, has contributed to that caution.

Furthermore, demand for major nuclear components is "lumpy" and unpredictable, particularly when compared to sectors like data centers, where major suppliers can secure predictable, fleet-scale build commitments. A data center client can forecast its needs with relatively high certainty and is willing to pay to lock up future factory capacity, offering a concrete opportunity that a less certain nuclear project cannot match. This dynamic forces suppliers to prioritize other markets and sets an exceptionally high bar for the demand signal needed to justify dedicating capacity to nuclear.

Overly Complex Specifications

Another significant constraint arises when technical specifications are written in highly prescriptive terms rather than performance-based terms. Reflecting on the AP1000 program, one procurement leader described receiving component specifications that defined exact materials, fabrication methods, inspection procedures, and documentation requirements instead of required performance outcomes. While often well-intentioned, this approach can narrow the vendor pool, increase bid preparation costs, and reduce manufacturability — particularly when layered with additional utility and EPC requirements beyond regulatory code minimums.

The interviewee noted that, in one case, the specification package for a single component filled 11.5 reams of paper. A potential supplier reportedly viewed the expectation to review and comply with that volume of documentation as disproportionate to the contract value and declined to bid. In the context of fleet deployment, such specification layering can suppress competition and constrain qualified manufacturing throughput.

Competition From Foreign Suppliers Backed by National Industrial Policy

Domestic manufacturers face structural disadvantages compared to foreign suppliers that operate within ecosystems of strong state support. These advantages—ranging from direct subsidies and low-cost financing to guaranteed demand through national energy policy—allow foreign competitors to invest ahead of orders, maintain excess capacity, and offer aggressive pricing. In contrast, U.S. manufacturers operating on purely commercial terms must absorb higher risks and justify capital investments without comparable public backing. In interviews, original equipment manufacturers (OEMs) that were sourcing internationally cited substantially lower costs as the reason for doing so.

For example, Électricité de France (EDF), a fully state-owned utility as of 2023, owns an 80.5% stake in Framatome,[51] a leading supplier of nuclear engineering services, reactor vessels, steam generators, and fuel components. Together, EDF and Framatome leverage state-backed financing and a large domestic market to compete effectively in global tenders.

Japan Steel Works (JSW)—one of the few companies in the world capable of manufacturing ultra-large nuclear forgings—continues to produce components that U.S. firms cannot match. JSW's capabilities were initially built through public investment and continue to benefit from long-standing industrial policy alignment.

South Korea's Doosan Enerbility, though publicly traded, benefits from government-led initiatives to promote national heavy industry and energy infrastructure exports. Doosan is a global supplier of major nuclear components, including reactor pressure vessels and steam generators, supported by South Korea's strategic industrial planning.

These firms illustrate how national policy alignment can translate into tangible industrial advantage.

Decline of the ASME N-Stamp and NQA-1 Qualified Supplier Base

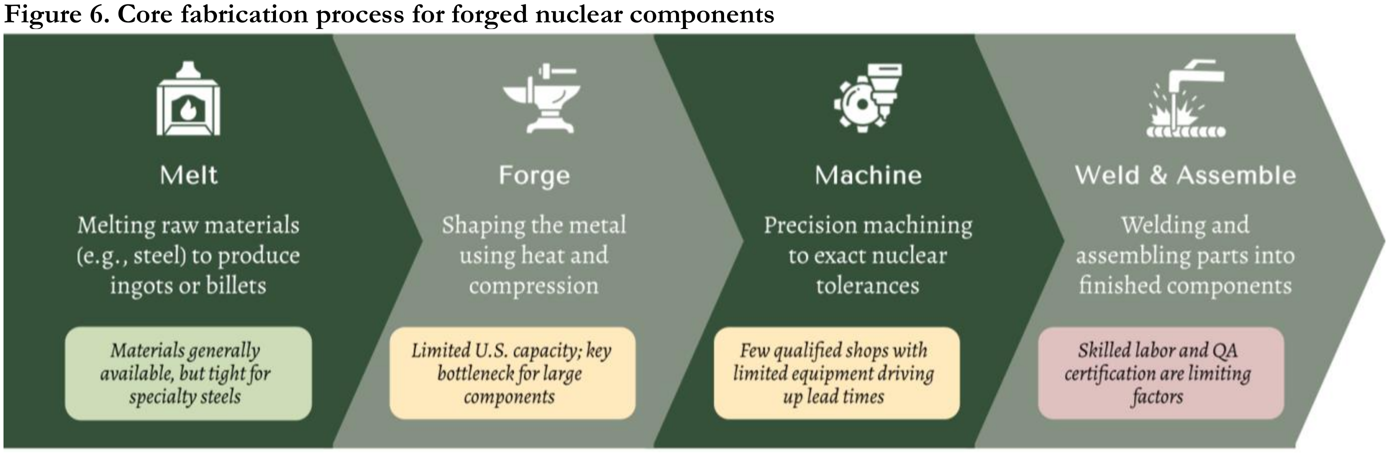
The number of U.S. suppliers certified under the ASME N-stamp program—a facility-level certification that authorizes an organization to fabricate safety-related nuclear components—has declined significantly in recent decades.

As of 2024, the limited domestic pool of N-stamp-certified machining and fabrication vendors constrained large-reactor deployment to about 3 GW per year.[52] The process to obtain an N-stamp can take over a year and cost hundreds of thousands of dollars.

A parallel decline has been observed in vendors maintaining quality programs implemented to meet NQA-1, the nuclear industry's consensus quality assurance standard, which establishes the organizational framework under which specific components, processes, and personnel are subsequently qualified for nuclear service.

Together, these trends create two distinct but compounding bottlenecks: a shrinking number of facilities certified to perform nuclear work at all, and a reduced capacity to qualify individual components, processes, and personnel within those facilities. This erosion of qualified suppliers narrows options for developers, increases risk, and makes it harder to recover manufacturing capability even when demand is present.

Figure 6. Core fabrication process for forged nuclear components



[51] Électricité de France, Consolidated Financial Statements at 31 December 2023, EDF, Feb. 16, 2024.

[52] U.S. Department of Energy, *Pathways to Commercial Liftoff*.

Opportunities and Strategic Pathways

To strengthen the U.S. manufacturing base for advanced reactors, targeted strategies can address bottlenecks and position domestic suppliers to meet future demand with greater speed, efficiency, and resilience.

Aggregate Orders to Create a Bankable Order Book

One of the most consistent messages from manufacturers is the need for demand certainty before they commit capital. Suppliers indicated that multiunit orders are often required to justify investments in new manufacturing capacity. Aggregating demand across utilities, developers, and government programs could create a bankable order book, giving manufacturers the confidence to expand capacity and reduce per-unit costs through economies of scale.

A real-world example of this strategy was the procurement approach for the AP1000 reactors at the Vogtle and V.C. Summer sites. Orders for many major components and bulk materials were placed for all four reactors simultaneously to create significant economies of scale. According to a former procurement leader for the program, this bulk ordering strategy resulted in price reductions of 25%-30% on key materials and secured a high degree of responsiveness from suppliers who prioritized the large orders.

Adopt Design for Manufacturability and Assembly Principles

Interviewees noted a disconnect between reactor design teams and manufacturing realities. Several pointed to the benefits of co-developing components with manufacturers early in the design phase to improve manufacturability. This includes reducing unnecessary fabrication and documentation burden by avoiding requirements that exceed what is necessary to satisfy the approved design and QA basis for the item's safety and performance intent; designing forgings with integrally machined nozzles to eliminate the need for time-consuming, costly welds; and avoiding overly complex geometries to align with existing, qualified manufacturing methods. Embedding manufacturability into early design decisions can reduce fabrication timelines, improve quality assurance, and expand the pool of viable suppliers, which is especially important given the limited N-stamp- and NQA-1-qualified base.

Beyond manufacturability, designing for assembly can further reduce timelines to turn fabricated parts into functional systems. Together, design for manufacturability and assembly (DfMA) can increase the output of existing manufacturing and construction capacity.

In practice, this approach works best when OEMs engage fabricators and EPC partners early in the engineering process, since these groups understand the real constraints of machining, welding, shop throughput, and field assembly. When reactor design teams incorporate those constraints into early decisions, components are far more likely to align with the capabilities of the domestic industrial base and the limited N-stamp vendor pool.

Although vertically integrated developers tend to adopt these practices more readily, interviewees noted that the same benefits apply to any designer, even if the incentives to do so are less immediate.

The same early engagement logic applies to transport and heavy-lift operations. These are globally shared, capacity-constrained services, and bringing heavy-lift partners in during design can surface constructability and sequencing choices that materially compress the schedule before procurement locks in assumptions. Similarly, engaging forging and fabrication suppliers early can reveal alternative forging/weldment architectures and module breakpoints that expand the number of qualified shops able to participate, reducing dependence on a small set of bottleneck vendors.

Much of the most impactful DfMA simplifies manufacturing within already qualified fabrication and inspection frameworks, reducing complexity without introducing new qualification hurdles. Where DfMA involves novel manufacturing or inspection approaches, the challenge shifts from manufacturability to qualification, as existing codes and inspection criteria are often written around legacy fabrication features and may not contemplate how to inspect or accept improved methods.

For example, some advanced welding techniques produce joints with no detectable weld seam or heat-affected zone, requiring new inspection data and acceptance methodologies before they can be incorporated into existing codes and standards. In practice, the greatest near-term gains come from applying DfMA to simplify designs within existing qualification frameworks, while selectively advancing new methods where the performance benefits justify the additional qualification effort.

Focus Investment on Post-Forging Capabilities

While forging capacity exists within the U.S. for SMR-scale components, several interviewees emphasized that machining and finishing are the real throughput constraints. The machining phase is labor-intensive, slow, and highly specialized—especially for nuclear-grade components that require rigorous nondestructive examination.

Stakeholders identified these post-forging processes as choke points that determine delivery timelines for major components. Because these constraints sit primarily within the domestic supplier base, expanding capacity will depend on coordinated action among manufacturers, their capital partners, and public programs that support industrial upgrades. Targeted public-private investment to expand capacity for machining, welding, and NDE would provide near-term relief and unlock latent forging capacity.

Utilize Advanced Manufacturing Techniques

Multiple interviewees suggested that the U.S. should "leapfrog" mature manufacturing models abroad by focusing on next-generation techniques. Oak Ridge National Laboratory (ORNL) is leading this charge by integrating 3D printing, AI, and advanced materials science to enable faster, safer, and more scalable production of reactor parts. Technologies like electron beam welding, powder metallurgy, and additive manufacturing could accelerate fabrication, reduce the number of welds and inspections, and allow for the construction of novel reactor geometries.

Indeed, ORNL has already demonstrated this potential by successfully producing nuclear-grade components like stainless steel irradiation capsules and fuel assembly brackets. A prime example of their enabling research and development (R&D) is a software algorithm that has reduced the inspection and qualification time for 3D-printed nuclear parts by 85%.[53]

Even with this progress, regulatory acceptance and qualification remain hurdles. The NRC requires safety-related components to meet ASME Section III, so new processes such as additive manufacturing are generally permitted only when incorporated into ASME Code/Code Cases or approved as a plant-specific alternative. Because ASME and the NRC are still finalizing additive manufacturing (AM) acceptance and qualification criteria, approvals for safety-related AM parts are largely case-by-case today.[54]

It takes both time and funding to prove out a new manufacturing process for safety-related applications in accordance with the NRC's Code of Federal Regulations (10 CFR) Part 50, Appendix B, which sets forth quality assurance requirements for nuclear power plants, or various ASME standards. This requires proving the process meets the existing standard, creating enough data to technically support a code case, or eventually changing the code to include the new methodology based on sufficient data collection.

ORNL's qualification campaigns are designed to change that**.** By producing the material-property, inspection, and performance data that those pathways require, they help convert bespoke approvals into standardized code cases and more routine alternatives, shrinking review time and de-risking adoption. In addition to ORNL, other national labs and the Electric Power Research Institute (EPRI) are working to qualify advanced manufacturing processes for use. Continued strategic investment by DOE labs, EPRI, and other applied nuclear research organizations in qualification and demonstration could yield a dual benefit: building advanced reactors faster while establishing U.S. leadership in cutting-edge nuclear manufacturing.

Support "Right-Sized" Manufacturing for SMRs and Advanced Reactors

A recurring theme in both the interviews and the literature was that many advanced reactor designs do not require ultra-large forgings. Instead, they rely on modular construction, welded steel plate vessels, and more compact geometries. Several stakeholders emphasized that the U.S. already has a foundation in these capabilities, but that additional investment by manufacturers and fabricators into nuclear qualification and workforce development—costs that are difficult to justify without multiunit demand certainty—is needed to adapt these facilities to nuclear-grade standards. Supporting "right-sized" manufacturing capacity for SMRs offers a lower-cost, scalable pathway to grow the U.S. nuclear manufacturing base without the massive up-front investments required for AP1000-scale forgings.

[53] *Nuclear Newswire,* "ORNL Algorithm Shows Promise for Faster Inspection of Nuclear Materials," Nov. 5, 2024.

[54] U.S. Nuclear Regulatory Commission, *Technical Assessment of Additive Manufacturing—Laser Powder Bed Fusion*, 2021

Supporting Components and Advanced Technologies

Today, the supply chain for nuclear components and advanced technologies is a blend of long-established nuclear vendors and newer entrants, all of whom face significant entry hurdles.

NQA-1 requirements are a prime example. This nuclear-specific quality assurance standard imposes heavy overhead costs and bureaucracy on suppliers. The QA regime is often seen as overly bureaucratic and expensive, deterring many potential suppliers from entering the nuclear market. Meanwhile, the U.S. is critically dependent on foreign sources for certain advanced reactor materials. For instance, there is currently no domestic production of nuclear-grade graphite, leaving the market largely reliant on Chinese suppliers.

Similarly, the enriched lithium-7 needed for PWR chemistry control and for fluoride salt coolant in some molten salt reactors is no longer made in the United States. American production ceased in the 1960s, and today China and Russia control the limited global supply.[55] These single-source dependencies pose strategic risks.

Advanced reactor developers are responding to these challenges by rethinking design and classification of components. While Gen III PWRs relied heavily on active safety systems, later designs like the Gen III+ AP1000 incorporate extensive passive safety features intended to reduce reliance on active equipment and operator actions. However, the AP1000 still includes many safety-related systems and components that must meet full NQA-1 standards.

By contrast, many SMRs deliberately limit the scope of safety-related SSCs. By employing inherent safety features and passive systems, SMR designs can classify more equipment as non-safety-related, thus allowing use of commercial-grade components with simpler QA. One example is TerraPower's approach of separating the nuclear island from the energy island, minimizing the equipment subject to nuclear QA rules. This "graded approach" to quality means fewer items require full nuclear pedigree, easing supply chain demands.

In summary, the current state is one of a cautiously expanding supplier base—incumbents and newcomers alike—attempting to navigate strict quality regimes and material dependencies as they support advanced reactor projects.

Key Players

The ecosystem of supporting components and advanced technologies in the U.S. nuclear supply chain—such as instrumentation and control systems, sensors, advanced materials, specialty isotopes, inspection and nondestructive evaluation technologies, and enabling manufacturing processes—is highly fragmented, encompassing a mix of legacy nuclear-qualified vendors, commercial suppliers with adjacent capabilities, and emerging technology firms.

Unlike large nuclear components—where a handful of manufacturers dominate—this segment spans thousands of components and subsystems, many of which have historically been sourced from specialized small and medium enterprises. However, the number of suppliers holding the ASME N-stamp or maintaining NQA-1 quality programs has declined, creating a narrower field of fully qualified providers and increasing the burden on the remaining players.

A few established firms serve as anchors for critical component supply. Eaton, for example, has provided commercial-grade electrical equipment that was qualified for nuclear use by partners like Westinghouse through formal dedication and oversight processes. Huntington Ingalls Industries (HII), long a key player in the Navy's nuclear propulsion programs, has leveraged its quality assurance infrastructure to support the commercial sector, offering commercial-grade dedication services that help bring non-nuclear vendors into the supply chain under controlled conditions. Several other defense and aerospace suppliers—accustomed to rigorous quality requirements—are also exploring entry into the civilian nuclear energy market as advanced reactor programs gain traction.

National laboratories and academic institutions also play a foundational role. DOE-backed facilities like Idaho National Laboratory have led initiatives such as the Graphite Core

[55] World Nuclear Association, "Lithium," updated August 2024.

Demonstration to accelerate qualification of key materials like nuclear-grade graphite.

These entities, along with ASME code committees and other standards bodies, are essential in validating new technologies like advanced instrumentation and control (I&C) systems, novel alloys, and NDE techniques for complex geometries.

As many advanced reactors move away from traditional large LWR plant designs and adopt more modular, simplified systems, the supply chain may open to new entrants from sectors like commercial electronics, precision manufacturing, and digital systems. However, most of these potential suppliers face a steep learning curve and substantial qualification barriers.

The result is a distributed but uneven supply base: Some capabilities are mature and well-established, while others remain nascent or constrained by qualification timelines, liability concerns, or regulatory uncertainty.

Bottlenecks

In addition to material-based dependencies, the supporting component supply chain faces a range of technical and regulatory hurdles that impede new market entrants, limit scalability, and slow innovation—all things that are needed to support robust scaling of new nuclear energy builds.

High Cost and Complexity of NQA-1 Quality Assurance

The expense and administrative burden of complying with nuclear QA standards (ASME NQA-1) are a major barrier to entry for new suppliers. Maintaining an NQA-1 program requires dedicated auditors, meticulous procedures, and frequent inspections. Small and medium enterprises often cannot justify these overheads without guaranteed large orders. Anecdotally, one business owner running a $120 million business estimated needing $6 million in additional assured revenue (a 5% increase) just to break even on becoming nuclear-qualified. Adding to the burden, global suppliers must often follow different procedures for identical parts: NQA-1 is largely unique to the U.S., forcing suppliers to run separate compliance pathways for domestic and international markets.

This challenge has led to a dwindling pool of NQA-1-certified vendors: The number of U.S. companies supplying nuclear components has fallen by over 80% since the late 1980s, and ASME N-type certificate holders (for pressure-retaining components) have dropped by more than 78% in the same period.[56] Advanced reactor developers worry that without changes, the limited supplier base and high QA costs will choke their ability to reliably source components and do so with competitive pricing.

Interviewees emphasized that large civil and mechanical scopes (e.g., massive concrete pours, heavy hatches, or reactor handling equipment) can be especially visible flashpoints where project owners and contractors default to requiring NQA-1 compliance, even if commercial standards might otherwise suffice. This conservatism is driven less by technical necessity than by the lack of consistent, widely accepted precedents demonstrating how alternative quality approaches can be defended to regulators, insurers, and owners for these scopes. While modern manufacturing controls, inspection methods, and materials characterization are significantly more robust than those used in earlier U.S. builds, the nuclear industry lacks a well-established body of accepted examples showing how these advances translate into reduced QA requirements. In the absence of such precedents, owners and EPCs tend to apply NQA-1 as a risk-management default, further narrowing the effective vendor pool and adding cost without a commensurate safety benefit.

Structural Limits of Volunteer-Based Code Governance

The ASME Boiler & Pressure Vessel Code—and related American Society for Testing and Materials (ASTM) material specs—is the gateway through which new technologies must pass to be used in nuclear plants. Notably, these codes are maintained by committees of unpaid volunteer experts from industry, labs, and utilities. This consensus process ensures technical rigor and safety, but it can be slow—proposals inch through subcommittee reviews, and meetings typically occur only a few times a year.

For example, it took nearly a decade to qualify Alloy 709, a high-performance stainless steel. As a result, otherwise viable materials and manufacturing methods can remain unavailable to reactor developers for years, creating a structural bottleneck for supply chain innovation.

[56] MPR Associates, United States Nuclear Manufacturing.

Incremental Design Changes Trigger Disproportionate Delays

One reactor developer noted that while they technically have thousands of suppliers for various component types, that breadth does not eliminate critical choke points. Bottlenecks arise when specialized tooling, fixtures, or testing rigs are unavailable, creating what the interviewee described as the "lead time to the lead time." Even seemingly modest specification changes (for example, adapting a 2-foot pipe design to 3 feet) can cascade into extensive rework: New tooling and test rigs must be built, procedures must be revised, and quality assurance documentation must be resubmitted. Suppliers may be technically capable of producing the part, but the need to adjust associated infrastructure and processes can extend schedules by months.

Lack of Clarity on Using Commercial-Grade Items

There is ongoing confusion and regulatory friction around when and how commercial-grade items (CGIs) can be used in safety-related applications via dedication. The existing fleet was built almost entirely with dedicated nuclear-grade suppliers, but advanced reactor developers plan to rely more on commercial components with special inspections. The nuclear industry does have a process for CGI dedication, but many suppliers find it opaque or inconsistent.

Global differences exacerbate the issue. As one source noted, "the rest of the world doesn't use NQA-1," meaning U.S. vendors like Westinghouse end up following two different quality procedures for identical parts depending on the customer. This lack of harmonization and clear guidance on alternative quality programs limits the ability to leverage broader industrial supply chains.

Inadequate NDE and Inspection Technologies

Many of the nondestructive examination (NDE) tools and inspection techniques used today were developed for conventional materials and components and may not be sufficient for novel designs. Advanced reactors employ new materials (high-temperature alloys, composites) and complex geometries (e.g., compact heat exchangers, 3D-printed components) that challenge current inspection methods. Interviewees noted that NDE providers must be involved early in the design phase ("design for inspection") so that components can be fabricated and examined reliably. There is also a need for new NDE technologies (e.g., improved radiography, ultrasonic testing, or AI-assisted techniques) to detect flaws in additive-manufactured parts or to inspect thick powder metallurgy with hot isostatic pressing (PM-HIP) components. Without innovation in inspection, manufacturers may be unable to prove the quality of advanced components to regulators' satisfaction, creating a bottleneck.

Liability Concerns for Commercial Suppliers

Large commercial manufacturers often are unwilling to assume the unique liabilities associated with nuclear applications of their products. For example, in interviews, a major electrical supplier noted that it supplies the same off-the-shelf equipment to nuclear plants as to other industries, but its contracts stipulate that the nuclear customer (or an integrator like Westinghouse) take on the liability for qualifying and using the item in a nuclear context.

This reflects a broader trend: Companies fear the potential legal and financial fallout if a standard component fails in a safety-related nuclear service. The result is that nuclear buyers must perform extra qualification (seismic tests, environmental qualification, etc.) and often indemnify the supplier. Many potential entrants simply opt out of the nuclear market given these perceived legal risks. This bottleneck means even commercially available components (valves, pumps, electronics) might not be offered to nuclear projects unless a third party is willing to shoulder the qualification burden and liability.

Insufficient Scale of PM-HIP and Additive Manufacturing

PM-HIP is a promising advanced manufacturing technique to create large near-net-shape components (like reactor vessel heads) without giant forgings. However, current U.S. PM-HIP capacity is too limited in scale for key SMR parts.

The largest HIP press in the U.S. (about 66 inches diameter) cannot produce the full-sized pressure vessel heads required by the reactor designs in the scope of this report. Scaling up to larger HIP equipment would be a significant investment. Additionally, PM-HIP currently lacks formal acceptance in the nuclear codes and regulatory framework. Despite successful use in aerospace and other industries, nuclear code committees have not yet fully qualified PM-HIP for primary pressure boundary components, so any reactor parts made this way would face a lengthy case-by-case approval process.[57] PM-HIP could potentially relieve the forging bottleneck, but today its capacity and code qualification status are insufficient for near-term deployments.

The same is true for additive manufacturing (AM), which faces challenges in producing fully dense parts without anisotropic

[57] MPR Associates, United States Nuclear Manufacturing.

material properties and currently lacks broad regulatory acceptance.[58]

Beyond the technical hurdles, the risk profile of reactor vendors themselves is a barrier. As one interviewee pointed out, it is unclear if a major vendor would want to add the risk of a new, unproven manufacturing technology on top of the already high risk of a new reactor project. However, AM does offer key advantages over traditional casting, which is widely disliked because of its inspection challenges and frequent need for weld repairs to address defects.

One interviewee emphasized that AM offers a value comparison that includes schedule and predictability, not just cost. Still, the lack of accepted in process and in situ inspection methods remains a major obstacle, and adoption into codes and standards is likely at least five years away.

Supply Chain for Key Raw Materials Exposed to Geopolitical Risk

Advanced reactors rely on several niche materials—most notably nuclear-grade graphite and enriched lithium-7—that are almost entirely sourced from abroad from non-allied countries. The global supply of these materials is highly concentrated, increasing exposure to geopolitical risk. China dominates the production and processing of high-purity graphite and has already employed export controls for strategic leverage. Russia and China also control the only commercial-scale enrichment capacity for lithium-7, an isotope essential for both pressurized water reactor chemistry control and molten salt reactor designs.[59] If access to either material were curtailed, advanced nuclear deployments could be significantly delayed or halted altogether.

Graphite: Many advanced designs—including the high-temperature gas reactor and molten salt concepts in the scope of this report—require large volumes of ultra-pure graphite for neutron reflection/moderation and structural core components. While industrial-grade graphite exists in the U.S., producing nuclear-grade material requires specialized feedstocks and extensive purification to remove neutron-absorbing impurities. Each supplier's graphite has unique characteristics and proprietary formulations, unlike metals and many other nonmetallics that follow standardized specifications.

Qualification for use in nuclear reactors is a lengthy process involving years of irradiation testing, and international suppliers often do not follow ASTM standards required under the ASME code, complicating qualification for first movers. Although the entire nuclear market likely represents less than 0.5% of global graphite demand—meaning base supply is not the issue—the demand signal has not yet been strong enough to justify major private investment. As one interviewee noted, this dependence on Chinese graphite poses particular concern for national security-related nuclear programs.

That said, one reactor developer using a graphite moderator noted that after six years of working with suppliers, they view the current supply chain as generally workable, provided that adequate lead time is available. While nuclear-grade graphite requires specialized processing—such as boron removal—existing raw material stockpiles suggest that manufacturing can be reliably managed with a planning horizon of a few years.

Lithium-7: The U.S. ceased enriched lithium production in the 1960s, and no commercial domestic supply chain has emerged since. LWR reactors require lithium enriched to >99.9% Li-7, as the Li-6 isotope absorbs neutrons and produces tritium. In the nuclear context, Li-7 is used in existing pressurized water reactors to maintain coolant chemistry via lithium hydroxide additives (and is thus also applicable to the Gen III+ pressurized water reactors in the scope of this report). It's a key constituent in both molten salt reactors in the scope of this report as part of the FLiBe coolant (a mixture of lithium fluoride and beryllium fluoride). Historically, all large-scale Li-7 enrichment relied on the mercury-based column exchange (COLEX) process, which the United States abandoned because of environmental and health concerns. Russia and China are the only countries producing Li-7 today using this method.

With demand for lithium increasing across multiple sectors—including batteries, which draw on the same upstream lithium mining and refining capacity—and several advanced reactors planning to use fluoride salt coolants, the lack of domestic Li-7 capacity is increasingly untenable. As one interviewee put it, the current dependence on foreign enrichment is an "environmental mess." A representative of one reactor design noted that while potassium hydroxide could technically serve as a substitute if supply constraints forced the issue, utilities are strongly reluctant to adopt it given the operational complexity and disruption it would entail.

Absent a domestic Li-7 enrichment pathway that avoids the legacy mercury-based process, both the existing LWR fleet and advanced reactors that rely on lithium-based coolants face a structural supply constraint driven by concentration, environmental viability, and geopolitical exposure.

Primary steel and metal powders: A more fundamental dependency exists for primary steel. As one interviewee noted, the U.S. largely remelts steel rather than manufactures it,

[58] MPR Associates, United States Nuclear Manufacturing.

[59] World Nuclear Association, "Lithium."

relying on imports from Germany, Japan, and other countries for high-quality primary production. This creates a critical vulnerability for advanced manufacturing, which requires extremely pure and precise metal powders for techniques like additive manufacturing. The supply chain for these essential powders is dominated by Japanese, German, Russian, Ukrainian, and Chinese suppliers, creating a significant and often overlooked geopolitical risk for additive manufacturing.

Helium: For certain designs like high-temperature gas reactors, helium is used as a coolant. An interviewee flagged that for GW-scale reactors requiring large volumes of helium, the availability of this commodity could become a bottleneck as it may not always be readily available at those quantities.

Zirconium: Supply of zirconium-based materials is emerging as a vulnerability in the fuel fabrication chain, driven by concentrated global production and rising demand abroad. Interviewees noted that U.S. fabricators depend heavily on zirconium products from China, including raw material and sponge used to meet scaling needs. Although supply has remained reliable, China's rapid reactor buildout is beginning to tighten export availability, and trade policy variability adds further uncertainty.

Only a small number of firms can convert zirconium feedstock into nuclear-grade tubing and components. In the United States, Westinghouse and Framatome are the only entities performing this transformation, while other vendors rely on them for finished zirconium products. Domestic conversion capacity is capped because of limited capability from Westinghouse and Framatome, requiring supplemental sponge imports when demand increases.

Given zirconium's role in LWR fuel and in structural components used by several advanced reactor designs, this concentration creates a Tier 2 materials dependency that could constrain deployment as manufacturing scales.

Beyond the materials listed above, beryllium, high-assay nickel alloys, PM-HIP alloys, iron-chromium-aluminum (FeCrAl) alloys, and hafnium may also face similarly constrained and opaque supply chains. The U.S. has limited PM-HIP manufacturing capacity at the scale required for major nuclear components. [60]

One reactor developer flagged that even for materials already well-established in nuclear service, such as high-alloy steels like 316H nickel-chromium (NiCr), supply chain constraints exist. In their view, the availability of these specific alloys—needed for corrosion and high-temperature resistance—is more concerning than the raw material inputs themselves. The constraint lies instead in downstream capacity: Manufacturing capacity for nuclear-qualified forms of these steels remains limited, and delivery timelines are often long, especially for components requiring additional processing or documentation for safety-related use.

Common materials: The COVID-19 pandemic triggered a fundamental and lasting shift in the market for key industrial metals. According to a materials procurement leader, what was once a predictable buyer's market has flipped. Before the pandemic, buyers had leverage; now the market is defined by a new, more volatile reality.

Persistent shortages in common materials like brass, copper, and steel—exacerbated by supplier shutdowns during COVID from which the market has never fully recovered—have eliminated the ability to negotiate. Suppliers now offer a "take it or leave it" proposition. This forces a change in procurement strategy from just-in-time ordering to a defensive posture of buying materials whenever they are available and stockpiling them, even at higher prices, just to avoid project delays. This unpredictability is the new status quo, adding a layer of risk to the supply chain that did not exist before.

[60] Oak Ridge National Laboratory, "ORNL Research Supports Domestic Manufacturing for Industry, Energy," Oct. 8, 2024.

Table 8. Key materials supply risk and readiness matrix				
Material	Domestic availability	Nuclear qualification maturity	Geopolitical risk exposure	Technical readiness of domestic suppliers
Graphite	***Limited.*** No domestic source; reliant on imports (China dominates).	***Low.*** Requires nuclear-grade qualification; few suppliers currently meet specs.	***High risk.*** >70% of world supply from China (single-country concentration).[61]	***Moderate.*** Graphite use in reactors is well-proven, but restarting U.S. production will take time and R&D.
Lithium-7	***Limited.*** Extremely few global suppliers; production capacity is small.	***Established.*** In PWRs Li-7 is a chemistry additive; (no alternative qualified yet).	***High risk.*** Only produced in Russia and China.[62]	***Low.*** No U.S. production capability exists currently.
Beryllium	***High.*** U.S. has a robust domestic supply (major world producer).	***Established.*** Metallic beryllium and salts (BeF_2) have known uses in reactors (e.g., Molten Salt Reactor Experiment); well-understood material.	***Low risk.*** Domestic sourcing covers demand; not dependent on adversarial nations.[63]	***High.*** Industrial production and nuclear experience (e.g., experimental reactors) demonstrate readiness.
PM-HIP alloys	***Moderate.*** Emerging domestic manufacturing capacity (limited suppliers).	***Low.*** Not yet fully qualified under nuclear codes (still undergoing testing and code certification).[64]	***Low risk.*** Relies on domestic know-how and common metals (no exclusive foreign raw dependency).	***Moderate.*** Process proven in aerospace/industry, but limited deployment in nuclear energy sector to date.
Zirconium	***Moderate.*** Relies on imported zircon feedstock; limited domestic sponge and tubing capacity.	***Established.*** Widely used in LWR fuel with established standards and manufacturing practice.	***Moderate risk.*** Significant dependence on Chinese zirconium products and sponge.	***High.*** Mature material with long operating history, though domestic processing capacity is constrained.

Long Qualification Timelines for New Materials

The process to qualify a new material for nuclear use under the ASME Boiler & Pressure Vessel Code can take the better part of a decade (or more). A recent example is Alloy 709, an advanced high-temperature stainless steel that took around 10 years to be approved into Section III code cases.

The lengthy timeline is caused by extensive testing requirements—materials must be characterized for strength, corrosion, creep, fatigue, and irradiation performance, often through long-duration experiments (creep tests can run for thousands of hours). These data then go through rigorous code committee review and eventually regulatory endorsement.

For advanced non-LWR reactors, which seek to use novel alloys (for higher-temperature operation) or new fuel forms and coolants, the qualification lag of materials is a major constraint. It means developers must either stick to decades-old materials that are already in the code (potentially limiting performance) or invest early and heavily in R&D to get new

[61] U.S. Department of Energy, *Nuclear Energy Supply Chain Deep Dive Assessment*.
[62] World Nuclear Association, "Lithium."
[63] Brian W. Jaskula, "Beryllium," *2020 Minerals Yearbook*, U.S. Geological Survey, 2022.
[64] Oak Ridge National Laboratory, "Experts Convene to Explore Strategies for Rejuvenating US Manufacturing at ORNL," ORNL news release, Nov. 26, 2024.

materials approved in time for deployment—an expensive proposition.

The code qualification bottleneck also extends to advanced manufacturing methods (like PM-HIP and additive manufacturing), which similarly require development of an acceptable technical basis before they can be widely adopted.

High-temperature designs further widen the qualification burden, since instrumentation, piping, valves, and other components must be developed and tested for far more demanding service conditions.

Also exacerbating this challenge, many advanced reactor materials (e.g., special alloys, salts, composites) lack the wealth of operational data that exists for traditional LWR materials. The current nuclear materials database is built on 50-plus years of operating LWRs, but for things like molten salt corrosion, graphite behavior under high fluence, or long-term creep of advanced steels, the data is sparse. This creates uncertainty in design and licensing. For instance, designers often must conduct new irradiation tests to generate material performance data, which is time-consuming and costly.

An EPRI materials expert noted that for graphite, the bottleneck is not raw availability but the "complex and arduous" testing and qualification process under today's standards—essentially, a FOAK material has to prove itself with extensive data. Initiatives are underway to mitigate this, such as using historical DOE test data to avoid duplicating experiments, but gaps remain for many new materials.

The lack of in-service experience with new coolants (like liquid salts or high-pressure CO_2) also means developers and regulators must conservatively address unknowns (material compatibility, neutron activation products, etc.), often adding extra analysis and prototype testing. For these reasons and more, the timelines for Gen IV reactors are, in many cases, longer than those for their Gen III+ counterparts.

The U.S. possesses strong capabilities for testing and qualifying components for existing LWRs, but its infrastructure is limited for the novel components and unique operating environments of advanced reactors.[65]

One utility expressed concern over the lack of infrastructure and space to test new components like heat exchangers at relevant temperatures and with the correct salt chemistry. This lack of domestic testing infrastructure creates schedule risks and forces U.S. developers to rely on foreign partners for essential validation and verification work. The limited existing data for novel materials and coolants poses a challenge for timely qualification and confident licensing.

Opportunities and Strategic Pathways

Despite constraints, interviewees and literature sources identified several promising pathways to expand capacity, lower barriers to entry for new suppliers, and accelerate the economic deployment of domestic new nuclear reactor builds.

Strengthening this segment of the supply chain will require not just funding, but integration—connecting emerging players to qualified prime contractors, enabling collaboration through R&D hubs, and aligning public and private stakeholders around shared standards and infrastructure.

Expand Acceptance of ISO 9001 and 17025 With Augmented Nuclear Controls

To lower QA barriers, the industry and regulators can broaden the use of high-quality commercial standards (ISO 9001 for manufacturing and ISO/IEC 17025 for testing labs) in place of NQA-1 compliance.

There are, of course, notable differences to address: NQA-1 is a nuclear-centric, safety-driven standard that prescribes detailed QA requirements (e.g., personnel qualification, supplier audits, software control, and nonconformance reporting) directly aligned with 10 CFR 50, Appendix B, and accepted by the NRC. On the other hand, ISO 9001 (manufacturing) and ISO/IEC 17025 (testing) are broader, process-based standards centered on general quality management and laboratory competence. As a result, ISO standards are more flexible but omit key nuclear-specific quality requirements like formal training, commercial-grade dedication, and prescriptive audit schedules. Without supplemental controls or equivalency demonstration, ISO standards adherence alone will not be sufficient for safety-significant nuclear components.

However, a major industry initiative (NEI 22-04) is already exploring a formal pathway for qualified ISO 9001 suppliers to provide safety-related components. Instead of requiring

[65] MPR Associates, United States Nuclear Manufacturing.

every vendor to implement a stand-alone NQA-1 program, the idea is that a nuclear licensee (purchaser) would perform a gap assessment and impose any additional controls needed to meet NRC criteria. Similarly, ASME code committees are considering recognizing ISO 9001 and ISO 17025 quality systems as equivalent in rigor to NQA-1 for certain applications.[66]

Other countries have relied on a more flexible, performance-based approach. The French nuclear industry, for instance, has historically used the RCC-M (Design and Construction Rules for Mechanical Components of PWR Nuclear Islands) code. While rigorously focused on safety and quality, RCC-M has not historically required the same level of formal supplier accreditation as the U.S. system. The quality assurance basis for RCC-M is the internationally recognized ISO 9001 standard, supplemented by nuclear-specific requirements.[67] France is now moving toward the nuclear-specific ISO 19443.[68] International standards like ISO 19443 are designed to integrate with existing ISO 9001 programs, providing a less disruptive path to nuclear qualification.[69]

By accepting robust commercial QA programs—with some oversight and add-ons—the supply chain could tap into a much larger pool of suppliers who operate at high quality levels in aerospace, automotive, or other industries. This approach would reduce costs and lower barriers for new suppliers (ISO certification is generally faster to establish and cheaper to both achieve and maintain) while also expanding the potential return on that investment by allowing suppliers to participate in parallel industries, further incentivizing entry into the nuclear supply chain. This graded approach retains safety but removes the prohibitive cost for newcomers. Formal acknowledgment from the NRC that Appendix B requirements are still met would open this pathway significantly.

Treat Nuclear Codes and Standards Development as Strategic R&D Infrastructure

Given that code updates (e.g., to include a new alloy or an additive manufacturing process) are pivotal for supply chain innovation, there is an opportunity for industry and government to invest in and accelerate code development. This could mean funding research and data generation that volunteers can use to justify code cases or providing recognition and incentives for experts to participate.

As one interviewee explained, ASME itself "just publishes the code books," while the technical work and decisions are driven by the volunteers. Thus, providing resources to these committees can yield high leverage: Modernizing design rules (for example, to allow higher-temperature operation or new fabrication techniques) will open the door for more suppliers and advanced designs.

This work is already being pursued by DOE's Advanced Materials and Manufacturing Technologies program, whose mission is to "accelerate the development, qualification, demonstration, and deployment of advanced materials and manufacturing technologies," and a key goal is to establish a "comprehensive framework for rapid qualification." Its five-year roadmap includes a specific milestone to engage with ASME code committees to secure a code case for stainless steel 316H produced via laser powder bed fusion.[70]

Complementary support could also be provided through DOE's Office of Nuclear Energy R&D programs, EPRI-led materials and code support initiatives, NRC-DOE joint research programs that generate confirmatory data for licensing, and targeted industry cost-share efforts aligned with specific code case objectives.

Treating code committee work as a strategic R&D activity—and supporting it through dedicated public and industry programs—can help break bottlenecks from the standards side.

Create Collaborative R&D Hubs for Advanced Technologies

The United States should establish regional innovation hubs where reactor designers, component suppliers, inspectors, and researchers co-locate and collaborate on advanced nuclear technologies. The aim is to spur rapid prototyping, testing, and knowledge-sharing to solve supply chain challenges.

National labs could serve as anchors for these hubs. One union group noted that labs are "very underutilized for place-based training and development" and could host satellite partnerships. For example, a hub might include a materials research center (for developing improved NDE methods or new alloy treatments), a university or lab test facility (for irradiating samples, testing digital I&C systems, etc.), and shared spaces to bring industry participants together. This proximity can accelerate problem-solving. If a novel

[66] Mark Richter et al., *Utilization of ISO 9001 and Other Non-nuclear Suppliers for Safety-related Applications*," Nuclear Energy Institute, Sept. 27, 2023.
[67] International Organization for Standardization, ISO 19443:2018: Quality management systems.
[68] EDF Group, "Supplier Quality Requirements," November 2022.
[69] International Organization for Standardization, ISO 19443.
[70] U.S. Department of Energy, *Advanced Methods for Manufacturing Technologies for Nuclear Energy Roadmap*, Office of Nuclear Energy, March 2023.

component fails an inspection, the designer, NDE expert, and lab scientist are all on hand to iterate the solution.

Collaborative R&D hubs also create workforce development pipeline (students and trainees can rotate through industry and lab assignments). Idaho National Laboratory already operates many elements of this model, serving as an anchor site where industry partners, universities, and federal programs access shared test reactors, materials qualification facilities, and component demonstration infrastructure. Most collaboration is organized through structured programs and user facilities rather than permanent, fully co-located industrial teams.

One approach already in practice is the use of hardware demonstrations, whereby a developer sponsors vendors to fabricate non-nuclear-grade prototypes before full NQA-1 production. Though costly, this hands-on learning familiarizes suppliers with nuclear specifications and de-risks later manufacturing. By building confidence early, these pilot projects shorten qualification timelines and broaden the pool of suppliers prepared to scale.

Leverage Additive Manufacturing for Low-Volume, Low-Consequence Components

Additive manufacturing (AM) is not yet widely deployed in nuclear supply chains, but interviewees noted its value for components that are expensive to qualify, produced at low volumes, or where maintaining multiple vendor qualifications is inefficient. Current best practice is to leverage AM on parts with low consequence of failure, where a modest performance gap (often about 20% lower fatigue strength than conventional equivalents, particularly in the build direction) does not compromise safety. Even in these applications, AM parts must still undergo testing to validate expected failure modes.

The advantages are notable: AM enables production without standing up new tooling or qualifying redundant vendors for seldom-used parts, and its layer-by-layer data capture provides more detailed process records than conventional NDE methods like computed tomography (CT) scanning.

For reactor developers, EPCs, and their supply chain partners, applying AM first to low-consequence components offers a practical way to generate material, inspection, and performance data while avoiding the cost and schedule risk of introducing novel manufacturing methods into safety-significant scopes too early. Over time, the goal is to produce AM parts that emerge from machines with minimal additional inspection and without the heavy quality-assurance labor burden (often about 40% of component cost today). Leveraging AM selectively in this way can reduce costs, increase supply flexibility, and build operator and regulator confidence for broader adoption in higher-consequence applications.

Use Prime Contractors and Commercial-Grade Dedication for Supplier Qualification

To lower the barrier for domestic small and midsize companies to enter the supply chain, the industry should continue to leverage experienced prime contractors or integrators to qualify suppliers under their existing programs.

Increasingly, developers themselves are leveraging commercial-grade dedication (CGD) to qualify commercial components for nuclear applications. In practice, this means a large OEM or EPC firm with an NQA-1 quality program partners with a non-nuclear supplier to oversee and certify its work for nuclear projects. The prime effectively extends its "nuclear umbrella" to the sub-supplier.

We have real examples. Eaton's commercial electrical components were "nuclear-qualified" by partners like Westinghouse for use in AP1000 plants. Westinghouse performed the necessary seismic and environmental tests and assumed responsibility for the item's nuclear application, while Eaton continued to manufacture its standard commercial product.

Scaling this model more deliberately—where primes proactively identify, onboard, and mentor suppliers critical to future build programs—would expand the qualified supplier base without requiring each firm to obtain full N-stamp certification independently. This kind of model can be encouraged more broadly. For instance, a reactor vendor or architect-engineer could adopt a promising new supplier and guide them through documentation, testing, and audits.

NRC regulations already allow purchasers to do CGD on parts from unqualified suppliers, so formalizing the "prime contractor as QA mentor" approach is feasible. The benefit is twofold: the new supplier learns and delivers under a watchful eye, and the industry gains additional capabilities without each supplier needing full certification from day one. Notably, some firms have begun offering this service commercially. HII, for example, performs CGD on behalf of clients, helping bridge the gap between qualified and unqualified suppliers.

Several advanced reactor developers have made CGD a central strategy to counter supply chain challenges. Kairos, for example, sources electronics and graphite from commercial markets and applies CGD to qualify them, often yielding better performance than historical nuclear-grade materials. This approach allows developers to bypass bottlenecks in the traditional qualified supply base while still meeting nuclear quality requirements.

While CGD offers a pathway to expand supplier participation, interviewees emphasized that its realities are far from simple. Standing up a CGD program is expensive and time-consuming, and even once established, suppliers are subject to repeated customer audits. Using a CGD-as-a-service vendor does not eliminate this burden, since insurers and regulators still require independent verification. For primes and EPCs, this creates an opportunity to position supplier qualification and CGD as a value-added service.

By explicitly offering to underwrite qualification, manage audits, and transfer nuclear pedigree to critical vendors, primes can reduce developer risk, accelerate schedules, and strengthen their competitiveness in reactor and facility procurements. Ultimately, success with CGD likely depends as much on fostering a culture that values quality assurance and collaboration as it does on meeting the technical requirements.

Leverage Public-Private R&D for Graphite Supplier Qualification

Given the strategic importance of nuclear-grade graphite and the high cost of qualifying it, a coordinated public-private program could jump-start a domestic graphite supply. DOE can provide unique testing infrastructure—for example, irradiation test reactors and post-irradiation examination facilities—and national lab expertise in graphite behavior.

Private companies, in turn, contribute candidate graphite materials and co-fund the development. A model for this is the ongoing effort by X-energy and Amsted Graphite Materials in partnership with government to stand up an integrated graphite production line. A scaled-up version of this example would systematically test those graphite samples for nuclear suitability (density, impurities, irradiation performance) in government labs, generating the data needed for ASME code qualification. By sharing the risk and cost at this "Demonstration & Qualification" phase, the government effectively de-risks private investment. Once a domestic graphite is proven and codified, multiple reactor developers can confidently source from it.

Aggregate Private Sector Demand

One market-driven strategy is to form a buyers consortium among EPCs or advanced reactor developers (and possibly owner/operators) to collectively commit to purchasing critical components or materials.

Many supply chain investments today are stymied by the "chicken-and-egg" problem: Suppliers will not build new capacity without firm orders, and reactor projects can't place firm orders until they're sure a supplier exists. An interviewee pointed out this deadlock, noting that private companies cannot get financing without offtake contracts, and customers cannot sign contracts without an assured supplier: "Nobody wants to be on the dance floor first."

By aggregating their demand, several reactor projects together could provide a large, bankable order volume that justifies a new factory or facility. For example, if five SMR developers jointly sign a long-term agreement to buy a total of X metric tons of lithium-7 or Y number of reactor vessels from a new domestic supplier, supporting financing to build necessary supplier production capability.

The consortium approach essentially shares the risk among the customers and gives the supply chain the demand certainty needed to de-risk the investment. This concept has precedent in other industries (airlines co-buying biofuels, automaker consortia for battery minerals, etc.), and it could be facilitated by an industry association or public entity. In the context of advanced nuclear, a buyers club might tackle areas like fuel fabrication services, heavy forgings, or specialty isotopes.

Expand Supply Chain Visibility Beyond Tier 1 Vendors

Reactor designers should run a risk-based supply chain assessment to identify single points of failure and intentionally dual-qualify them even when a second source is more expensive. This delta can be treated as a resilience premium, The small, known cost of maintaining a second source is outweighed by avoided downtime, re-qualification delays, and line-down risk when a sole supplier fails QA or misses delivery.

To put this in context, one reactor developer described how they pre-funded and guaranteed minimum orders with a second supplier for a critical specialty chemical, even though their primary source was reliable and lower cost. When that primary supplier unexpectedly failed QA, the backup immediately provided deliveries, demonstrating how a modest resilience premium can protect against severe business interruption.

Another reactor developer emphasized their challenges at sub-tier single-sourcing: They might have multiple Tier 1 suppliers for a component, but those multiple suppliers may all depend on the same sub-tier supplier, which is a single-point-of-failure risk.

This issue becomes especially acute when large LWR builds re-enter the market. If Westinghouse proceeds with its stated intention to begin construction of up to 10 AP1000 units before 2030, interviewees noted that the resulting surge in demand could absorb substantial Tier 2 and Tier 3 capacity. Even if other reactor developers do not share Tier 1 suppliers with these large projects, they may still face bottlenecks in machining, specialty metals, electronics, sub-tier forge shops, and other constrained vendors further down the chain.

One approach worth consideration may be the pursuit of collective mechanisms to help ensure that single points of failure are avoided for specialty chemicals, consumables, graphite grades, seals, and COTS electronics. Where risks are high, approaches such as buyers consortia, pooled minimum-offtake agreements, or joint qualification programs by EPCs or industry associations could help maintain readiness at an alternate supplier.

Establish a National Strategic Reserve of Critical Isotopes

Given the extreme concentration of certain nuclear materials, the U.S. government could create a strategic reserve program (analogous to the petroleum reserve) for isotopes like lithium-7. In the near term, this might involve directly funding and operating a pilot lithium-7 enrichment facility domestically, even if it's not immediately cost-competitive. The product could be stockpiled as a strategic material. Doing so would ensure that early advanced reactor deployments, the existing LWR fleet, and emerging fusion reactor programs are not stalled by supply disruptions.

Over the longer term, such a program sends a strong demand signal that the U.S. will support domestic production—potentially encouraging private ventures to invest in full-scale facilities. This approach addresses both supply security and market creation. For example, a government-sponsored pilot plant could demonstrate modern lithium enrichment techniques (since the old mercury-based process is environmentally unacceptable) and produce enough lithium hydroxide enriched in lithium-7 to support initial reactor cores.

Similarly, a reserve concept could apply to other crucial materials (such as backup inventories of HALEU fuel or helium coolant) to buffer against market shocks. This kind of public sector leadership can reassure reactor developers that critical materials will be available when needed, thereby encouraging investment in new nuclear projects.

Workforce and Human Capital

The nuclear energy sector faces a widening gap between projected demand for skilled workers and the available supply. This shortfall is driven by multiple converging trends. Fierce competition from other sectors (e.g., data centers, defense, clean energy, oil and gas) is siphoning away talent, making it harder for nuclear projects to recruit and retain the people they need. At the same time, proactive long-term workforce development has been lacking. Building a specialized nuclear workforce requires significant lead time, yet most efforts are reactive and short-term.

To support 200 GW of new nuclear energy capacity by 2050 (which is less than the 300 GW of new capacity targeted in the executive orders of 2025), the U.S. workforce would need to grow from approximately 100,000 workers today to around 375,000 (275,000 in construction and manufacturing and 100,000 in operations.) By 2030, an estimated 50,000 workers will be needed just for construction and manufacturing, including about 10,000 skilled craft workers, a group already in short supply.[71] There also are acute shortages of qualified engineers in disciplines such as civil/structural, instrumentation and control. However, the pipeline for new (not qualified) engineers is well-established domestically.

Interviewees described the skilled trades as a "leaky pipeline." Many potential recruits enter the pipeline, but along the way numerous factors, like competition from other industries, low apprentice wages, and childcare difficulties, cause individuals to drop out before becoming fully qualified. Only a small stream of journeyman-level workers is produced at the end of the pipeline.

Compounding this problem is a looming retirement wave. A projected workforce gap is emerging as we approach 2030. Retirements of experienced nuclear workers are expected to accelerate sharply, while the rate of new apprentices and graduates lags behind. The area between these two curves represents a critical gap in workforce volume and experience—a deficit of both head count and hard-earned know-how that could undermine the execution of new nuclear projects.

These challenges are not unprecedented. The initial scale-up of nuclear technology in the 1950s and '60s also faced acute workforce shortages. At that time, the U.S. government, educational institutions, and private companies launched a coordinated, three-pronged response. The Atomic Energy Commission (AEC) played a central planning and funding role, overseeing national education strategy, providing direct investment in training institutions and facilities, and establishing specialized fellowships and lab-based learning opportunities. Universities responded by creating nuclear engineering programs, while AEC-sponsored initiatives helped integrate nuclear topics into high school and college curricula. At the same time, utilities, unions, and private firms rolled out internal training programs that gave workers direct experience in nuclear plants and research labs.[72]

A similar scale of coordination and foresight will be needed today. More broadly, this challenge reflects the decentralized nature of workforce development in the United States. Education, training, and labor market programs are spread across state systems, local institutions, employers, and unions rather than directed through a single national framework. Nuclear is not exempt from that fragmentation, but its historically more regulated, standardized, and institutionally coordinated training environment may provide a stronger foundation for rebuilding as compared to other industries. Even so, addressing the nuclear workforce gap will require deliberate, collaborative investment across government, industry, academia, and labor—focused not just on filling short-term roles, but on building long-term capacity and know-how.

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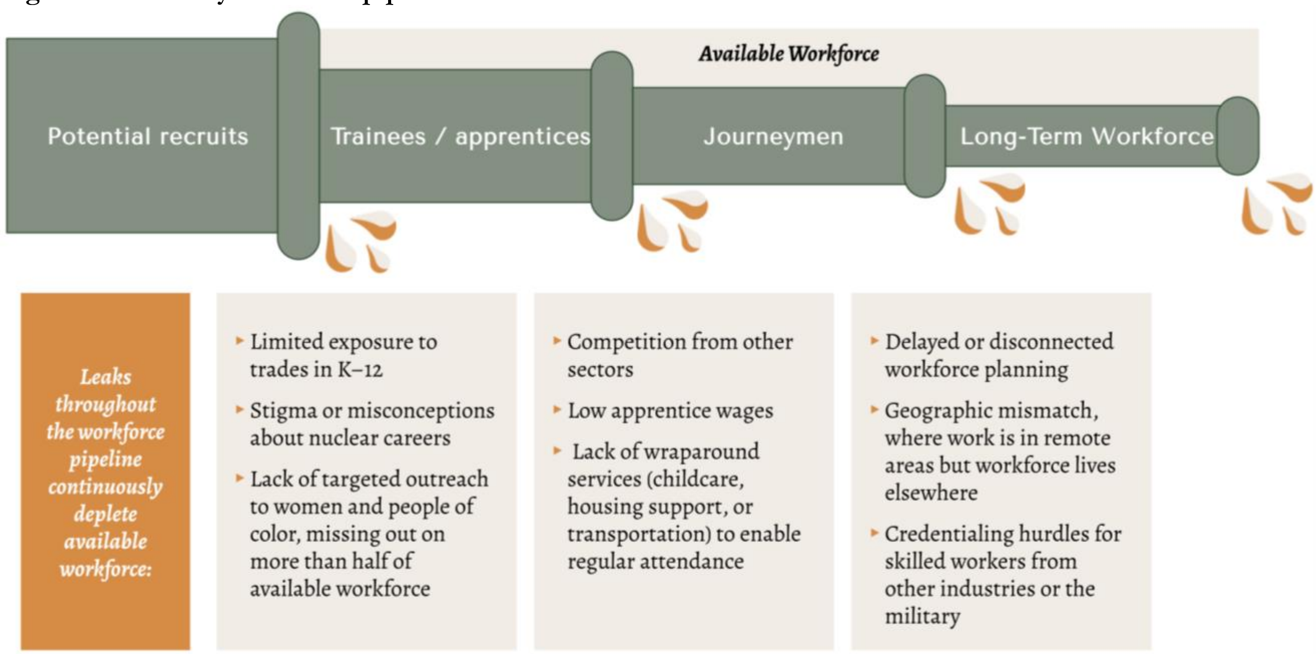
[71] U.S. Department of Energy, *Pathways to Commercial Liftoff.*

[72] David Foster et al., *Energy Workforce Development in the 21st Century*, MIT CEEPR, September 2020.

Figure 7. The leaky workforce pipeline



Key Players

The nuclear workforce development landscape in the U.S. is decentralized, spanning unions, trade schools, industry, national laboratories, universities, and state and federal agencies. Each plays a distinct role in shaping workforce readiness, though coordination is limited and often reactive.

Trade Unions and Apprenticeship Programs

Several national trade unions play a critical role in building and maintaining the skilled craft labor pipeline needed for nuclear construction, though capacity and structure vary by trade. Unions like the Ironworkers operate standardized, nationwide training programs and maintain flexible labor models, including assigning a dedicated "traveler" unit of trained ironworkers directly to worksites so they are collocated for the duration of priority projects.

Others, like the Boilermakers and Pipefitters, are piloting short-duration boot camps and hybrid training approaches to accelerate entry, with examples of three-week intensive programs that grant apprentice status. Sheet Metal Workers and Electrical Workers unions also are adapting curricula to support clean energy projects, and some local unions are embedding pre-apprenticeship programs into high schools or developing community-based recruitment strategies.

The International Brotherhood of Electrical Workers (IBEW) is a thought leader in this area. Their Industrial Nuclear Power Course, introduced in 1966, provides foundational training on nuclear plant electrical systems. Their Nuclear Mechanic Apprenticeship Program (NMAP) is a key qualification pathway required for work at nuclear sites. Local agreements, such as IBEW-131's 2025 memorandum of understanding, require NMAP certification for Palisades work. Not all unions run full training programs, but those that do are increasingly partnering with owners and contractors to scale capacity, raise apprentice-to-journeyman ratios, and tailor pipelines to specific project demands.

The nuclear power industry exhibits a particularly high unionization rate of 19%, well above the private sector average of 7%. This level of union density shapes not only workforce culture and training models but also hiring dynamics.

Another aspect of unionized employment is the reported ease of hiring. Union employers consistently report significantly lower difficulty in finding qualified workers.[73] The strength of the union network and its embedded training infrastructure

[73] U.S. Department of Energy, *U.S. Energy & Employment Report 2024*.

appear to reduce friction in mobilizing skilled labor, especially for specialized or large-scale projects.

Unions report varying levels of readiness for a potential nuclear construction buildout. The Ironworkers, for example, cite 80,000 journeymen (fully trained and certified tradespeople) and nearly 15,000 apprentices across North America, supported by more than 130 certified training programs. Their traveler model—such as Local 845—allows them to quickly mobilize hundreds of experienced workers across the country, including to recent nuclear energy and megaproject construction sites. In interviews, they emphasized that workforce development is a shared responsibility. Owner and contractor engagement through Joint Apprenticeship Training Committees (JATCs) and per-hour contributions to Apprenticeship Trust Funds are essential to growing and sustaining the pipeline.

Across all unions interviewed, there was strong interest in expanding outreach to nontraditional labor pools—including veterans, women, formerly incarcerated individuals, and transitioning fossil fuel workers—paired with increasing use of federal workforce grants to fund training and pre-apprenticeship models.

While unionized trades remain the backbone of nuclear craft labor, sustaining this pipeline will require long-term collaboration among labor groups, contractors, and project developers.

Community Colleges and Vocational Schools

Community colleges, vocational institutes, and technical high schools serve as critical on-ramps for developing the skilled workforce required to build and operate nuclear energy projects. These institutions provide foundational training for electricians, welders, machinists, I&C technicians, and other roles essential to the nuclear supply chain. However, many programs have withered because of underinvestment, declining enrollment in skilled trades, and a broader societal emphasis on four-year college degrees.

While thousands of community colleges operate in the United States, the number with dedicated nuclear technology programs is remarkably small. The most definitive quantification comes from the Nuclear Energy Institute, which in 2015 identified 31 community colleges (out of more than 1,000) as participants in its Nuclear Uniform Curriculum Program (NUCP).[74] The NUCP was established to create a standardized associate degree program that would produce technicians for the nuclear industry. The program was largely successful, with 83% of graduates securing employment in a nuclear or related technological field (compared to an average of 39% for other community college graduates at the time),[75] though the program has seen contractions as a result of nuclear plant closures in previous decades.[76]

There are recent bright spots indicating a potential resurgence in this educational sector. New programs are emerging to meet anticipated demand, such as the one at Western Wyoming Community College, developed in partnership with TerraPower to support its forthcoming advanced reactor.,[77] A new radiochemistry technician program at Roane State Community College was created with Oak Ridge National Laboratory to address the national workforce gap.[78]

These efforts are part of a broader trend to modernize and expand nuclear education and training. For example, Bismarck State College in North Dakota offers an online Nuclear Power Technology A.A.S. degree program that leverages a comprehensive, full-fidelity light-water reactor control room simulator to provide hands-on training to students across the country.[79] Located near the Hanford Site, Columbia Basin College's Nuclear Technology program in Washington is deeply integrated with the local nuclear industry, offering a curriculum aligned with the standards of the Institute of Nuclear Power Operations (INPO).[80]

National Laboratories, DOE Programs, and Universities

DOE and its network of national laboratories—most notably ORNL and INL—play a central role in supporting the nation's nuclear workforce. These institutions fund and coordinate a range of programs that connect industry, academia, and local communities. Examples include DOE-sponsored fellowships and internships for students in nuclear disciplines, research partnerships with universities and suppliers, and pilot retraining initiatives aimed at transitioning fossil fuel workers into clean energy careers. National labs also serve as conveners and technical authorities, helping to define skill needs and align workforce development efforts with emerging reactor technologies.

[74] Nuclear Energy Institute, "Schools in the Nuclear Uniform Curriculum Program," May 2015.
[75] Nuclear Energy Institute, "NEI Study Finds Nuclear Education Program Helps Grads Find Jobs," Power News Wire, Oct. 17, 2016.
[76] Ibid.
[77] *SweetwaterNow*, "Western Receives $1.9 Million for Nuclear Technology Program," June 29, 2024.
[78] *Oak Ridger*, "Pellissippi State, Roane State to offer new programs to meet workforce needs at Y-12, ORNL," Jan. 26, 2024.
[79] Bismarck State College, "About the Nuclear Power Technology Program," 2025.
[80] Columbia Basin College, "Nuclear Technology," 2025.

Universities are another key player in the nuclear talent ecosystem. Leading academic institutions with nuclear engineering programs train the next generation of engineers, analysts, and designers. These programs serve as pipelines for both the commercial and research nuclear sectors. Beyond nuclear engineering, universities continue to provide the primary pipeline for other engineering disciplines (e.g., mechanical, electrical, civil), which make up the bulk of the nuclear industry's engineering workforce.

Industry and national labs have begun working with universities to expand interdisciplinary offerings that support construction and strengthen exposure to real-world project environments. However, some gaps between the classroom and practical skills can only be closed with progressive, real-world experience.

Together, national laboratories and universities form the backbone of the professional nuclear workforce. For example, INL created both the Energy Systems Technology and Education Center (ESTEC) and the Center for Advanced Energy Studies (CAES) with various nearby universities. The former serves as a pipeline for technicians and skilled trades, while the latter focuses on university R&D. Their ability to scale enrollment, modernize curricula, and build stronger ties to industry will shape whether the sector can deliver on its projected growth.

Private Industry and Project Developers

Utilities, reactor developers, and EPC firms sit at the center of nuclear energy project delivery—and therefore define the workforce skill sets needed on the ground. These companies are not just end users of trained labor; they increasingly shape workforce development efforts through direct partnerships with trade unions, educational institutions, and community organizations. One example of broader utility-sector workforce coordination is the Center for Energy Workforce Development (CEWD), a nonprofit consortium of utilities, labor organizations, educators, and other energy stakeholders. Some firms are sponsoring prospective tradespeople to attend short-term training programs or union boot camps, offering rapid entry into skilled trades. Others have piloted retraining pathways for workers transitioning from adjacent sectors like fossil fuel generation—especially coal—into nuclear construction and operations. In parallel, a small number of developers are creating site-specific training programs to ensure local labor is prepared in time for project mobilization. TerraPower, for example, has partnered with Wyoming training institutions to support workforce preparation for the Natrium reactor demonstration project in Kemmerer. However, workforce efforts like this remain fragmented and limited in scale, with most industry players still in early phases of workforce planning.

Importantly, industry also plays a leadership role in establishing qualification pathways and defining the expectations for suppliers and contractors. The degree to which prime contractors, utilities, and vendors engage early and consistently on workforce issues—including apprentice ratios, training content, and geographic deployment—has a direct impact on labor availability and project risk. While a few developers have begun building out dedicated workforce teams, many still rely on legacy approaches or assume labor capacity will materialize when needed—a risky assumption given today's constrained pipeline.

State and Regional Workforce Boards

State workforce boards play a pivotal role in mobilizing local training systems, particularly when nuclear projects are sited in their jurisdictions. One state official emphasized the need for project developers to engage early and clearly with state agencies to ensure that workforce systems have time to prepare.

While nuclear energy is not always a familiar industry for state-level planners, there is growing openness to support it—especially if developers articulate specific timelines and labor needs. Many state systems are in the early stages of aligning career and technical education (CTE) programs with the specialized demands of advanced nuclear deployment.

Bottlenecks

The workforce pipeline for nuclear energy is under acute strain. A wave of retirements is converging with limited new entrants, training shortfalls, and a decline in institutional know-how. These pressures are compounded by geographic mismatches and rising competition from other sectors, creating persistent constraints on nuclear deployment.

Impending Retirement Wave of Experienced Workers

The U.S. nuclear energy sector workforce (including both operators and nuclear construction personnel) skews older than other energy industries, with an outsize portion of the workforce nearing retirement age. In fact, about 25% of the nuclear workforce is over age 55, and nearly 9% are already 65 or older (retirement-eligible).[81] As a result, experts project a significant wave of retirements in the next decade. One estimate suggests roughly one-third of nuclear workers could retire by 2033.[82] A large cohort of highly experienced nuclear professionals will leave the field between now and 2045, creating a potential knowledge and staffing gap. This high-clearance (e.g., background checks, psychological testing), high-standards labor is not easily replaceable.

Beyond these systemic pressures, the nature of advanced reactors introduces additional complexity to workforce planning. The craft labor pool for nuclear is already tight, and while advanced reactors require many overlapping skills with the operating nuclear fleet, their needs are not identical. Some advanced designs simplify operational roles compared to large LWRs, but others introduce new requirements that do not fit neatly into legacy job categories, notably in IT fields as advanced reactors adopt more digital systems and in manufacturing as technologies require more factory-based modular construction.

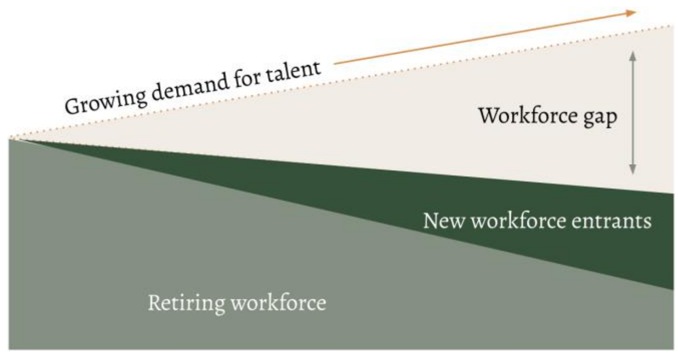
Entry Pipeline and New Workforce Supply

Offsetting these departures is a much smaller influx of new talent. This is not nuclear-specific problem but a reflection of a nationwide manufacturing labor gap, with one recent analysis showing approximately 400,000 unfilled manufacturing jobs across the country.[83] This workforce erosion cannot be separated from broader U.S. trade and industrial policy over the past several decades, which incentivized offshoring of manufacturing, weakened domestic production ecosystems, and reduced the demand signal for domestic skilled trades. As manufacturing activity moved overseas, training pipelines atrophied, employer-led apprenticeships declined, and generational knowledge transfer was disrupted.

The root of the problem is therefore both structural and cultural. As one economist noted, “We spent three generations telling everybody that if they didn't go to college, they are a loser,” creating a societal stigma around the very trades the nuclear industry desperately needs.

As baby boomers retire, few young people are choosing to replace them in blue-collar roles. The result is a severe skills mismatch, as described by the CEO of Carrier Global, who stated that for every 20 job postings his company has, there is only one qualified applicant.[84] If tariff policy succeeds in reshoring manufacturing more broadly, this challenge may be exacerbated.

Figure 8. Growing workforce gap in nuclear energy



Skilled trades and technician roles—crucial for plant construction and operation—face a pipeline crunch. For every five skilled workers retiring from the energy sector, only one new worker enters the trades,[85] meaning there’s a looming shortfall of welders, pipefitters, electricians, and reactor operators. Unless recruitment and training accelerate, the nuclear sector will not backfill retirements at the needed rate, let alone grow the workforce. Indeed, DOE warns that, to support growth in nuclear energy (such as the stated goal of a tripling nuclear capacity by 2050), the workforce must expand by hundreds of thousands of additional workers by 2035.[86]

Compounding this entry shortfall is an insufficient and under-scaled training and apprenticeship pipeline. Apprenticeship programs are growing, but still constrained, and retention remains a concern. Current training programs and apprenticeships are not scaled to meet the coming demand from a new wave of nuclear build projects. Some state-based (CTE) programs are being developed to feed skilled trades pipelines, for example, in Tennessee. However, officials cited gaps in faculty and curriculum that create barriers for pilot and regionally anchored programs.

This challenge is exacerbated by a shrinking pipeline of talent from the U.S. Navy: The civilian nuclear industry has historically relied heavily on former “Navy Nukes,” but as the Navy has downsized its fleet since the end of the Cold War, the supply of these experienced military-trained workers is no longer as great as it once was.

The industry projects that new builds will require an apprentice ratio of 20%-25% (apprentices as a share of the

[81] Peter Wilson, “A generational turnover could jeopardize the nuclear industry’s recent momentum,” *Power Magazine,* April 15, 2024.
[82] International Atomic Energy Agency, “Sustainability through capacity building,” July 16, 2024.
[83] Farah Stockman, “Why Factories Are Having Trouble Filling Nearly 400,000 Open Jobs,” *The New York Times*, June 23, 2025.
[84] Ibid.
[85] *ISHN,* “Baby Boomers retiring, leaving many open trades positions,” March 6, 2019.
[86] U.S. Department of Energy, *Pathways to Commercial Liftoff: Advanced Nuclear*, Office of Clean Energy Demonstrations, March 2023.

craft workforce), a substantial increase from roughly 5% a decade ago. Ramping up apprenticeship intake to this level is challenging, and high turnover among apprentices is undermining the effort. Trade unions interviewed reported that many apprentices drop out before completion because of systemic issues—low starting wages (making it hard to support a family) and personal hardships like lack of affordable child care, elder care, or reliable transportation. The training pipeline is not only too small, but also leaky (high attrition), which prevents a robust flow of new journey-level workers.

Shortage of Existing Skilled Labor

There is a nationwide shortage of skilled tradespeople needed for large-scale construction, including welders, pipefitters, electricians, and I&C technicians. Nuclear projects feel this shortage even more acutely because they require trade workers with additional qualifications (e.g., nuclear-certified welders) and a strong safety culture.

The nuclear industry is competing for a limited pool of engineers, project managers, and skilled workers against other booming sectors. Defense contractors, tech and data center projects, renewables, and infrastructure programs are all drawing from the same talent pool, often with jobs that are more centrally located or offer more modern perks. This competition makes it harder for nuclear employers to attract candidates.

Many non-nuclear companies can offer daytime schedules, urban locations, or better work-life balance, making them attractive alternatives. Furthermore, several interviewees noted that the industry's strict drug-testing requirements (particularly for marijuana, which can remain detectable for weeks) further constrain the available labor pool. Unlike other sectors that have adopted more flexible approaches, nuclear work maintains rigid testing standards, and repeated failures can permanently bar individuals from eligibility, narrowing the pipeline at a time when labor demand is rising.

Several interviewees also emphasized that parts of the fuel cycle and advanced reactor ecosystem require extensive background checks, which further narrows the hiring pool. Companies must recruit candidates who are eligible for security clearances, a requirement that limits recruitment to U.S. citizens, and clearance processing itself can take a year or more. As a result, organizations may need to hire and train large cohorts well in advance of operations, adding another layer of complexity to workforce planning.

Shortage of Digital I&C Expertise

As the sector upgrades from analog controls to modern digital instrumentation and control (I&C) systems, there is a shortage of specialized talent and experience. Developing and licensing digital reactor protection systems requires skills in software engineering, cybersecurity, and hardware-software integration that are in high demand across other industries.

Interviewee feedback highlighted that I&C technicians are a "high-demand field" and more training programs are needed. Moreover, current regulations around safety-critical software are stringent, and few U.S. nuclear facilities have implemented fully digital control systems, leaving a limited base of experts. Even highly trained ex-military (Navy nuclear) I&C technicians typically require additional certifications and plant-specific qualification programs before transitioning into civilian nuclear plants. This expertise bottleneck could slow deployments as advanced reactors seek to implement state-of-the-art control and automation.

Shortage of Indirect and Management Talent

Beyond craft labor, nuclear projects struggle to find enough project management personnel, construction supervisors, and project controls specialists with relevant experience. These roles are critical for planning and executing complex multibillion-dollar builds. Many of the seasoned managers in these areas are the same individuals approaching retirement, and relatively few younger professionals have managed nuclear projects, given the long gap in new construction.

Siloed Teams and Lack of Project Integration

The AP1000 projects at Vogtle and V.C. Summer provided a stark lesson in the consequences of poor project integration. According to a former procurement leader on the projects, the engineering, procurement, and construction teams were siloed, leading to design decisions being made in a vacuum without critical stakeholder alignment and resulting in costly and time-consuming rework. This experience underscores that a true partnership, with deep integration among the owner, the reactor vendor, and the teams executing the project, is critical to managing scope and preventing the kind of cascading failures that drive up costs and delay schedules.

Geographic Mismatch of Labor

There often is a mismatch between where skilled workers live and where new nuclear projects are located. Large construction projects are frequently sited in rural or remote areas, while much of the specialized labor force (and new graduates) reside in other regions or urban centers. Relying on workers to travel long distances or relocate for the job has become less feasible. The old assumption that "if you build it, they will come" no longer holds true. Attracting and retaining skilled workers on remote job sites is a serious challenge, especially given the competing opportunities mentioned above.

Lack of Long-Term Workforce Planning

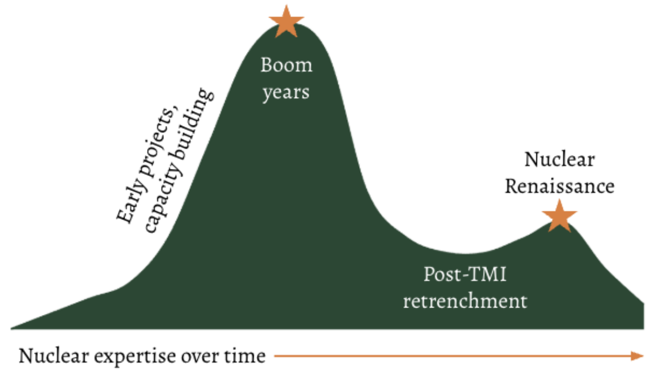
Workforce development efforts in the nuclear sector have tended to be reactive and short-term. In reality, a major project needs a five- to seven-year lead time to recruit, train, and certify a sufficient workforce pipeline in advance. This means engaging potential workers early (even in high school or earlier) and funding training well before construction starts. Currently, however, such systematic early workforce planning is not happening at the needed scale. The consequences of this short-term, project-based approach are severe. A key lesson from the construction of Vogtle Units 3 and 4 was that, according to one constructor interviewed, 4,000 people were trained for the project and then let go upon its completion, squandering an immense investment in human capital and loss of an established, experienced workforce that could have been deployed to the next project.

In contrast, much of China's rapid progress is credited to programmatic builds and clustering. Multiple units of the same design are often constructed back to back at the same site (e.g., Qinshan, Ling Ao, Fuqing). This creates continuity in supply chains, construction crews, and regulators, shortening build times and lowering costs on successive units. The Organisation for Economic Co-operation and Development (OECD) cited this as a core reason why Chinese build schedules have been shorter than those in the West.

Erosion of "Nuclear Culture" and Know-How

The decades-long hiatus in U.S. nuclear construction has led to an erosion of the collective nuclear safety culture and know-how.[87] The industry's muscle memory for building new plants—the ingrained habits, rigorous safety and quality standards, and on-the-job wisdom—has faded as experienced people retired or moved on. New entrants have had fewer mentors to learn from. According to economist John Quiggin of the University of Queensland, the 13,000-strong workforce that built Vogtle's new reactors (the short-lived "Nuclear Renaissance") is "a rapidly depreciating asset," and much of its institutional knowledge will be lost within five years unless new projects are initiated immediately.[88]

Figure 9. Nuclear energy project expertise



A detailed statistical analysis of U.S. PWR construction projects found that the two cost centers with the highest variance—and therefore the greatest source of financial risk—were home office engineering and services and field office supervision. Because these two categories together account for over 60% of all indirect costs, their high variance translates directly into greater schedule-driven cost escalation and financial risk.[89] This finding suggests that even a perfect manufacturing supply chain could be undermined by inefficient project management, engineering, and field supervision.

The degradation of the U.S. supply chain is not just a loss of manufacturing capability but also a loss of the deep industry expertise required to manage megaprojects under a strict nuclear regulatory framework. Indeed, studies have shown a trend of declining labor productivity in the U.S. nuclear industry, and it is estimated that approximately 80% of the domestic expertise needed to support consistent new builds has disappeared since the 1980s.[90]

This erosion of project execution capability is a primary source of the cost uncertainty that deters investment and stalls new projects. Rebuilding this culture of excellence and safety is difficult and time-consuming, and its absence can be a hidden bottleneck affecting productivity and quality

[87] MPR Associates, United States Nuclear Manufacturing.
[88] Gautama Mehta, "Georgia's Vogtle Plant Could Herald the Beginning — or End — of a New Nuclear Era," *Grist*, April 8, 2024.
[89] Benjamin T. Starkey, *Cost Estimation Model for U.S. Pressurized Water Reactor Construction through Multiple Regression,* Doctorate of Engineering praxis, The George Washington University, Aug. 31, 2022.
[90] Ibid.

Opportunities and Strategic Pathways

Despite these challenges, industry, government, and educational stakeholders can pursue strategies that will narrow the workforce gap.

Broaden Investment in High School-Level Vocational Pathways

Expanding vocational training in high schools can rebuild the beginning of the pipeline. Rather than focusing solely on postsecondary STEM programs, stakeholders should support the return of vocational programs in welding, machining, electrical work, and other trades at the high school level. Early exposure to these skills can spark interest among students who might not pursue four-year college degrees, shorten the training timeline for new tradespeople, and diversify the talent pipeline.

Revitalizing shop classes and trade academies in school districts (especially near prospective nuclear project sites) could yield a new generation of young workers ready to enter apprenticeships upon graduation.

Recent standout models include Middleton High School in Wisconsin, where 75% of students now take technical education classes,[91] and Rock Ridge High School in Minnesota, which boasts a $122 million career academy campus with pathways in construction and manufacturing.[92] Other promising examples include Los Angeles County's Skilled Trades Summers, which offer high schoolers paid summer training in welding and construction,[93] and Michigan's Clare-Gladwin CTE hub, where a voter-supported property tax millage has secured long-term funding for high school vocational training.[94]

Dramatically Expand and Modernize Apprenticeship Programs

Construction firms and trade unions, in partnership with federal and state workforce agencies, should scale up apprenticeship programs in the nuclear construction trades to meet future demand. In practical terms, this means aiming for an apprentice-to-journeyman ratio of 20%-25% on new projects. These apprenticeships should also be modernized in format and content, incorporating nuclear-specific skills and accelerated learning modules. Long-term funding (potentially with government support) can ensure programs are sustained through the build cycle. The goal is a larger, more qualified graduating class of journey-level craft workers each year.

Another promising strategy is being pursued by the construction firm AECON, which sponsors students to attend the Boilermakers' nuclear-specific, three-week welding boot camp in Chattanooga, Tennessee. This offers an accelerated pathway for apprentice entry, which is especially valuable in ramp-up scenarios. Other unions noted similar efforts, including stackable credentials and multi-trade collaboration pilots.

Upon graduation, participants receive an apprentice card, providing a rapid, multi-week pathway into the skilled trades pipeline, after which they can continue their training on the job. Supporting and scaling such accelerated entry models represents a key opportunity to recruit new apprentices.

Form Regional Workforce Training Hubs

Regional construction firms, nuclear industry suppliers, and other industry leaders—working with unions, community colleges, and local and state government—should establish regional training centers tailored to nuclear project needs. These hubs would ideally be located near clusters of planned projects (or in regions with multiple nearby plants) and operate through partnerships among community colleges, trade schools, unions, and nuclear companies. By offering hands-on training with the specific skills needed for local projects (for example, training on exact reactor component weld procedures or quality standards), regional hubs can create a local talent pool that is well coordinated with industry needs.

This place-based approach is already being implemented by industry leaders. Holtec, for example, has partnered with a local community college to develop an 18-month nuclear operator training program to staff its facilities. Similarly, AECON is engaged in a form of "DIY certification" by working directly with owners like Duke Energy and the Tennessee Valley Authority to create their own dedicated training and qualification centers tailored to project needs. This place-based approach also helps workers build roots in the area, making them more likely to stick with jobs at nearby project sites.

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[91] Ian Lee, "Trade Classes Boom at High School as Students Eye Six-Figure Jobs," *CBS News*, 2025.

[92] Kraus-Anderson, "Kraus-Anderson Duluth Completes $122 Million Rock Ridge Career Academy High School in Virginia, Minn," Feb. 7, 2023.

[93] Harbor Freight Tools for Schools, "Los Angeles County."

[94] Dave Clark, "Clare-Gladwin voters approve CTE millage renewal by wide margin," *Midland Daily News*, Feb. 28, 2024.

DOE's national laboratories could serve as nuclear workforce training anchors in their regions. Many national labs (INL, ORNL, etc.) already have facilities and expertise in nuclear tech. By hosting satellite university programs or advanced trade training on-site, labs can help attract students and apprentices to nuclear careers. They also can facilitate apprenticeship rotations or co-op programs that give trainees real-world experience on nuclear research projects, instilling the specialized safety culture and practices earlier in their careers.

Market the Nuclear Energy Value Proposition to a New Generation

DOE and industry organizations could launch a coordinated national recruitment and branding campaign to improve the image of nuclear careers. This campaign would emphasize attributes that younger workers find appealing, such as high-tech innovation and combating climate change. For example, framing nuclear energy projects as crucial to solving environmental challenges could attract mission-driven young talent. The campaign could leverage social media, success stories of young nuclear professionals, and outreach at colleges/trade schools to change perceptions.

Nuclear energy work also offers long-duration projects, steady hours, competitive pay, and opportunities for overtime. Interviewed unions highlighted the importance of job longevity and the strong safety culture that characterizes nuclear construction, both of which set it apart from other job opportunities.

The industry would be well served by proactively selling itself as an employer of choice, not a relic of the past. Some efforts of this type are already underway. In January 2025, the Nuclear Energy Institute launched the Nuclear Works platform to raise awareness of career opportunities and connect job seekers to employers in the sector.[95]

Recruit From Diverse Talent Sources

Many skilled workers from sectors like oil and gas, petrochemical, or the military have competencies that overlap with nuclear construction (for instance, heavy rigging, welding, power plant operations). Developing a credentialing system or bridge training that formally credits these workers for their prior experience can shorten their path to nuclear qualification. This might involve challenge exams, accelerated courses on nuclear-specific regulations, or modular "stackable" credentials. By smoothing the transition, the nuclear sector can tap into a broader labor pool of mid-career tradespeople who might be looking for stable, well-paying work as their current industries change.

A particularly strong opportunity lies in leveraging the pipeline of skilled Navy veterans—especially those from the nuclear Navy programs—by establishing state-sponsored certification programs for ex-military personnel. Veterans from naval reactors and submarines have extensive training in nuclear operations; however, they may still need civilian licenses or certifications to work in commercial nuclear plants or construction. States (possibly with federal matching funds) could offer subsidized programs to help cover the cost of obtaining these civilian credentials and provide refresher training tailored to translating Navy experience to the commercial context. Fast-tracked pathways that formally recognize their skills would help ex-Navy technicians and operators quickly enter the nuclear energy workforce, benefiting the individuals and the industry. Veterans represent a highly qualified and motivated talent pool. As one union leader noted, they "already know how to work, know how to show up to work, have a great work ethic."

This approach also applies to the coal-to-nuclear transition. As coal-fired power plants retire, their workforces present a valuable recruitment pool for nuclear projects. A targeted pilot program could retrain coal plant workers for jobs in nuclear, especially in communities slated for new reactor projects.

These pilots would identify the roles at a coal plant (operators, maintenance, electricians, etc.) that are most transferable to nuclear plant operation or construction. With focused training modules and on-site apprenticeships, many workers could transition without having to relocate. A 2022 report found that over 80% of the roles at a coal plant have direct nuclear analogs, with approximately 60%-70% of existing skills transferable without modification.[96] Operations, maintenance, and I&C workers are particularly well-aligned, while administrative and non-technical roles require minimal retraining. This strategy not only supplies talent to new nuclear endeavors but also provides an economic lifeline for communities losing coal jobs, making nuclear development more politically and socially palatable.

In addition to mid-career transitions, there are also opportunities to create new entry points for younger or less-experienced workers. Some trade unions offer intensive short-term boot camp programs, such as the Boilermakers' three-week welding program described above. Nuclear developers or contractors can sponsor local students or job seekers to attend these boot camps, covering their tuition and/or

[95] American Nuclear Society, "NEI Launches Nuclear Works for Career Awareness," *ANS Newswire*, Jan. 6, 2025.

[96] Idaho National Laboratory, Investigating Benefits and Challenges of Converting Retiring Coal Plants into Nuclear Plants (C2N). INL/RPT-22-67964, December 2022.

providing stipends. Upon completion, participants receive an apprentice card or entry-level certification in the trade.

This approach can rapidly inject semiskilled workers into the project's workforce pipeline in a matter of weeks, rather than years. It's a quick-win solution to spark interest and give people a foothold, after which they can continue in formal apprenticeships on the job.

This kind of rapid entry model is promising, but to truly grow the pipeline, it needs to reach a broader and more diverse audience.

Women make up 36% of the nuclear workforce,[97] but in construction trades—where labor needs are most acute —they represent less than 5% across all industries.[98] It's hard to scale a workforce when half the population is missing from the pipeline. As WWII showed, the U.S. is capable of rapidly mobilizing women into industrial roles when the imperative is clear. Expanding women's participation will require more than recruitment; it means increasing visibility of trade careers, challenging outdated perceptions, and ensuring workplaces are equipped to support and retain a more diverse workforce.

Move Over Bob, a campaign led by tradeswomen and allies, is addressing this gap by showcasing young tradeswomen in a magazine distributed to tens of thousands of students in Arizona. By reshaping the narrative around who belongs on job sites, initiatives like this help normalize women's presence in the trades and broaden the appeal of these careers. Small but meaningful investments—such as proper gear and facilities that accommodate pregnancy and lactation—can make a difference.

Partnerships with community organizations and targeted outreach to nontraditional candidates have also shown promise. In many cases, the stability of long-term projects has helped make trades careers more appealing to a broader talent pool.

To address capacity gaps and smooth peaks and valleys in labor demand, jurisdictions could emulate the United Arab Emirates' approach at Barakah. During Barakah's commissioning and early operation, the Emirates Nuclear Energy Company (ENEC) signed an operating support services agreement with Korea Hydro & Nuclear Power, under which several hundred Korean experts (including licensed operators and engineers) are dispatched annually to the UAE through 2030 to assist with operations.

These time-limited deployments are designed to provide flexible access to highly skilled labor during critical ramp-up phases while the domestic workforce matures. Beyond professional services, there was a significant international construction labor force used to fill the gap in available domestic labor. This model allowed ENEC to bridge immediate gaps with international expertise while phasing in national training programs, ensuring schedule adherence without leaving permanent labor overhang once the project stabilizes.

Embed Workforce Planning Into Project Development

Comprehensive workforce development could be mandatory when new reactors are planned. For instance, when companies apply for federal support or licenses for a new build, they could be required to submit a detailed workforce plan showing how they will source, train, and retain the necessary labor over the project life cycle. This plan should start from the pre-construction phase (e.g., outreach to schools, training program commitments) and extend through commissioning. Unions emphasize the importance of being engaged early, as well, so that they can begin planning and training for project-specific workforce needs. By baking workforce considerations into the front end of project development, developers would be forced to think long term and invest in human capital early, rather than scrambling when construction is underway.

Fund Training Centers at Project Sites

Funding should be allocated to establish on-site (or near-site) training and qualification centers for each major project. Rather than relying only on distant trade schools or union halls, a project can host its own training facility where workers are trained and tested on the specific tasks and quality standards that the project requires. For example, a site training center could have mock-ups of reactor components for welders to practice on, or classrooms for teaching nuclear safety procedures. This ensures training is tailored to the project's needs and creates a direct pipeline from training to employment. It also signals to the local community that the project is investing in them—training locals to fill the jobs.

Prioritize Local Hiring and Community Engagement

To address geographic mismatches, project developers should implement robust local hiring programs. Engaging with the community through job fairs, informational sessions, and collaborations with local leaders also can build trust and interest in the project. By prioritizing hiring from the local region, projects can reduce the need for long-distance travel

[97] U.S. Department of Energy, *Energy & Employment Report*.

[98] Institute for Women's Policy Research, "Numbers Matter: Clarifying the Data on Women Working in Construction," March 9, 2023.

or relocation, improving retention. A strong community partnership may also help with ancillary issues like housing and transportation for workers, as local authorities might assist if they see the benefit to their constituents.

Improve Apprentice Retention With Direct Support and Cultural Change

High apprentice dropout rates must be curbed by addressing the root causes. Companies and labor organizations should go beyond traditional training and provide support mechanisms for apprentices facing modern economic and personal challenges. Apprentice retention issues affect all construction trades across all regions, but they carry heightened risk in nuclear construction, where long qualification pathways and limited labor depth amplify the impact of attrition. In practice, a combination of financial support and cultural shifts is needed to improve retention.

Employers could, for example, provide stipends or "wraparound services" to apprentices to help cover expenses like transportation, child care, and tools. This kind of support has precedent. For example, the natural gas utility sector's veteran training programs offer wraparound services to ensure trainees can focus on learning. Covering these extra costs can significantly ease the burden on apprentices with families or other obligations.

Employers also could explore wage subsidies or accelerated pay steps. If an apprentice can't earn a livable wage for several years, those with family responsibilities simply won't stay. Bridging that gap—through stipends, bonuses for milestones, or changes to apprenticeship wage scales—can make the apprenticeship a viable option for more people.

Cultural factors matter just as much. Companies should foster a "field-first" culture on job sites that values craft workers' contributions and well-being. This involves treating craft employees with respect, encouraging open communication between management and crews, and actively soliciting workers' input on schedule and work processes. As one interviewee noted, "Nobody knows more than the person who is actually doing the work." Making field staff feel heard and valued improves morale and loyalty, which in turn boosts retention.

Finally, it's essential to ensure apprentices get real, meaningful work experience rather than just menial tasks or prolonged shadowing. Hands-on involvement in actual project work (under supervision) helps apprentices build confidence and skills. It also reinforces their sense of purpose—feeling like a true part of the team rather than cheap labor. A purposeful training assignment can keep apprentices engaged and progressing to journeyman status.

Leverage International Expertise Through Structured Partnerships

Interviewees emphasized that the United States could accelerate nuclear deployment by partnering with countries that have maintained active, large-scale nuclear construction programs. Many foreign firms possess recent experience delivering multiunit reactors, managing complex integration, and sustaining a skilled workforce across successive builds. Korea Electric Power Corp. (KEPCO) and its associated Korean engineering and construction companies were cited as an example of a system that has preserved capabilities the U.S. has not exercised in decades.

Precedents from other industries show that this model can succeed when partnerships are explicitly structured around capability transfer rather than permanent reliance. In the automotive sector, Japanese manufacturers partnered with U.S. firms to transfer production systems and workforce practices, after which domestic manufacturers internalized those capabilities and operated independently. As trained American engineers and supervisors moved on to other firms and facilities, those capabilities diffused across the domestic industry, allowing U.S. manufacturers to operate independently at scale.[99]

Structured partnerships or joint ventures would allow the U.S. to draw on this expertise while rebuilding its own capacity. International teams can help deliver early units, support workforce development, and share lessons from mature build programs, and they may also be willing to assume a defined share of project risk to make early deployments feasible.

These collaborations should be designed to build domestic capability rather than create long-term dependence on foreign companies. International partners can assist with initial projects, after which U.S. firms can take on a larger role as the market moves from FOAK to repeat builds. Done well, this approach provides a bridge that helps re-establish the skills and scale needed for a sustainable U.S. nuclear construction program.

By pursuing these opportunities in tandem, the nuclear industry can begin to close the workforce gap, securing not just the head count of workers needed but also rebuilding the depth of experience and culture that major projects demand.

[99] Richard Florida and Martin Kenney, "Transfer and Replication of Organizational Capabilities: Japanese Transplants in the United States," *The Nature and Dynamics of Organizational Capabilities*, 2001.

Table 9. Workforce action matrix			
	EPCs and unions	**State and local government**	**DOE and industry orgs**
Near-term impact	• Expand and modernize apprenticeship programs • Support accelerated entry models • Recruit from diverse talent sources	• Coal-to-nuclear transition pilots (local retraining)	
Medium-term impact	• Form regional workforce training hubs • Embed workforce planning into project development • Fund training centers at project sites	• Support regional training hubs via community colleges and trade schools	• Broaden investment in high school vocational pathways (shop classes, CTE high schools)
Long-term impact		• Broaden investment in high school vocational pathways (shop classes, CTE high schools)	• National campaign to market nuclear careers

Policy, Investment, and Regulatory Environment

Despite strong high-level policy signals (e.g., bipartisan support, new tax credits, and a clear need for firm power—with preference for emissions-free technologies in some cases), the advanced nuclear sector remains mired in a market deadlock.

No single private actor wants to be the first mover to underwrite a new nuclear project, especially for an unproven reactor design, creating a market paralysis that stalls both demand and supply. This impasse is exacerbated by implementation delays and policy uncertainty. For example, DOE funding programs—even when fully appropriated by Congress—are often disbursed slowly and with complex requirements, postponing projects and chilling private investment.

Two broad strategies compete to address this deadlock. One is a market-pull approach—creating guaranteed demand (e.g., through firm government or consortium orders) so that "supply follows" with new factories and components. The other is a market-push strategy—using direct subsidies or grants to build out manufacturing capacity in advance of demonstrated orders.

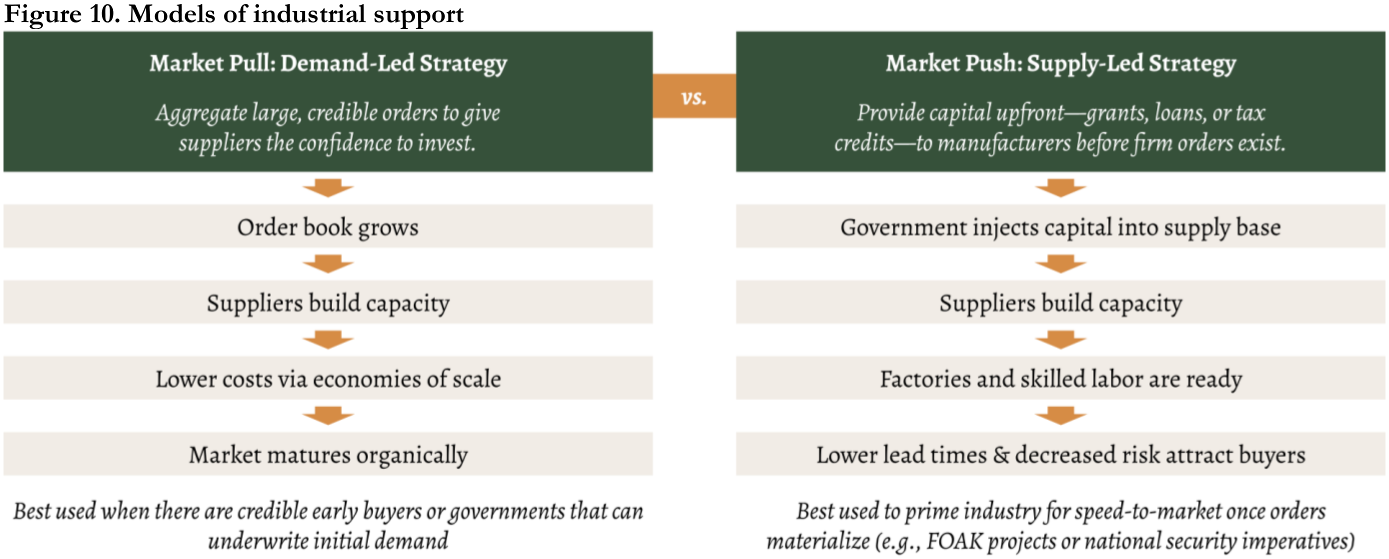
In France during the 1970s, the Messmer Plan represented a textbook example of a market-push strategy. In response to the 1973 oil crisis, Prime Minister Pierre Messmer directed state financing and orchestration to rapidly build out the nuclear supply chain (including enrichment facilities and heavy-component manufacturing) well before reactor demand had fully materialized. This resulted in early underutilization of supplier capacity, but once the fleet ramped up, France benefited from a highly standardized, vertically integrated domestic supply chain that enabled fast serial builds at relatively lower cost.

By contrast, the United Kingdom has largely followed a market-pull model. Rather than prebuilding supplier capacity, the government and entities such as the British subsidiary of EDF issued firm large-scale contracts (backed by state guarantees and long-term contracts) to stimulate supplier investment. This approach avoids excessive up-front investment in idle capacity, but it carries risks: Supply chains often scramble to scale up, leading to bottlenecks, rising costs, and construction delays. For instance, Hinkley Point C's cost has risen into the tens of billions of pounds, and its schedule has slipped by several years because of a combination of factors including supply chain rebuilding, labor and material shortages, Brexit, and COVID-19.

France's push approach created temporary inefficiency, but paid off through rapid, lower-cost scaling once demand arrived. The U.K.'s pull approach sidestepped overbuilding, aligning supply with confirmed demand, but left the industry exposed to capacity shocks, cost escalation, and timing delays when supply did not keep pace.

Current policy debates revolve around these models, and in practice U.S. support has not decisively favored one over the other. The resulting strategic incoherence (push vs. pull) has left suppliers uncertain of how best to invest and has failed to resolve the underlying risk-sharing problem.

Figure 10. Models of industrial support



While this impasse is often framed as a modern market failure, it is more accurately understood as the result of abandoning a previously successful national industrial strategy. The original U.S. commercial nuclear industry and its supporting supply chain were not the product of organic market development, but the result of a deliberate, intensive, and evolving public-private partnership led by the federal government.

A 2017 EPRI historical analysis reveals that the U.S. government played a foundational role by establishing a clear national mandate, funding early stage R&D, providing essential infrastructure like test reactors, and acting as the sole fabricator and supplier of nuclear fuel for early projects. Two programs were instrumental: the Industrial Participation Program (IPP), which gave more than 60 private companies access to restricted government data and labs to build technical expertise, and the Cooperative Power Reactor Demonstration Program (CPRDP), which used flexible cost-sharing contracts to build 11 demonstration reactors.[100]

The first full-scale commercial nuclear power plant, Shippingport, was one of those reactors. Completed in 1957, Shippingport was executed with significant government support. Although originally initiated as a government-funded naval propulsion project, it was repurposed as a civilian plant in partnership with Duquesne Light Co. The total cost was approximately $72.8 million (equivalent to roughly $800 million today), and the project was completed in about five years, demonstrating the speed and effectiveness possible under coordinated federal leadership.

This was a massive joint investment. Over the decade of the CPRDP, the total combined public and private investment was approximately $1.76 billion (equivalent to about $19.2 billion in 2025 dollars), with the U.S. government contributing 58% and private industry contributing 42%. It was this decisive, coordinated industrial policy that created the conditions for a private supply chain to form. Critically, this investment was made against a credible expectation of sustained nuclear construction, enabling suppliers to invest beyond individual projects and form a durable private supply chain.

Figure 11. Geopolitical dependencies in the advanced nuclear supply chain

[100] Electric Power Research Institute, *Program on Technology Innovation: Government and Industry Roles in the Research, Development, Demonstration, and Deployment of Commercial Nuclear Reactors,* 2017.

International Dependencies

Today's nuclear supply chain reflects the cumulative outcome of decades of policy choices rather than a single market failure. As domestic industrial capacity declined and demand signals weakened, production consolidated across a small number of highly specialized international suppliers, many of them in allied countries.

This global integration is not inherently negative and, in many cases, reflects rational specialization in capital-intensive and highly regulated industries. However, the resulting structure leaves U.S. deployment sensitive to external capacity constraints, timelines, and policy decisions outside its direct control. Figure 11 illustrates the current international concentration of critical supply chain segments supporting U.S. nuclear projects.

Key Players

A range of stakeholders are shaping the future of the U.S. nuclear supply chain, each playing distinct roles in catalyzing—or constraining—momentum.

The Federal Government

The federal government plays a central role in shaping the policy, investment, and regulatory landscape for nuclear energy. DOE serves as the main driver of public investment through research and development programs, demonstration project funding, and financing tools like the Office of Energy Dominance Financing (formerly the Loan Programs Office). DOE also sets strategic direction for the sector through its Office of Nuclear Energy and administers multiyear programs focused on advanced reactors, supply chain development, and critical fuel infrastructure.

Complementing DOE's investment and policy role, the NRC provides the independent oversight and licensing framework that determines how and when these projects can move forward. As the gatekeeper for both reactor and fuel facility approvals, NRC regulatory clarity—or lack thereof—directly affects developer timelines, supplier confidence, and investment decisions.

Congress establishes the legal and budgetary foundation for nuclear support through appropriations and legislation such as the Inflation Reduction Act, which created tax credits and incentives relevant to advanced nuclear deployment. Congressional action also funds DOE initiatives and determines the scale and continuity of federal support.

Additionally, the Department of Defense (DoD) has emerged as an early mover in small-scale advanced nuclear through efforts like Project Pele, a transportable microreactor program designed to provide resilient, off-grid power for military operations. Building on that momentum, the Janus Program, led by the U.S. Army with support from the Defense Innovation Unit (DIU) and technical collaboration with DOE laboratories, is deploying commercial microreactors at military installations using a milestone-based contracting model aimed at fielding resilient power by 2028. By funding early prototypes and assuming technical and financial risk, DoD is helping prove out advanced reactor technologies that could later find commercial applications.

Reactor Developers and Utilities

Private vendors and utilities shape market expectations and are key to mobilizing the supply chain, but few are willing to commit to multiunit orders without a clear risk-sharing structure. Developers look to the federal government for demand aggregation or cost backstops to de-risk FOAK and early fleet deployments that will lock in learning and supplier continuity.

Manufacturers and Trade Associations

Major suppliers and industry associations have pushed for more decisive policy direction, advocating for both "market-pull" and "market-push" support mechanisms. Their lobbying and technical expertise inform DOE and congressional decisions.

Offtakers and Strategic Investors

Offtakers (e.g., hyperscalers, large industrial users, etc.) and infrastructure-focused investors have emerged as potential new drivers of nuclear energy demand. Cloud service providers and data center operators—often referred to as hyperscalers—are exploring nuclear power as a long-term solution to their growing electricity needs, given its reliability and 24/7 zero-carbon profile. Some have made public announcements regarding nuclear development, while others are participating more quietly in early market-shaping efforts.

These hyperscalers, with deep balance sheets and large, geographically distributed energy loads, could theoretically act as anchor customers for SMR deployments. However, most remain hesitant to act as first movers and take on development and execution risk alone, particularly given the lack of standardization, regulatory clarity, and cost certainty around advanced nuclear projects.

Meanwhile, infrastructure-focused investors—including private equity, pension funds, and sovereign wealth funds—are expressing interest in nuclear energy as part of their clean energy portfolios. These investors are primarily seeking bankable projects with predictable returns and have not yet committed to the high-risk early stages of advanced nuclear deployment, in large part because they, like hyperscalers, are disinclined to shoulder unbounded execution risks.

Despite their hesitancy, hyperscalers and private capital markets remain essential long-term players. If demand signals solidify and public-private risk-sharing models mature, these actors could play a transformational role in scaling deployment and shifting nuclear energy into mainstream infrastructure finance.

Bottlenecks

Despite growing interest in advanced nuclear energy, systemic barriers in the policy and investment environment continue to stall progress. A combination of market paralysis, slow public sector implementation, financing hurdles, and policy volatility has left suppliers and developers in a holding pattern.

Market Deadlock Due to Lack of First Mover

The absence of a creditworthy lead customer with significant capacity to enable an order book and willing to be the first mover creates paralysis. Suppliers report that without a firm multiunit contract, they can't justify at-risk investments in new equipment or plants, yet buyers (utilities, industrials, even large tech data centers) will not sign such contracts without assured capacity (including cost estimates) from suppliers. When demand is not certain, investment stalls, and when capacity is lacking, project risk spikes. This loop has become the defining market failure: The entire advanced nuclear supply chain waits on a commitment that never materializes.

Slow and Indecisive Government Program Implementation

Even after Congress has appropriated funding for nuclear projects (e.g., HALEU fuel infrastructure or clean energy R&D), DOE and other agencies have been slow to deploy appropriated funds, hampered by complex application processes and reluctance to make definitive technology bets. Interviewees and reports note that protracted award timelines and diffuse funding signals create high uncertainty. In practice, many potential FOAK projects languish in limbo as companies await clear governmental backing.

Policy Volatility and Unstable Demand Signals

Suppliers face major headwinds from the lack of a stable, long-term national policy framework for nuclear energy. Federal energy and climate priorities often shift with each administration, creating persistent uncertainty about market demand, funding programs, and regulatory direction. This volatility makes it difficult for suppliers to justify capital investments in new facilities, equipment, or certifications—especially those with long payback periods.

Tariff and trade-policy uncertainty further compounds this challenge. One EPC firm noted that price quotes from its Tier 2 suppliers are often valid for only two weeks, forcing the firm to requote if a customer cannot decide within that window. This churn adds cost, delays decision-making, and undermines the stability needed for long-term project planning. Compounding this is the absence of mechanisms that fully compensate power produced by nuclear reactors across all of their attributes (e.g., firm capacity, emissions-free generation, ancillary services, etc.). Without confidence in sustained demand, suppliers are unlikely to re-enter or expand in the nuclear space at the scale required.

Incomplete Designs and Scope Risk

Many proposed projects are still far from final design, forcing constructors and vendors to bid on incomplete plans. Suppliers say this dramatically raises the risk of midstream changes, scope creep, and cost overruns. As a result, suppliers either price in substantial risk premiums or hold off participation until designs firm up. The resulting cost estimates may appear uneconomic to buyers, dampening demand signal formation, but they are a rational response to unresolved scope and execution risk. This has the practical effect of delaying supply chain mobilization. Companies will not retool their lines for a design that might still change, further slowing project development and reinforcing a cycle of elevated costs and hesitant demand.

Opportunities and Strategic Pathways

To overcome bottlenecks and mobilize the supply chain, a set of policy and financial interventions can reduce risk, signal demand, and unlock private investment.

Reform and Accelerate DOE Funding Mechanisms

Rather than spreading funds too thinly across dozens of concepts, DOE could select a focused portfolio of reactor technologies and commit decisively to near-term technology commercialization and expansion of critical supply chain capacity. Industry stakeholders that were interviewed, including potential award applicants, recommend replacing cumbersome application cycles with milestone-based awards and decisive down-selects so companies know which technologies will advance. Doing so would help suppliers plan ahead. Instead of uncertain trickles of funding, they would see a clear, time-bound pipeline of work aligned to commercialization milestones and capacity expansion.

A more efficient DOE process would also signal that the government is serious about acting quickly, further encouraging private co-investment. Recent actions under DOE's HAP demonstrate how this approach can be implemented in practice.

South Korea offers a compelling example of the benefits of such an approach: By standardizing to a single design and building reactors in series, it has achieved consistent cost reductions, culminating in overnight capital costs of approximately $2,300/kW in 2010 (about $3,400/kW in 2025 dollars) for its large light-water reactors.[101]

Engage DoD as Early Risk-Validation Partner

One supplier noted that defense partners sometimes advocate for broader, higher-risk scope than the vendor would otherwise propose. While the vendor recommended a more conservative path, they were consistently impressed by the military's willingness to underwrite early iterations with a higher risk profile. By contrast, commercial buyers often require firm warranties and guarantees up front, terms that typically become feasible only after risk has been mitigated and the supply base has matured. While the DoD, cannot directly support civilian nuclear deployment, defense programs can absorb first-article and FOAK risk for mission-specific applications in ways that generate transferable benefits for the civilian supply chain.

Building on that dynamic, the industry might engage the DoD as an early risk-validation partner to generate reusable qualification data, validated manufacturing processes, and proven component designs before utility orders are placed. This is a natural fit given the range of defense nuclear use cases—Project Pele (the Strategic Capabilities Office's transportable microreactor prototype), the Department of the Air Force/DLA Eielson AFB microreactor pilot (commercially owned and operated, NRC-licensed), DIU's Advanced Nuclear Power for Installations (ANPI) program, and the Army's Janus Program. Across these efforts, defense-driven deployments can validate components, supply chains, and delivery models that later reduce risk for NRC-licensed civilian projects.

Adopt Collaborative Contracting Models

Project contracts themselves can be re-imagined to reduce risk. Rather than traditional cost-plus EPC contracts, parties could use open-book or alliance-style agreements for FOAK projects. In these models, owners, developers, and constructors share information and savings, aligning incentives. Early supplier involvement and cost transparency help contain changes, and risk is managed jointly rather than contested—shifting the dynamic away from finger-pointing and helping speed advanced-reactor builds.

One major nuclear constructor interviewed underscored why such collaboration matters: Suppliers see an order book of four units as too small to justify serious commitment and prefer to engage only when they can see approximately 20 units. They propose leveling margins across the fleet—accepting a smaller return on the first unit in exchange for higher, guaranteed returns on later units—so that suppliers are rewarded for staying the course as learning-curve efficiencies accrue.

Leverage Allied Supply Chains While Rebuilding Domestic Capacity

In the near and medium term, strategic partnerships with allied countries will remain essential. In practice, ultra-large forgings remain most efficiently sourced from Japan, South Korea, and Italy, while LEU conversion and enrichment are supplied by Canadian and European allies. This near-term reliance on allies reduces schedule risk while the domestic base is rebuilt. Even as the U.S. works to reduce its exposure to brittle supply chains, maintaining strong nuclear energy trade relationships

[101] U.S. Department of Energy, *Pathways to Commercial Liftoff.*

with nations like Japan, South Korea, France, and the United Kingdom will be critical to ensuring resilience and reliability across the full life cycle of reactor development and operation.

As one interviewee noted, the Chinese model for nuclear industrialization involved sourcing their first AP1000 reactors internationally and then using that experience to gradually build up their own domestic supply chain for subsequent units. A similar strategy could allow the U.S. to accelerate near-term deployment while methodically rebuilding its own industrial capabilities over time.

Collectively, these measures offer a practical playbook for policymakers to break the current stalemate.

Microreactors

Generally defined as producing less than 50 megawatts thermal (MWth), many microreactors are conceived not as industrial construction megaprojects, but as factory-fabricated products or very small site builds, and thus their supply chains are significantly different from their larger SMR counterparts. This approach trades the traditional economy of scale for an economy of multiples, shifting the central supply chain challenge from managing a complex, decade-long megaproject to mastering high-volume factory production, intricate logistics, and a novel regulatory framework.

Microreactors are not immune to the systemic challenges identified earlier in this report. The most acute bottlenecks—the absence of a commercial HALEU fuel supply, a looming workforce crisis, and the prohibitive cost and complexity of NQA-1 quality assurance—affect the entire advanced nuclear sector. However, the microreactor business model alters the nature of these challenges and introduces a new set of unique considerations. For that reason, this section explores bottlenecks and opportunities unique to these designs.

The fundamental economic driver for microreactors is not to compete with natural gas on the bulk power grid, but to displace expensive and logistically fragile power sources in niche, high-value markets such as remote communities, industrial mines, military bases, and disaster relief operations. In these contexts, the incumbent energy source is often diesel fuel, which carries high delivered cost and significant logistical vulnerabilities. Consequently, the success of the microreactor supply chain is measured less by its ability to compete with the cost of a combined-cycle gas plant and more by its capacity to deliver a product that is more reliable and ultimately cheaper over its life cycle. This reframes the supply chain problem around mastering factory production, logistics, and reliability, not just minimizing the overnight capital cost of a single unit.

The U.S. microreactor sector is led by a small set of developers pursuing diverse technical approaches, business models, and target markets. While their designs differ in power output, fuel type, and manufacturing strategy, most are pursuing factory fabrication and high-volume production models that distinguish microreactors from larger SMRs.

This report focuses on five of the leading U.S. designs that exemplify the diverse technological and strategic approaches being pursued.

Table 10. Microreactor designs

	Aalo Atomics (Aalo-1)	**BWXT (BANR)**	**Radiant (Kaleidos)**	**Oklo (Aurora)**	**Westinghouse (eVinci)**
Power output	10 MWe (in 50 MWe “Pod”)	50 MWth (~15-20 MWe)	1 MWe/1.9 MWth	Up to 75 MWe	5 MWe/15 MWth
Fuel type & enrichment	Ceramic UO_2 (LEU+ at 8%)	TRISO (HALEU)	TRISO (HALEU)	Metallic (HALEU or plutonium)	TRISO (HALEU)
Coolant	Liquid sodium	Helium	Helium	Liquid sodium	Sodium heat pipes
Key components	Sodium electromagnetic pumps, modular civil structure	HTGR components, TRISO fuel compacts	Graphite moderator, turbomachinery	Fast reactor core, heat pipes, supercritical CO_2 power conversion	Nuclear-grade heat pipes, graphite core block, control drums
Manufacturing model	High-degree vertical integration; “factory-as-a-product”	In-house manufacturing leveraging naval reactor experience	High-degree vertical integration; “mass-producible package”	Vertically integrated energy service provider	Leverages existing global supply chain; acts as integrator
Target market	AI data centers, industrial	Remote industrial, military bases	Diesel generator replacement, mines, military, disaster relief	Data centers, industrial, defense facilities	Remote communities, mining, industrial heat, defense

Microreactor Differentiators

Several features of microreactor design and deployment create a supply chain profile that differs markedly from other reactor classes.

Figure 12. Microreactor differentiators

Larger SMRs	vs.	Microreactors
Centralized grid supply	➡	Remote/off-grid applications
On-site construction	➡	Factory-built, shipped whole
Occasional fuel delivery	➡	Entire fueled unit transported
Established transport packages	➡	No certified transport packages

Manufacturing at Scale

Startups in the microreactor space, such as Aalo Atomics and Radiant, are internalizing the manufacturing process, treating the factory itself as a core product. This approach is designed to exert direct control over quality, schedule, and cost, enabling a rapid learning curve that is impossible in the traditional project-based model.

Aalo Atomics explicitly states that it is pursuing two "minimum viable products" simultaneously: the reactor and the factory.[102] The company's long-term vision is to launch multiple "gigafactories," each capable of producing more than 100 reactors annually, equivalent to 1 GW of energy production per year.

Radiant is pursuing a similar strategy, with plans to construct a factory capable of producing up to 50 of its Kaleidos reactors annually by the mid-2030s.[103]

This internalization of manufacturing shifts the primary business risk for these startups. The challenge is no longer one of supply chain access, but one of manufacturing execution. These companies must now master the complexities of high-volume, nuclear-grade manufacturing and assembly while maintaining a rigorous NQA-1 quality program.

Notably, several microreactor developers are making commercial-grade dedication a central part of their strategy. Aalo, for example, has implemented an NQA-1 program and uses CGD where vendors lack that qualification. Much of the microreactor construction at DOME t INL also relies heavily on CGD to qualify commercial components. At microreactor scale, however, CGD can be disproportionately expensive, creating pressure to minimize the number of safety-related components that must go through dedication. This makes fuel designs such as TRISO especially important: Because each TRISO particle has its own robust containment barrier, the reliance on external safety-class systems is reduced, limiting the scope of what requires costly CGD.

High-Precision Modules

While microreactors successfully bypass the bottleneck of ultra-large forgings that constrain larger reactor designs, they introduce a new set of manufacturing challenges centered on the high-volume production of smaller, high-precision components and modules.

Instead of low-volume, massive pressure vessels and other components, microreactor factories must be capable of repeatably and reliably producing thousands of complex, integrated components. A prime example is the heat pipe, which is the central technology in Westinghouse's eVinci design. These passive devices, which use sodium as a working fluid to transfer heat from the core to a primary heat exchanger, must be manufactured to exacting nuclear-grade standards. Producing thousands of these 12-foot-long components, each a sealed and critical system, represents a novel manufacturing challenge that combines metallurgy, precision welding, and stringent quality control.

Similarly, designs that use liquid sodium (Aalo, Oklo) or high-temperature helium (Radiant, BWXT) as coolants depend on a supply of specialized, compact components such as electromagnetic (EM) pumps, heat exchangers, and high-speed turbomachinery. These components must be designed for extreme reliability, as they are often sealed within the reactor unit and intended to operate for years without maintenance.

Advanced materials also present a key supply chain consideration consistent with other Gen IV reactor designs. The use of nuclear-grade graphite as a moderator and structural component in high-temperature gas-cooled designs like Radiant's Kaleidos and BWXT's BANR creates a direct dependency on a supply chain that is currently dominated by China. To mitigate this significant geopolitical risk, developers are forming strategic partnerships to onshore this capability. Radiant's memorandum of understanding and significant

[102] Yasir Arafat, "Our Manufacturing Thoughts and Plans," Aalo Atomics, Jan. 27, 2025.

[103] Katie Brigham, "The Nuclear Startup That's Ready for a Second Trump Term." *Heatmap*, June 12, 2025.

purchase order with Amsted Graphite Materials, a U.S.-owned producer, is a clear example of a proactive strategy to secure a domestic supply of this critical material.

Balance of Plant

Another significant innovation in the microreactor manufacturing model is the extension of factory fabrication beyond the nuclear island to encompass the entire balance of plant. Developers like Aalo are designing their product not just as a reactor, but as a complete, containerized power plant, the Aalo Pod.[104] This modular system includes the reactor, the power conversion system, instrumentation and control modules, and even the civil structure, all designed to be manufactured in a factory and shipped to the site for rapid assembly.

By moving the vast majority of construction and assembly activities into a controlled factory environment, developers aim to achieve a level of predictability and speed that is unattainable with traditional on-site construction methods. This vertically integrated model, where the developer delivers a turnkey power plant, also concentrates the economic value. Unlike a large reactor project where value is distributed among an owner, an EPC firm, and hundreds of suppliers, the microreactor developer captures the value of the entire system.

Transportation

While many supporting supply chain players for microreactors overlap with those described in other sections, transportation and logistics partners take on an unusually central role in this segment. In the microreactor business model, the ability to move a factory-fueled and sealed reactor module from the manufacturing site to a customer location—and then back again for refueling or refurbishment—is not a peripheral activity but a critical feature of the product and business model.

Among the microreactor designs explored in this report, however, this transportable, refuel-by-replacement architecture is not universal. Oklo's Aurora reactor, for example, is designed as a fixed installation rather than a transportable unit, with fuel remaining on-site for the life of the reactor and decommissioning occurring in place. While fuel and spent fuel still require transportation, logistics in this model are limited to discrete fuel shipments rather than recurring movement of the integrated reactor module.

A typical life cycle begins with manufacturing and assembly in a centralized factory, often with the reactor fully fueled and potentially tested before shipment. The sealed unit is then transported to its destination, where it operates for years—often a decade or more—without refueling. At the end of that operational run, the entire reactor, now containing irradiated fuel, is shut down, packaged, and shipped back to a central facility for decommissioning or refurbishment and redeployment.

Both shipment legs carry high replacement-value exposure because the integrated module is itself extremely costly; any incident in either direction risks damaging the product. The return leg then layers on additional radiological packaging, licensed carriers, security/escort, and routing constraints.

These challenges place specialized nuclear packaging and cask design firms, NRC-licensed carriers, heavy-haul and "last mile" logistics providers, and security and escort services at the heart of the value chain. For microreactor developers, these partners must be engaged early in design to ensure that the reactor's dimensions, shielding, and weight can be accommodated across every segment of its route, and to enable the certified transport solutions, without which the business model cannot function.

This "refuel-by-replacement" model is a paradigm shift. It transforms transportation from a peripheral activity involving fuel and waste into a central, recurring operational activity involving the entire nuclear power plant. This introduces a mobility paradox: The very feature that makes microreactors uniquely valuable is also the source of their greatest and most complex regulatory, technical, and social challenges.

Figure 13. Microreactor life cycle

[104] Yasir Arafat, "Our Manufacturing Thoughts and Plans," Aalo Atomics, Jan. 27, 2025.

Regulators

The U.S. Nuclear Regulatory Commission is actively adapting its regulatory framework to accommodate the unique characteristics of microreactors, creating a more streamlined path to deployment for this specific class of technology. This represents a significant departure from the one-size-fits-all regulatory approach of the past.

Historically, the NRC has held the position that a reactor is "in operation" as soon as nuclear fuel is loaded into the core. Under this interpretation, a factory-fueled microreactor would require a full facility operating license before it could even be fueled, and its transport would be governed by regulations designed for a static, operating power plant—a clear impossibility. This single issue created a cascade of regulatory issues to be worked through, effectively blocking the envisioned deployment model.[105]

Recognizing this impasse, the NRC has embarked on a significant policy shift. Through a series of white papers, public meetings, and formal policy decisions, the NRC has established a new position: A factory-fabricated microreactor loaded with fuel may be considered not "in operation" provided it incorporates robust, verifiable "features to preclude criticality."[106] These are engineered systems (e.g., locked-in control rods, fixed neutron absorbers, or decoupled drive mechanisms) that make it physically impossible for the reactor to sustain a nuclear chain reaction during transport.[107] This policy decision is the fundamental regulatory enabler for the factory-fueling concept, allowing a fueled reactor to be treated as a transport package rather than an operating facility.

Furthermore, the NRC will allow pre-operational testing of these commercial reactors at a factory under the more lenient regulations governing non-power research and test reactors.[108] Together, these policies significantly reduce the regulatory burden and timeline associated with the manufacturing phase compared to operating under the previous regime.

In May 2025, an executive order directed the NRC to reform its structure and regulations to expedite new reactor licensing and promote deployment of advanced nuclear technologies. This includes engaging directly with DoD and DOE demonstration efforts and developing a comprehensive regulatory framework for microreactors that could potentially combine the licenses for manufacturing, testing, fueling, and transportation into a single, streamlined process.[109]

This policy evolution is creating novel licensing pathways. Instead of seeking a traditional site-specific operating license simply to load fuel, a developer can now pursue a more streamlined approach. The current model being developed involves a combination of licenses:

1. A 10 CFR Part 52 Manufacturing License would approve the standardized design of the microreactor module and its fabrication process at the factory.
2. A 10 CFR Part 70 License for the "Domestic Licensing of Special Nuclear Material" would authorize the possession and handling of HALEU fuel at the factory for the purpose of loading it into the manufactured reactor.
3. For developers who wish to perform operational testing at the factory before shipment, the NRC has indicated it may allow this to be authorized under the more flexible and less prescriptive regulations governing non-power research and test reactors, rather than the full suite of power reactor regulations.[110]

Once a fueled microreactor leaves the factory, its transport is governed primarily by 10 CFR Part 71, Packaging and Transportation of Radioactive Material. These regulations, which are harmonized with those of the U.S. Department of Transportation (DOT), establish stringent requirements for the design, fabrication, testing, and operational control of packages used to ship radioactive materials.[111]

The core challenge is that Part 71 was written with the assumption that the radioactive material is placed inside a package. For a microreactor, the reactor module is the package, or at least the primary component of it. This requires novel interpretations and potentially new guidance to apply the existing performance standards—for containment, shielding, and criticality control under normal and hypothetical accident conditions—to this new type of shipment.[112]

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105 U.S. Nuclear Regulatory Commission, *Micro-Reactor Licensing and Deployment Considerations: Fuel Loading and Operational Testing at a Factory*, Office of Nuclear Reactor Regulation, preliminary white paper, NRC staff, August 2023.
106 Nuclear Engineering International, "NRC eases microreactor rules," June 23, 2025.
107 Nuclear Regulatory Commission, *Licensing and Regulating Factory-Fabricated and Assembled Micro-Reactors*, draft white paper, September 2023.
108 Brian Martucci, "Nuclear Regulators Lighten Microreactor Restrictions," *Utility Dive*, June 24, 2025.
109 Ibid.
110 Brian Martucci, "Nuclear Regulators Lighten Microreactor Restrictions," *Utility Dive*, June 24, 2025.
111 U.S. Nuclear Regulatory Commission, "10 CFR Part 71 Subpart G – Operating Controls and Procedures," Electronic Code of Federal Regulations, Title 10, Chapter I.
112 Harold E. Adkins Jr. and Steven J. Maheras, "Microreactor Transportability Challenges," WM2021 Conference, March 8-12, 2021.

Deploying microreactors to overseas markets or transporting them by sea introduces even greater regulatory complexity, involving a web of international treaties and standards. Furthermore, sea transport is subject to an additional, stringent set of rules.

The concurrent evolution of microreactor technology and its governing regulations creates a high-risk, high-reward environment. The NRC, DOE, and industry are essentially co-developing a FOAK regulatory system for an object that defies traditional categorization.[113] This means that regulatory decisions, such as the specific criteria for "features to preclude criticality," will directly shape the engineering designs that vendors must pursue.[114]

Furthermore, while substantial progress is being made on the regulations for transporting a new, freshly fueled reactor, the return trip remains the true regulatory frontier.

Bottlenecks

Microreactor deployment introduces new constraints on fuel and component transport, requiring a fundamentally different logistics and regulatory model.

Lack of Certified Transportation Packages

The transport of a microreactor after years of operation, when its core is highly radioactive and generating decay heat, presents a formidable challenge. This irradiated module would contain high-level waste and would unambiguously require a certified Type B package for transport.[115]

The radiation dose rates from such a package could be high enough to require a standoff distance of approximately 30 meters to meet regulatory limits for public exposure, a logistical near-impossibility for standard highway transport that would necessitate special permits, escorts, or other compensatory measures.[116] This implies that the entire microreactor system—the reactor itself and its transport package—cannot be designed solely for the relatively simple outbound journey. It must be engineered from the outset to meet the far more demanding safety, shielding, and regulatory constraints of the return journey, a factor that will profoundly impact its final design, weight, and cost.

Currently, there are no NRC-certified casks designed to efficiently transport large quantities of HALEU, let alone a fully fueled microreactor. While casks designed for highly enriched uranium (HEU) could theoretically be used, their small capacity would make HALEU transport prohibitively expensive, requiring thousands of individual shipments to fuel a single advanced reactor. Recognizing this critical gap, DOE has initiated a funding program to accelerate the development and qualification of new HALEU-specific transportation packages, but this process is expected to take several years.[117]

U.S. and international regulations mandate that shipments containing high quantities of radioactivity, a category that would certainly include an operated microreactor containing its irradiated fuel, must be transported in a certified Type B package.[118] These packages are engineered to be exceptionally robust, designed, and tested to withstand a sequence of severe hypothetical accident conditions without releasing their contents. These tests include a 9-meter (30-foot) free drop onto an unyielding surface, a 1-meter drop onto a steel puncture bar, a 30-minute engulfing fire at 800 degrees Celsius (1,475 degrees Fahrenheit), and an eight-hour water immersion test.[119]

No certified Type B package currently exists that is designed to hold an object with the size, weight, and complexity of an entire microreactor.[120] The current fleet of Type B casks was designed to transport traditional nuclear fuel assemblies or canisters of vitrified waste. The internal cavities of these casks

[113] U.S. Nuclear Regulatory Commission, *Micro-Reactor Licensing and Deployment Considerations: Fuel Loading and Operational Testing at a Factory*, Office of Nuclear Reactor Regulation, draft white paper, August 2023.
[114] U.S. Nuclear Regulatory Commission, *Micro-Reactor Licensing and Deployment Considerations: Fuel Loading and Operational Testing at a Factory,* Office of Nuclear Reactor Regulation, SECY Paper ML23207A250, August 2023.
[115] U.S. Nuclear Regulatory Commission, *Risk-Informed Methodology for a Future Transportable TRISO-Based Micro-Reactor Package Application,* SECY-24-0062, July 22, 2024.
[116] Steven J. Maheras et al., *Microreactor Transportation Emergency Planning Challenges*, Rev. 1, Pacific Northwest National Laboratory, September 2024.
[117] U.S. Department of Energy, *High-Assay Low-Enriched Uranium (HALEU) Transportation Package, Inflation Reduction Act (IRA)*, Funding Opportunity DE-FOA-0002967, Idaho Operations Office, posted Nov. 19, 2024.
[118] Wayne L. Moe, *Key Regulatory Issues in Nuclear Micro-Reactor Transport and Siting*, Idaho National Laboratory, September 2019.
[119] U.S. Nuclear Regulatory Commission, "Part 71 — Packaging and Transportation of Radioactive Material," *Title 10 CFR Part 71.*
[120] World Nuclear Association, "Transport of Radioactive Material," April 2025.

are far too small to accommodate a microreactor module, which could be several meters long and weigh over 14 metric tons, based on historical precedents like the ML-1 reactor.[121]

This leads to a critical strategic choice for developers: whether to ship their reactors fueled or unfueled. Shipping a fully fueled reactor is the ideal scenario, as it aligns with the rapid deployment model. However, this would require certifying the entire reactor unit (a complex assembly of fuel, moderator, reflectors, and shielding) as a Type B fissile material package. This represents a "significant paradigm shift" from the current regulatory framework and is a technical and licensing challenge.[122]

The alternative, shipping the reactor and its fuel separately, greatly simplifies the transportation logistics but undermines the core value proposition. It necessitates complex and time-consuming on-site fueling procedures, effectively turning a "product" delivery into a mini-construction project and erasing, or at least reducing, a key competitive advantage over larger SMRs.

The challenge is further compounded by the back end of the business model. Many microreactor developers, including Radiant and Westinghouse, plan for the entire reactor unit to be returned to the factory for refueling after its operational life of five to 10 years. Transporting an irradiated reactor, which contains a significant inventory of fission products, presents a different and much greater radiological hazard than transporting fresh fuel. This will require an even more robust and heavily shielded transportation cask, the design and qualification of which is another FOAK challenge that has yet to be fully addressed. Without a certified and economical solution for both outbound and return logistics, the "nuclear battery" life cycle remains incomplete.

That said, one microreactor developer who was interviewed for this report said they are not concerned about this challenge and are already advancing their transportation plan. Their approach is to ship the reactor in its irradiated state, supported by strong interest from suppliers. They are developing their own transport shielding, including an overpack around the container, and are working through the DOT process in coordination with DOE. Shielding suppliers are available to potentially support this approach, though this application will require different sizes and thicknesses of shield than historically have been used. The goal is a package compact enough to move on a single railcar or travel aboard a C-17 aircraft.

Logistical Management of Transport Route

A transport plan is only as robust as its most constrained segment. A critical challenge for microreactor deployment is ensuring that the entire route, from the factory gate to the final installation pad, can physically accommodate the shipment. This is particularly acute for the "last mile," which may involve travel over local or unpaved roads to reach a remote site.[123]

Logistics providers must conduct exhaustive route surveys to identify and plan for any potential obstacles. These include vertical clearance issues with low bridges and tunnels, horizontal constraints on narrow roads, and the weight-bearing capacity of bridges and roadbeds.[124] These infrastructural limits act as a hard constraint on the design of the reactor and its transport package.

The NRC's anticipated "crawl-walk-run" strategy for transportation package approval, which prioritizes highway transport first before moving to other modes, makes road and bridge limits a primary design driver for the first generation of commercially deployed microreactors. The necessity of navigating existing public infrastructure may ultimately dictate the maximum size, weight, shielding, and therefore power output of these systems. Further, the infrastructure generally becomes more challenging as destinations become more remote.

Establishing Emergency Planning Plans Across Transit

The complexity of mobile reactor deployment also introduces unprecedented emergency preparedness and response planning requirements. Unlike a stationary power plant with a fixed Emergency Planning Zone (EPZ), a transported microreactor becomes a mobile radiological source requiring coordinated planning across its entire route.[125]

A single cross-country shipment could involve dozens of unique jurisdictions including state, Tribal, and local responders, all of whom may need to be trained, briefed, and equipped to respond in the event of an incident. Establishing coordinated emergency plans with all of these entities is a massive undertaking, with one analysis suggesting that the

[121] Harold E. Adkins Jr., "Microreactor Transportability Challenges – 21072," Waste Management Symposia (WM2021), March 8-12, 2021, Phoenix, Arizona, Pacific Northwest National Laboratory.
[122] Spencer Maher et al., *Foundational Technology and Methods for Microreactor Transportation*, Idaho National Laboratory, September 2021.
[123] Ibid.
[124] Stven J. Maheras et al., *Draft Prototype Microreactor Transportation Safety Program*, Pacific Northwest National Laboratory, April 2025.
[125] Wayne L. Moe, *Key Regulatory Issues in Nuclear Micro-Reactor Transport and Siting*, Idaho National Laboratory, September 2019.

necessary engagement and planning could take two to three years for each new transport route.[126]

Furthermore, these plans must be tailored to the specific hazards of the microreactor being transported. Some designs may use materials like beryllium or liquid sodium as coolants, which present unique chemical hazards and may require specialized equipment and training for first responders that are not standard in many jurisdictions.

Security is an equally significant concern. The transport phase is widely recognized as the point at which nuclear materials are most vulnerable to theft, diversion, or sabotage. Consequently, security protocols for the transport of microreactors, especially those containing HALEU or irradiated fuel, must be exceptionally stringent. The potential introduction of plutonium-bearing fuel would exacerbate these challenges. Regulatory oversight for this is shared among DOE, NRC, and DOT.

Scaling Constraints on Specialized Components

A central bottleneck for microreactors emerges when projected production volumes are scaled to the levels envisioned by leading developers. Many microreactor business models assume factory output on the order of 50 to 100 reactors per year, a rate far exceeding historical production levels for nuclear-grade components in the United States. Several categories of specialized equipment would face immediate pressure under such a manufacturing schedule.

One interviewed developer noted that meeting a production target of 100 reactors per year would require more nuclear instrumentation assemblies than the U.S. has produced in total across decades of commercial reactor construction. Similar constraints would apply to other precision, safety-related components such as heat pipes, sodium or helium-compatible pumps, compact heat exchangers, and high-speed turbomachinery—none of which have been manufactured at anything approaching these volumes for nuclear service.

This scale mismatch does not undermine the viability of microreactor manufacturing, but it does underscore a critical supply chain reality that is not unique to microreactors. If even a single developer reaches its target throughput, the supporting vendor ecosystem for high-precision nuclear-grade components must expand dramatically and in parallel, or risk becoming a primary gatekeeper on deployment across microreactors, SMRs, and large reactors alike.

Opportunities and Strategic Pathways

While current bottlenecks are considerable, early action by developers and government agencies could define viable transportation pathways and de-risk microreactor logistics at scale.

Finalize TRISO as Functional Containment to Streamline Microreactor QA

A major driver of microreactor cost and schedule risk is the breadth of components subject to nuclear grade standards. By designing reactors so that the fuel itself serves as the primary containment boundary (through TRISO particles whose multilayer coatings individually retain radionuclides), developers can materially reduce the number of safety-related systems that must go through expensive dedication processes.[127] TRISO fuel has been demonstrated to withstand extreme conditions and maintain its integrity at high temperatures, and the planned licensing strategy is to show that the fuel itself serves as a "functional containment."[128] Embedding this principle in microreactor design would shift the regulatory burden from qualifying thousands of components to demonstrating the robust performance of the fuel, which has already been extensively tested in accident scenarios.[129]

Regulators have signaled openness to this kind of approach. The NRC is developing risk-informed, performance-based, technology-inclusive licensing pathways for advanced reactors (e.g., the forthcoming Part 53 rule) that explicitly allow applicants to justify safety through alternative design features like TRISO containment. In such a framework, developers must provide objective evidence that TRISO meets the necessary safety functions, but the result could be a reduced

[126] Steven J. Maheras et al., *Microreactor Transportation Emergency Planning Challenges*, Rev. 1, Pacific Northwest National Laboratory, September 2024.
[127] Jason Andrus et al., "TRISO Fuel's Safety Functions, Contributions to Reactor Safety, and Necessary Safety Limits," *Nuclear Technology*, vol. 211, no. 8, December 2024.
[128] U.S. Department of Energy, "TRISO Particles: The Most Robust Nuclear Fuel on Earth," July 19, 2019.
[129] A.J. Huning, *Considerations for Improving the Technoeconomic Viability of Functional Containment for Microreactors*, Oak Ridge National Laboratory, March 2024.

reliance on costly CGD and a more scalable path for microreactor deployment.

A recent example is X-energy's July 2025 Topical Report, which advances a "functional containment" safety case for the Xe-100 using TRISO fuel.[130] Government support could further accelerate this transition by funding TRISO qualification campaigns, clarifying how containment performance is treated in licensing pathways and fostering early alignment with insurers and regulators on its acceptance. In the meantime, developers are depending on licensing topical reports to justify the concept for their applications.

Explore Alternative Test-Reactor Framework to Reduce Manufacturing Bottlenecks

The NRC has signaled that certain pre-operational factory tests for microreactors may be conducted under the simpler rules that govern research and test reactors, but only if the module includes robust "features to preclude criticality," meaning it physically cannot sustain a chain reaction during these tests.

This allowance would not substitute for a full commercial license, but it could shift key validation activities upstream to the factory floor. The impact on the supply chain is twofold:

1. Reduced licensing friction in early phases. Vendors could run systems checks, heat removal tests, and component integration trials at the manufacturing site without triggering the full suite of power-reactor regulatory requirements. This lowers both regulatory risk and cost during fabrication.
2. Improved throughput and scheduling flexibility. By clearing some testing before shipment, vendors can shorten the commissioning period at the deployment site. This helps ease one of the sharpest constraints the industry faces: limited skilled craft labor and specialized installation capacity.

Taken together, the option to leverage the test-reactor framework would not eliminate the need for a Section 103 license, but it offers a supply chain relief valve that accelerates time to market while preserving safety margins.

Develop Certified Transportation Solution in Parallel With Reactor Design

Microreactor developers and their supply chain partners must begin transportation package development as a parallel workstream, not a late-stage afterthought. This reality presents developers with three potential pathways, each of which are technically and regulatorily demanding:[131]

1. Design a New Type B Overpack: This approach involves engineering a very large, certified Type B cask that would function as an overpack, with the entire microreactor module placed inside it for transport. This would be a massive and complex piece of equipment in its own right.
2. Qualify the Reactor as the Type B Package: This more integrated approach would involve designing the microreactor's own vessel, shielding, and structural components to serve as the Type B package itself. This would require the reactor to be able to withstand the severe accident test conditions directly, adding immense structural and thermal performance requirements to the reactor design.
3. Consider an altogether different approach with regulators based on microreactor source terms relative to past Type B shipments.

The development and qualification of a suitable transport cask is therefore on the critical path for the entire transportable microreactor industry. A vendor cannot commercially deploy a reactor, especially for its return trip, without a corresponding licensed transport solution. The process of designing, testing, and licensing a FOAK package of this nature is a multiyear, multimillion-dollar endeavor. This elevates the cask from a mere accessory to a co-equal critical system whose development timeline and cost may rival that of the reactor itself.

That said, lessons can be learned from the U.S. Army's ML-1 program (1961-65). ML-1 was a truck- and air-transportable reactor that met its mobility goals, fitting into four containers (about 38 tons total), deployable by truck, rail, or C-130, and relying on a 500-foot exclusion zone instead of heavy shielding.[132] While mobility was achieved, viability was not. The project was beset by material failures and reliability issues, leading to shutdown on May 29, 1964, after only limited testing.[133] The lesson is clear: Microreactor design should not

[130] "X-energy LLC's Xe-100 Licensing Topical Report – Mechanistic Source Term Approach, Revision 3," Letter to Advisory Committee on Reactor Safeguards, July 25, 2025. ADAMS Accession No. ML25204A121.

[131] Wayne L. Moe, *Key Regulatory Issues in Nuclear Micro-Reactor Transport and Siting*, Idaho National Laboratory, September 2019.

[132] G.A. Linenberger, *The ML-1 Design Report.*, U.S. Atomic Energy Commission, Idaho Operations Office; Aerojet-General Corporation, May 16, 1960.

[133] U.S. Department of Energy, *History of the Idaho National Laboratory*.

over-index on transportability at the expense of operational reliability, performance, and economics.

Pre-FIT (fabrication, inspection, and test) drawings rarely capture the real envelope, handling limits, and heat profile—and the module is costly to damage in either direction. Reactor developers will be well-served to finish factory integration and test to establish the as-built baseline, then finalize the transport package/cask to that baseline in order to minimize rework, protect a high-value module on both transport legs, and improve cost and schedule predictability.

Establish a National Microreactor Transport Framework

To avoid piecemeal progress and duplicative efforts, federal agencies and national labs should lead the development of a coordinated transportation and emergency response framework for microreactors.

National laboratories have begun to outline the elements of a comprehensive microreactor transportation safety program. Drawing on the successful model of the Waste Isolation Pilot Plant (WIPP) transportation program, this effort will endeavor to create a holistic system covering every aspect of the move, including qualification and training standards, as well as inspection and maintenance protocols.[134]

By treating microreactor logistics as national infrastructure rather than a project-by-project burden, this kind of framework could accelerate early deployments, de-risk investments, and demonstrate federal commitment to microreactor commercialization.

[134] Steven J. Maheras et al., *Draft Prototype Microreactor Transportation Safety Program*, Pacific Northwest National Laboratory, March 2025.