EFI FOUNDATION

ENERGY FUTURES FINANCE FORUM

Making Small Modular Reactors Bankable Investments

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ENERGY FUTURES FINANCE FORUM

The Energy Futures Finance Forum (EF^3) is a program within the EFI Foundation that examines barriers to the flow of private capital to clean energy and industrial decarbonization opportunities. By reflecting the investor perspective, its primary focus is enhancing the bankability of projects and business models essential for the energy transition. Through rigorous analysis, thought leadership, stakeholder convening, and public education, EF^3 develops actionable policy and financial sector recommendations to address challenges and drive at-scale capital deployment.

Acknowledgments

Project Team

Stephen D. Comello . . . *Senior Vice President, Strategic Initiatives; Co-Managing Director, Energy Futures Finance Forum*

Madeline I. Cohen . . . . . *Research Associate*

Additional Contributors

Ernest J. Moniz . . . . . *Chief Executive Officer and President*

Joseph S. Hezir . . . *Executive Vice President, Treasurer*

Communications Team

Adrienne Young . *Senior Communications Lead*

Ben Cunningham . . . . . . *Graphic Designer, MG Strategy + Design*

Copy Editing

Jane Hirt . . . . *M. Harris & Co.*

Danielle Narcisse . . . . *M. Harris & Co.*

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Stephen S. Greene
Matthew Bowen
Jeffrey D. Brown
Minji Jeong
Michael Downey

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Executive Summary

Supporting the scale-up of new domestic nuclear deployments and capabilities is in the national interest of the United States because nuclear energy can fulfill multiple security, resiliency, reliability, and decarbonization goals. Nuclear reactors produce large quantities of clean, firm power in a relatively compact footprint; are capable of greater than 95% capacity factor operation; and new and evolutionary reactor designs incorporate notable passive safety features.

To achieve domestic net zero by 2050, a U.S. Department of Energy (DOE) analysis indicates that the United States needs more than 200 gigawatts (GW) of new nuclear capacity to be built over 20 years—double the size of the existing fleet that has taken 65 years to build. From an energy demand perspective, the United States expects significant growth in electricity demand due to recent surges in data center deployment, manufacturing capacity expansion, and an overall shift to electrification of transportation, heating, and some industrial processes, and possibly others, such as a major buildout of a clean hydrogen economy. Internationally, at the 28th Conference of the Parties to the United Nations Framework Convention on Climate Change (COP28) in December 2023, 25 countries (including the United States) signed a Declaration to Triple Nuclear Energy by 2050 as part of an overall decarbonization strategy. This would mean the world needs to deploy 50 GW of new nuclear per year, which is 50% greater than the peak year of deployment experienced in the early 1980s. Taken together, the rationale for a major nuclear expansion is compelling.

Small modular reactors (SMRs) offer distinct advantages that alter the traditional nuclear business model, streamline delivery, and expand nuclear energy's potential applications.

Of course, large nuclear reactors (typically 1 GWe and larger) can, and likely will, be important contributors to a major nuclear expansion. However, small modular reactors (SMRs) also offer distinct advantages that alter the traditional nuclear business model, streamline delivery, and expand nuclear energy's potential applications. Rather than relying on economies of scale, SMRs use modular, standardized components that can be fabricated in factories. This "market modularity" allows for aggregation of reactor units—built in series or parallel—to establish larger nuclear plants. This can remove redundancies in regulatory approvals and construction while taking advantage of more durable demand signals. Repeat builds using standardized components, similar to solar panels and battery modules, can drive down costs, making SMRs a bankable, cost-competitive solution. For this to happen, the focus must shift from single plants to "orderbooks."

An orderbook is defined as firm commitments for multiple, identical installations of a particular design. While the FOAK build may be costly, anticipated economies of series should reduce both costs and uncertainties in successive builds. An orderbook backed by a pool of creditworthy strategic investors—those requiring SMR output—sends a robust demand signal that can induce capital deployment across the value chain. This mechanism pools demand among project proponents and shares risks across public and private actors, laying the foundation for a new domestic SMR industry.

However, several challenges must be addressed to enhance the bankability of SMRs, including (1) orderbook cost magnitude coupled with cost uncertainty, (2) uncertainty surrounding licensing by the U.S. Nuclear Regulatory Commission (NRC), (3) an inadequate or nonexistent fuel supply chain, (4) the lack of a clear national pathway for spent fuel, and (5) difficulty in achieving community-level social acceptance. Despite policy support for research and development, commercial SMR deployment is making slow progress, with private capital largely remaining on the sidelines. SMRs are currently not seen as bankable investments due to a lack of a clear demand signal and the necessary project sponsors to commercialize these reactors.

Substantial private sector capital will be required over a long period to fund SMR construction, fuel supply chains, and workforce development. These capital providers will consider the orderbook, along with the interconnected upstream and downstream supply chain and customer base. They will use a broad set of criteria to determine the extent to which an investment strikes the right risk/reward balance. Central to this process is the identification of risks that exist along the entire value chain of an opportunity. If any one of these risks, wherever located in the value chain, is deemed too great given the expected returns, then the opportunity is rejected.

The SMR industry—both private and public stakeholders—must work to address a series of investment risks to make orderbooks of Gen III+ (LWR) and Gen IV (non-LWR) reactors bankable. These investment risks are present across the capital stack, from the strategic investors and vendors who will place equity into orderbook formation; to the developers, EPCs, and manufacturers who place their own capital at risk; to the DOE Loan Programs Office (LPO), which can offer substantial financing through low-cost, public sector debt.

This study provides policy recommendations in response to the challenges faced to SMR scale-up. Each set of policy recommendations aims to increase the likelihood of orderbook formation by motivated strategic investors and affiliated capital providers.

Challenge 1: Orderbook cost magnitude and cost uncertainty.

Given that there is little real-world validation of cost estimates, lenders and equity investors are wary of the economic viability of SMRs. Any lender, whether private or the federal government, is likely to require that project funding plans include some form of large and readily available financing reserves (e.g., cash, letters of credit, or funding availability) to cover cost contingencies. This adds a substantial capital cushion to the overall capital commitment. Even with such project cost buffers, there remains significant risk that orderbook costs will surpass construction cost estimates. The specter of these uncapped, unplanned costs is a first-order challenge to the formation of SMR orderbooks, since capital providers generally highly value predictability regarding capital requirements needed to reach profitability.

Policy recommendation: DOE's Loan Programs Office should offer a cost stabilization facility (CSF) in the form of a special credit mechanism to provide liquidity in the event that an orderbook of SMRs faces unplanned costs. Employing existing authorities within LPO, the CSF would be an augmented loan product designed to significantly reduce the construction cost risk faced by pioneering SMR project proponents. The CSF would be available only to those project sponsors who align with cost containment best practices. Crucially, the CSF would be applied to the entire orderbook, helping remove the "first-mover disadvantage" faced by the first reactor project and smooth costs across all builds in the project.

Challenge 2: NRC licensing uncertainty.

The business case for SMRs hinges on the regulatory environment, as innovations in reactor design, construction, efficiency, and safety require NRC approval. While progress has been made, applicants face challenges navigating licensing processes originally meant for larger light-water reactors, leading to lengthy and costly interactions with the NRC. Rapid deployment of SMRs depends on a regulatory framework that supports new technologies and high-volume licensing while maintaining the NRC's world-class standards. Without this, developers may have to compromise on design, affecting modularity, standardization, and cost reductions. One-off construction of an SMR may represent a start but also undermines a key premise for significant cost reduction through a manufacturing paradigm.

Policy recommendation: The ADVANCE Act, signed into law in July 2024, reforms the NRC by reducing licensing costs for advanced nuclear reactor projects, enhancing international competitiveness, and improving Commission efficiency. The Act lowers hourly fees for advanced reactor license applicants, but foundational issues with the fee structure remain, limiting NRC activities and financially disincentivizing some applicants. Building on the ADVANCE Act, there are additional targeted actions Congress can take to address the fee structure, while DOE and NRC should work together to increase regulatory process efficiency and effectiveness. First, Congress should exempt FOAK SMR pre-application and licensing activities (irrespective of number of reactors in the first NRC review) from the mandatory fee base and offset the cost to the NRC with congressional appropriations to encourage robust pre-application activities. FOAK exemptions would be allowed regardless of chosen regulatory pathway (i.e., Part 50, 52 or 53). Such actions would improve application and engagement quality as well as enhance the NRC's preparedness by signaling which core resources, competencies, and budget it would need to support reviews. Second, as the costs of licensing standardized designs are better understood, Congress should consider fixed application fees for licensing activities. Additionally, rather than a front-end service fee, back-end fees could enable vendors to repay the additional upfront appropriations requirements over time as projects are successfully built and operated. Third, based on the results from the advanced methods of manufacturing and construction report mandated by the ADVANCE Act, DOE and the NRC should consider creation of a working group that is focused on SMR manufacturing, coordinating resources across Office of Nuclear Energy, Office of Manufacturing and Energy Supply Chains and relevant national laboratories. Finally, DOE and NRC should pursue several joint initiatives to create regulatory infrastructure and transfer knowledge via official reviews on cross-cutting technical uncertainties. This model was effective in developing guidance for principal design criteria for non-LWR reactors and could be used to create guidance for advanced fuel concepts, micro reactors, and other cross-cutting regulatory topics.

Challenge 3: Inadequate, and in some cases nonexistent, fuel supply chain.

A reliable, secure nuclear fuel supply chain enables on-time deployments of nuclear reactors and uninterrupted operations over several decades. However, the current fuel supply chain is challenged by several factors, leading to investment risk. Currently, the United States relies on Russia for 24% of its low-enriched uranium (LEU) supply, making this a critical vulnerability in the nuclear fuel market. The Prohibiting Russian Uranium Imports Act of May 2024 bans Russian uranium products, with limited exemptions through 2028. With this ban, there is now even greater emphasis on bolstering the domestic fuel supply chain to ensure energy security. This ban unlocks $2.72 billion in appropriations (enabled by the Consolidated Appropriations Act of 2024) to support new domestic low-enriched uranium (LEU) and/or high-assay LEU (HALEU) supply chain development. Deployment of new domestic LEU production will take time, leaving the U.S. at risk if Russia retaliates by accelerating a cutoff of supply. Deployment of domestic HALEU production at commercial scale is starting from scratch, as there are currently no commercial suppliers outside of Russia and China. The U.S. needs a fully domestic fuel supply chain to support nuclear national security requirements, including LEU for tritium production, high enriched uranium (HEU) for naval reactors, and HALEU for research and demonstration reactors. Current international agreements restrict the use of non-U.S. enrichment technology to serve U.S. national security applications. Consequently, national security needs require fuel supply technologies, as well as uranium, that are U.S.-designed, manufactured, and sourced. Currently, no U.S.-based enrichment facility operates at scale to meet these needs, posing risks to future nuclear national security fuel supplies. Building new domestic enrichment capacity utilizing domestic uranium feedstock and U.S. enrichment technology offers the opportunity to address both national security requirements and the growing SMR fuel supply chain.

Policy recommendation: Congress should take one action, while DOE's Office of Nuclear Energy (NE) should focus on another. Congress should mandate that all new nuclear fuel supply contracts post-2028 include a portion of fuel eligible for national security purposes, with additional appropriations covering any associated premiums. Ensuring an independent, domestic nuclear fuel supply chain based on U.S. technologies is critical not only for energy security but also for maintaining the integrity of national defense systems that rely on secure, uninterrupted access to nuclear fuel. The United States has a strategic interest in using a portion of its fuel for both civilian and national security needs. While allied and domestic supply can address much of the civilian demand, only U.S.-based facilities using domestic enrichment technologies can meet national security requirements under current international agreements. These U.S.-based facilities are limited in number. To kick-start this supply chain without passing along premiums to customers, some of the $2.72 billion made available due to the Russian import ban could cover the price difference of domestically sourced fuel through a cost subsidy mechanism (e.g., contract-for-difference), or possibly via the Defense Production Act. By building U.S. enrichment capacity that in part employ U.S. technology and ensuring fuel contracts prioritize national security requirements, the United States can create the commercial conditions for long-term energy security while harnessing innovations. Finally, NE should explore a contract-for-difference option for HALEU appropriations, paired with a domestic supply mandate, to maximize the impact of limited federal funding made available through the Consolidated Appropriations Act of 2024 for such purposes.

Challenge 4: Lack of a clear national pathway for spent fuel.

As clean energy and energy security ambitions converge with increasing electricity demand, support for nuclear energy facilities now outweighs opposition. However, spent nuclear fuel (SNF) management remains a concern for the public and other stakeholders, adding uncertainty for SMR developers and investors. SMRs, whether Gen III+ or Gen IV, still ultimately require geological disposal of spent nuclear fuel. Additionally, some spent fuel stream generated by Gen IV designs might be significantly different from those generated by existing nuclear reactors, creating some uncertainty surrounding long-term storage approaches. While current disaggregated interim storage protocols suffice for now, long-term solutions will be necessary as the nuclear industry scales.

Policy recommendation: Congress should take four actions to address SNF management. First, amend the Nuclear Waste Policy Act to allow consolidated interim storage to be constructed before permanent geological disposal, streamlining DOE's interim storage facility process. Federal law restricts construction of federally owned consolidated interim storage facilities until substantial progress is made on a permanent repository, though planning efforts are allowed to continue. Privately owned facilities, while legally permitted to proceed with siting and construction if licensed by the Nuclear Regulatory Commission, often face political and legal challenges at the state and local levels that can significantly delay or impede progress. The recommended separation between permanent disposal and interim storage would enable current work on interim storage to be accelerated. Second, establish dedicated escrow or trust accounts for new SMR developments to set aside funds for SNF disposal, addressing the current lack of financial provision. Third, create a specialized SNF management office either within DOE or within a quasi-government spent nuclear fuel management corporation to streamline operations and ensure continuity across administrations. Fourth, explore regional approaches to consolidate interim storage, and expand SNF research to reduce transportation burdens and enhance political support.

Challenge 5: Community-level social license to operate

Project developers seek communities that support not only the nuclear plants but also the upstream and downstream infrastructure such as SMR component manufacturing, fuel fabrication, and spent nuclear fuel facilities. Capital providers, such as commercial lenders and private equity firms, are reluctant to invest in new nuclear projects if communities have a negative view of SMRs. Many institutional investors now consider social impact in their portfolio criteria. Therefore, understanding specific communities' perceptions of hosting SMR facilities, rather than generalized public opinions, is crucial for bankability. Realistically, facilities will not be deployed if communities are not interested in hosting them.

Policy recommendation: To scale nuclear energy significantly, host communities and the broader public must be well-informed and actively engaged. The Secretary of Energy should create a new office within the department focused on gathering, producing, and conveying accessible, accurate, and reliable information to the public. This office can likely be established without an act of Congress. It would be adequately staffed to engage with energy communities, existing nuclear communities, and those interested in hosting new nuclear facilities. This office would expand upon the current efforts of the Gateway for Accelerated Innovation in Nuclear (GAIN) at Idaho National Laboratory. It would coordinate with relevant national laboratories, the Office of Energy Justice and Equity, the Office of Nuclear Energy, the Office of Clean Energy Deployments, the NRC, the White House Office of Science and Technology Policy, and the Environmental Protection Agency. The office would also collaborate with impartial nuclear experts, project developers, academia, and communities to create a comprehensive SMR community engagement database. This database should build on existing GAIN materials and provide accessible information on sites, costs, risks, benefits, reactor technologies, safety, and environmental data for a lay audience. Integrating DOE resources, international agencies and credible NGO inputs into this user-friendly platform will enhance transparency and trust. Of course, there is a key role for project developers. Project developers should integrate SMRs into broader economic development strategies, collaborating with both new and established industries to secure sustained social and economic advantages for host communities. Before publicly announcing projects, developers should engage with diverse local stakeholders to comprehend and align with the community's desired development trajectory.

The Emerging Investment Case for Nuclear Energy

Supporting the scale-up of new domestic nuclear deployments and capabilities is in the national interest of the United States because nuclear energy can fulfill multiple security, resiliency, reliability, and decarbonization goals. Nuclear reactors produce large quantities of clean, firm power in a relatively compact footprint; are capable of greater than 95% capacity factor operation; and new and evolutionary reactor designs incorporate notable passive safety features.

From a decarbonization perspective, a U.S. Department of Energy (DOE) analysis indicates that achieving net zero by 2050 requires more than 200 gigawatts (GW) of new nuclear capacity in the United States.[1] This is two times larger than the existing fleet and must be built in 20 years. It took 65 years to build the existing nuclear fleet. Global energy scenarios also indicate that nuclear energy is essential to reach net zero.[2,3,4]

The United Nations' Intergovernmental Panel on Climate Change (IPCC) calls for 1,160 GW of nuclear electrical capacity by 2050 to align with the 1.5°C target[i] compared with the 394 GW of operating global capacity in 2020.[5]

At the 28th Conference of the Parties to the United Nations Framework Convention on Climate Change (COP28) in December 2023, 25 countries (including the United States) signed a Declaration to Triple Nuclear Energy by 2050 as part of an overall decarbonization strategy.[6] Taken together, the world needs to deploy 50 GW of new nuclear per year, which is 50% greater than the peak year of deployment experienced in the early 1980s.[7]

From an energy security perspective, concerns driven by Russia's invasion of Ukraine have motivated governments to reconsider nuclear in their national energy strategies. In June 2022, the European Parliament voted to include nuclear activities in the EU sustainable finance taxonomy. France, the United Kingdom, Japan, and South Korea have launched plans to restart, build new, or reverse the phaseout of nuclear plants. At the same time, countries (including the U.S., with the passage of the Prohibiting Russian Uranium Imports Act of 2024) are also making efforts to secure existing and future nuclear supply chains given the dominant share of state-owned Russian and Chinese suppliers in the international nuclear energy market. Currently, 58 nuclear reactors are under construction in 17 countries; 46, or about 80%, of these reactors are of Russian or Chinese origin.

From an energy demand perspective, the United States expects significant growth in electricity demand due to recent surges in data center development, manufacturing capacity expansion, and an overall shift to electrification of transportation, heating and some industrial processes, and possibly others, such as a major buildout of a clean hydrogen economy.[8] The Federal Energy Regulatory Commission's 2023 nationwide forecast of electricity demand grew from 2.6% to 4.7% over the next five years, representing at least 38 GW of new summer peak electricity demand to come on line through 2028.[9] Even these projections are likely underestimating the actual load growth, namely because of anticipated growth in data centers that is not yet reflected in projections.[10] Globally, the International Energy Agency forecasts energy demand growth to accelerate to an average of 3.4% from 2024 through 2026, compared with 2.2% growth in 2023.[11]

Taken together, the domestic and international demand for nuclear is massive. U.S.-based technology, capital, and expertise could play a substantial role in meeting this demand. Existing commercialized nuclear technology (e.g., fission reactors using water as a nuclear reaction moderator and coolant) is already proven, having been successively refined since the first commercial power plant started generating electricity in 1958 in the United States. Currently, there are 93 operating commercial nuclear reactors at 54 power plants in 28 states.[12] The average reactor size is about 1 GWe, and nuclear power plants account for about 18% of the nation's electricity generation, which is by far the largest source of emissions-free power.[13]

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i Refers to the Paris Agreement target of limiting global average surface warming of 1.5 degrees Celsius above pre-industrial temperatures.

However, over the past 40 years, the construction of these large-scale facilities has been mired in significant cost and schedule overruns. Increasing safety requirements and licensing delays during a period of rising interest rates greatly impacted nuclear project costs in the late 1970s and early ’80s. Lack of standard designs, greater construction complexity, relative loss of skilled management and labor capabilities, and changing electricity market conditions have reduced the demand for new nuclear and the ability to deliver it economically. The United States is not alone. Peer Western nations including Finland, the United Kingdom, and France have experienced the same, which has led some studies to conclude that the construction cost of nuclear reactors experiences negative learning rates.[14] Meanwhile, Russia, China, South Korea, and newcomers like the United Arab Emirates have maintained and grown their ability to build traditional nuclear plants.

Yet there is hope. The United States has tremendous research and development (R&D), regulation, project management, construction and operations, maintenance, decommissioning, and spent fuel management capabilities in nuclear energy.

For example, Vogtle Units 3 and 4—the first nuclear plants built in this century, after a multi-decade hiatus—experienced a number of workforce, supply chain, and licensing challenges to reach operation. This included the development of a nuclear construction workforce on a scale previously nonexistent in the United States. With more than 9,000 workers on-site during peak construction, thousands of civil, electrical, mechanical, piping, and instrumentation personnel have been trained and obtained real construction experience.[15,16] Even when new nuclear builds were halted, nuclear workforce development and maturation continued through the extension of existing nuclear plants.

The United States has tremendous research and development, regulation, project management, construction and operations, maintenance, decommissioning, and spent fuel management capabilities in nuclear energy.

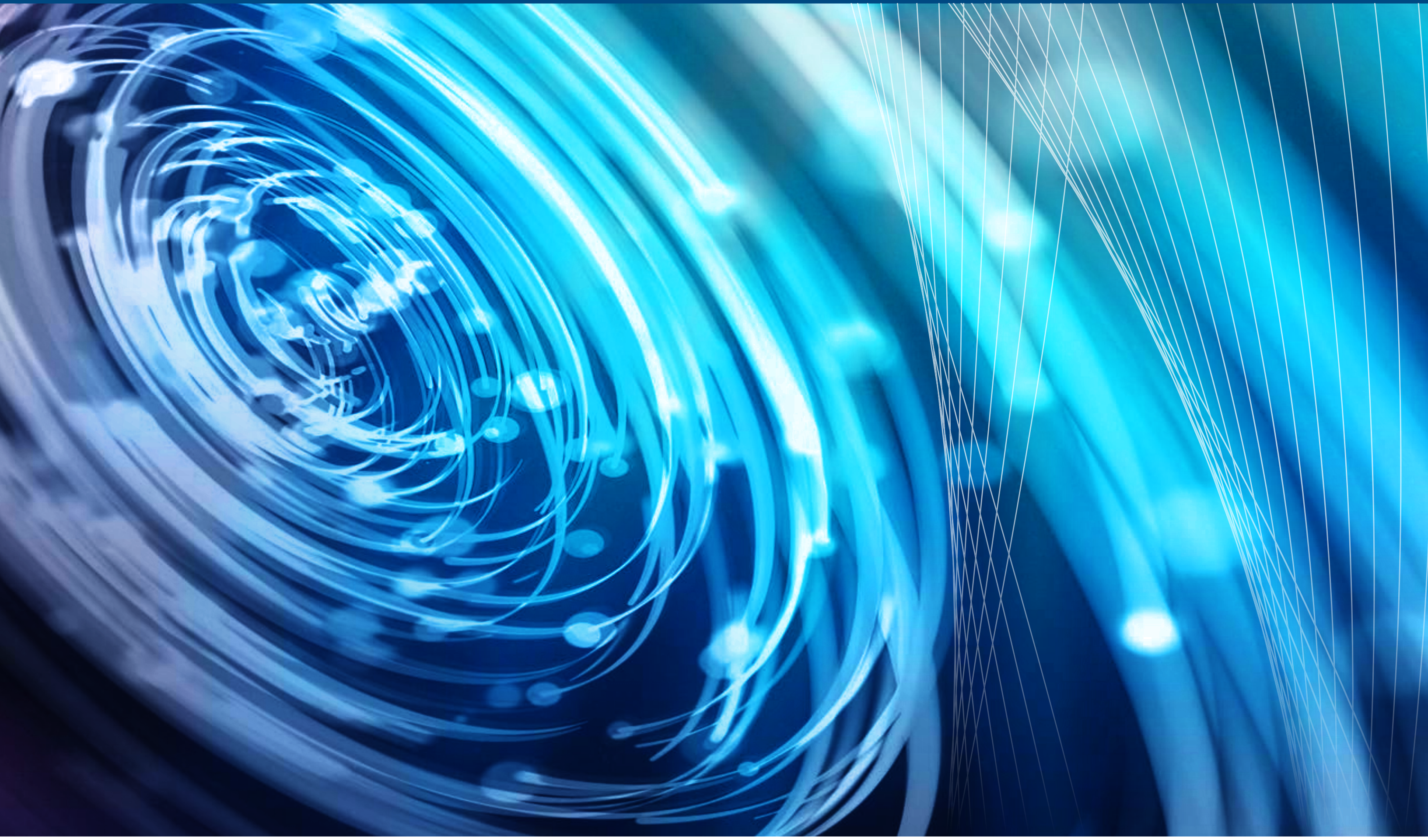
The Nuclear Regulatory Commission (NRC) approved license extensions for 61 plants between 2000 and 2019, with three additional plants under review.[17] Additionally, Holtec has ambitions to restart the Palisades Nuclear Plant in Michigan with assistance from a $1.5 billion loan from DOE, marking the first time a permanently closed reactor would restart, providing an opportunity to enhance the U.S. nuclear knowledge base.[18]

Further, durable federal R&D funding has bolstered a pipeline of innovations and a next generation of nuclear reactor designers and engineers in the United States. The innovations include the development of new reactor types, accident-tolerant fuels, and advanced construction methods. The Advanced Reactor Demonstration Program (ARDP) is supporting the demonstration of two full-scale Gen IV commercial reactors and the development of eight other small modular reactor designs. Entities such as the Gateway for Accelerated Innovation in Nuclear (GAIN) and the National Reactor Innovation Center (NRIC) support technical, economic, and regulatory risk reduction by providing industry with funds and access to National Laboratory capabilities.[ii]

Because of the anticipated demand for new nuclear and the vast capabilities the United States possesses, it is strategically important to motivate capital providers to invest in industrial expansion. There is increasing interest in nuclear energy from the private sector as a viable approach to addressing important issues including: the clean energy needs posed by decarbonization policies, energy security concerns, spurring economic development, and maintaining energy reliability and resiliency.[19, 20, 21, 22] In October 2024, Google signed a cooperative agreement with SMR developer Kairos Power, while Amazon invested in SMR developer X-Energy and signed two agreements with utilities pursuing SMRs.[23, 24]

Further, public opinion on nuclear energy has shifted, especially in the United States and Europe. Support for nuclear far outweighs opposition, even in nations that are perceived to be strongly against the technology (such as Germany).[25] One kind of nuclear energy technology—small modular reactors—is of particular interest, and there is capital waiting on the sidelines ready to be deployed under the right conditions.

ii GAIN distributes quarterly voucher awards that provide laboratory access to industry for specific projects. The National Reactor Innovation Center (NRIC) provides end-to-end assistance in the construction and demonstration of advanced reactor systems, giving access to demonstration infrastructure and assistance with site preparation, fuel fabrication, and risk reduction. For example, one NRIC focus is to reduce construction risk for new reactors by 2025 via demonstration of three advanced construction technologies.



A New Vector of Growth: The Promise of SMRs

Small modular reactors (SMRs) are a promising form of nuclear energy technology. SMRs are a pathway to harnessing the technical capabilities of nuclear energy and packaging that into a bankable, commoditized product, similar to large, factory-built products like airplanes and gas-fired turbines.

SMRs alter the business and delivery model of traditional nuclear. Rather than bespoke, stick-built, complex, large nuclear reactors relying on economies of scale to drive cost efficiency, SMRs are smaller in size and fabricated in factories using modular, standardized components. Cost reductions are driven through “economies of series,” in which product costs are reduced as a result of learning-by-doing through repeated builds. Repeat builds using standardized, modular components is an approach used in solar panel and battery module manufacturing to accumulate experience and drive down costs. Many projections of nth-of-a-kind (NOAK) SMRs forecast cost-competitive facilities as a result of accumulated know-how across the supply chain, manufacturing, and construction/installation.

SMR designs are typically less than 300 megawatts electric (MWe), lowering the upfront total investment compared to large reactors (e.g., 1 GWe) and enabling fit-for-purpose deployments. While some SMR designs take the latest existing nuclear technology and effectively "shrink" it down to a smaller capacity (i.e., Gen III+), other designs—many of them based on technologies first developed in the 1960s and 1970s—use advanced coolants, moderators, and fuels. These so-called Gen IV reactors expand the market breadth and depth for nuclear energy, as most of these "advanced" reactors are able to generate higher-quality heat useful for decarbonizing processes in the chemicals, oil and gas, and steel industries (in addition to their ability to produce electricity).

SMRs alter the business and delivery model of traditional nuclear. Rather than bespoke, stick-built, complex, large nuclear reactors relying on economies of scale to drive cost efficiency, SMRs are smaller in size and fabricated in factories using modular, standardized components.

In general, Gen IV SMRs are expected to have improved thermal, fuel, and water efficiency compared with Gen III+ designs.[iii] While many SMR designs use low-enriched uranium (LEU) very similar to that used in reactors operating today, some of the Gen IV reactors require high-assay low-enriched uranium (HALEU), a fuel type that employs a higher enrichment level than LEU and one for which there is currently no domestic supply. Crucially, both Gen III+ and Gen IV designs take advantage of decades of safety advances that essentially eliminate the risk of incidents like those experienced at Three Mile Island, Chernobyl, and Fukushima.

Taken together, the (1) promise of rapid cost reductions through accumulated learning effect, (2) ability to "right-size" deployments, (3) expanded market breadth to include both power and heat, and (4) augmented safety case have raised interest in SMRs among a variety of potential customers and capital providers.

iii The reactor environment and operations of Gen III+ designs are quite similar to that of a large LWR, thus do not typically boast these same advantages.

Economies of Series: From Single Projects to an Orderbook of Products

SMRs promise substantial cost reductions through learning effects from repeated construction and the inherent efficiency of using standardized parts in a factory setting. Further, off-site product manufacturing provides workforce stability and training benefits compared with prolonged on-site construction, which in turn enhances learning effects.

Yet in terms of cost efficiencies, there is an inherent trade-off between traditionally built, large-scale nuclear reactors and their SMR counterparts. The capacity of nuclear plants increased soon after smaller research reactors validated the technology in the 1950s. Reactor sizes grew from more than 500 MWe in the early 1960s to consistent orders for 800 to 1,100 MWe by 1969.[26,27] Progress from early demonstration reactors between the late ’50s and late ’60s suggested increased capacity size would favor reactor economics. Costs dropped from a high of $6,800 per kilowatt (kW) to a low of $1,300 per kW as reactor size increased from under 80 megawatts (MW) to 620 MW. [28]

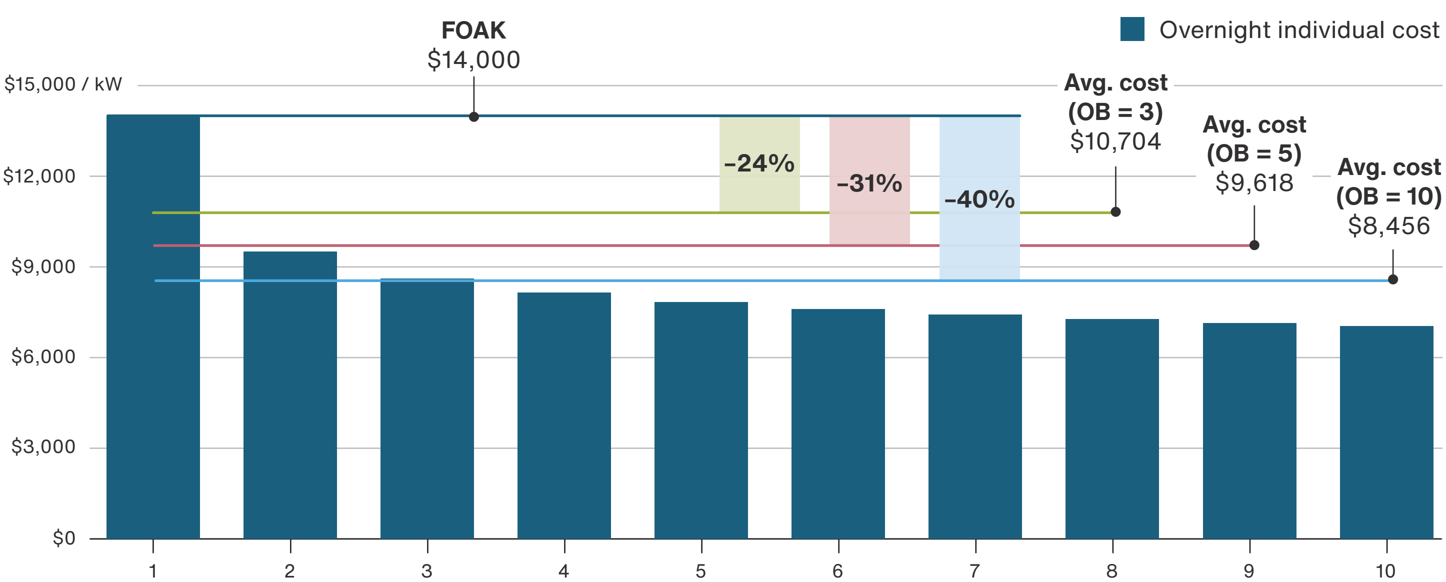
The logic behind the march toward larger and larger capacities is straightforward: Like other industrial processes, larger facilities benefit from economies of scale. Economy of scale is predicated on the notion that there are proportionate savings in costs gained by increased levels of production. In the case of a traditionally built nuclear power plant, the cost of energy produced per unit of capacity (based on initial cost estimates) will decrease over time. While theoretically true and in large part validated by builds in the United Arab Emirates and South Korea, for example, the larger capacity has led to design, project management, and construction complexities that have caused significant cost and schedule overruns in the United States and its Western peers.[29] This was driven by the relative “lumpy” deployment cadence of nuclear energy (e.g., two new reactors in United States in the last 30 years), leading to a degree of “institutional forgetting” as capacity to execute these complex projects has waned.

SMRs are by definition “small” relative to the GW-scale traditional nuclear power plant footprint. While some technological advances reduce the unit cost disadvantage, at least initially, SMRs could be less cost efficient on a unit basis. However, it would be incorrect to compare one GW-scale plant to an SMR on a unit cost basis, because that would neglect the concept of economies of series. Similar to what has been observed in solar panels, wind turbines, and lithium-ion batteries, cost reductions are achieved through learning-by-doing in a manufacturing environment. Essentially, as experience and knowledge are accumulated through performing the same tasks using the same components, costs will decrease as the number of units built increases. SMRs are designed to take advantage of this approach to cost reductions.

Crucially then, for SMRs to achieve their promise of cost-competitiveness and become a viable clean energy solution, the unit of analysis must shift from a single plant to an "orderbook." An orderbook is defined as firm commitments for multiple, identical installations of a particular design. While the first-of-a-kind (FOAK) and second-of-a-kind (2OAK) builds may be relatively costly, the anticipated learning effects should reduce costs with successive builds (Figure 1).[iv,30] Cost reductions from multi-unit efficiencies and learning have been demonstrated in successive large nuclear builds on the same site, such as with Barakah Units 1-4 and Vogtle Units 3 and 4. Barakah Unit 1 had a capital cost of $5,452/kW compared to $2,300/kW for Unit 4.[31] The commissioning of Vogtle 4 occurred in approximately 30% less time than Vogtle 3.[32]

Indeed, DOE called for an initial mass of five to 10 deployments of one reactor design for suppliers to make capital investment decisions. Moreover, given that SMRs promise to be largely manufacturing-based, the facilities to fabricate and assemble the plants and their components will largely need to be built. A robust demand signal from an orderbook is needed to induce the capital deployment for this upstream value chain. In a sense, an orderbook is the locus from which an industry can be formed.

Figure 1: **ILLUSTRATIVE SMR CAPITAL EXPENDITURE (CAPEX) COST TRAJECTORIES FOR ORDERBOOKS OF DIFFERENT SIZES**



Note: OB refers to the number of reactor builds per orderbook (e.g., OB = 5 denotes an orderbook of five reactor builds of a single design). While FOAK costs are relatively high, subsequent installations could have meaningful cost reductions because of supply chain maturity, manufacturing efficiency, workforce development, serial deployment, and investor comfort leading to lower costs of capital, among other factors. The average cost per installation decreases as orderbook size increases, given the subsequent cost reductions through learning effects. This orderbook approach has the effect of removing the first-mover disadvantage. Data from: See first figure mention in text for source.

iv For cost assumptions, please refer to Moniz et al. in indicated citation.

This orderbook concept is employed in the aviation industry, where multiple airlines create a trajectory of future purchases of aircraft of a specific design. For example, from November 2022 to March 2023, Boeing received orders from Air India, United Airlines, and two Saudi airlines amounting to approximately 200 787 Dreamliners to be delivered in the coming decade.[33] Such demand certainty not only motivates aircraft manufacturers to invest in the necessary, costly facilities to produce the airplanes, but also enables the spread of capital recovery over a relatively large number of units, thereby reducing unit prices to airlines.

Modularity: Innovation driving the SMR orderbook business model

The core innovation in SMRs that drives a new business model and the focus on the orderbook to kick-start and maintain the industry is modularity, or modularization. Two types of modularity are relevant for nuclear development. The first, market modularity, can allow for the aggregation of reactor units (built in series or partly in parallel, mitigating investment risk) to establish a larger nuclear plant. This can remove redundancies in regulatory approvals, design, and construction site mobilization, and take advantage of more durable demand signals.[34] From a bankability perspective, market modularity offers the prospect of lower total capital invested in any one year, compared with large-scale reactors, which bring in revenue more quickly because of their shorter deployment schedules. As a result, SMRs will accumulate less interest during construction, which will lower total capital costs, and they may attract lower-cost capital via lower interest rates once they are at commercial maturity.[35] Market modularity and the orderbook approach also lend themselves to new opportunities for financial risk sharing among a set of project proponents such as offtakers; manufacturers; engineering, procurement, and construction (EPC); and technology vendors.

The second type of modularity that is relevant for nuclear development, production modularity, can support the use of prefabricated modules with final assembly at the actual site. This can reduce costs and allow for faster project delivery.[36,37] Market and production modularity are intertwined, with the key driver being the key enabler of the SMR business model.

If SMR industry scale-up depends on an orderbook that aggregates enough demand to drive cost reductions to NOAK through accumulated experience, it is important that successive builds are identical or nearly identical. This is necessitated by—and is a benefit of—factory-built SMRs, which are built using processes that produce and assemble standardized parts in a controlled environment. This production modularity reimagines nuclear plant construction, breaking down the whole plant into several standardized modules, allowing for factory fabrication off-site and minimal on-site construction and assembly.[38,39,40]

It is production modularity that drives an economy of series, on the promise of offsetting the loss of economies of scale. However, this claim is dependent upon SMR design, degree of modularity, and advancements in—and the acceptance of—manufacturing technologies of both nuclear and structural components.[v,41,42,43,44,45,46] Benefits of production modularity include reduced capital costs along four dimensions versus bespoke, stick-built nuclear reactors:

Reduced component cost through (1) advances in manufacturing of both nuclear and structural components, and (2) increases in quality and quality assurance because components are produced and assembled in a controlled environment.

Reduced labor cost through increased workforce productivity by leveraging common processes, tools, and manufacturing methods reduces total number of laborers. Since building smaller reactors requires a smaller workforce, staffing limitations are less likely, reducing the risk of schedule delays.[47] Further, the total absolute cost of delays is estimated to be significantly lower and poses less financial risk. Large reactors commonly experience schedule delays when the project cannot hire enough skilled workers, as the Vogtle project experienced. In addition, obtaining skilled labor in a factory setting is simpler than acquiring a large team on-site, particularly in remote locations. However, labor benefits are contingent upon a continuous pipeline of nuclear projects with a relatively steady development cadence, rather than isolated projects. This is necessary to sustain on-site and factory workforces and talent pools. For example, South Korea has emerged as a world-class designer and constructor of nuclear reactors largely because it routinely has been deploying nuclear reactors domestically and abroad for more than 40 years.[48]

Reduced interest during construction (IDC) due to schedule compression, a result of increased labor productivity and reduced occurrence of rework due to increased quality assurance. Traditional nuclear projects require five to 15 years to construct, and expenditures throughout the project accrue interest until the asset begins generating revenue; this is IDC.[49] IDC is one of the largest cost components of a new nuclear plant.[50] For example, assuming a 5.9% borrowing rate and an 80% debt-to-capital ratio, the IDC would account for a 13% increase in the overnight cost for a four-year project, whereas IDC would add 31% for a 10-year project.

Tasks performed in parallel rather than sequentially at plant site. Factory fabrication of modules reduces expensive and time-consuming on-site construction and enables greater standardization. The standardization of modules enables suppliers to replicate production in a highly controllable and efficient factory environment, leading to stronger and faster learning. The learning rate of the SMR industry could be 5% to 10% higher than the estimated 1% to 5% learning rate of large reactors, depending on the degree of modularity and factory fabrication, design standardization, consistency of delivery chain, and regulatory environment.[51,52,53]

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v Degree of modularity refers to the number of components that can be manufactured and assembled within a factory setting and then transported to a site and installed. A higher degree of modularity connotes a higher proportion of SMR components that are factory-built and assembled.

Production modularity through factory fabrication also may allow for diffusion of advanced manufacturing (AM) techniques over time, such as electron beam welding, powder-metallurgy hot isostatic pressing, diode laser cladding, and additive manufacturing.[54,55] AM aims to enhance the performance of large nuclear power plants (NPPs) and improve industry's ability to manufacture SMRs, reducing the overall cost and schedule without sacrificing quality or performance.[56,57]

For SMRs in particular, AM may be used for equipment that fulfills safety functions and forms integral parts of the reactor pressure vessel (RPV).[58] While these same AM techniques have been deployed in other industries such as aerospace, implementation in nuclear has been limited because of the different regulatory requirements and material properties.[59] A number of nuclear developers are examining AM for their projects, including, among others, NuScale, Framatome, Westinghouse, and Siemens.[60] NuScale's AM program, supported by both DOE and the U.K. government's Nuclear Advanced Manufacturing Research Centre, aims to demonstrate a 40% reduced manufacturing cost of a NuScale SMR RPV and a build time under 12 months.[61]

Modularity in other industries and application to SMRs

The production modularity promised by SMRs is not new. Techniques used to manufacture and assemble structural and process components have been used in the oil and gas and chemical industries for decades. Many of the lessons learned in those industries can directly apply to or inform SMR design, manufacture, and installation.

Modular projects can have cost savings of 20%, partly because of notable reductions in project schedules.[62,63] A literature review of modular projects across several industries found schedule savings between 40% and 50%.[64] One analysis found that modular engineering concepts can save up to 10% of the total cost of a facility, cut on-site labor by 25%, and reduce the working area by 10% to 50%.[65] Cost savings are also gained through the quality assurance available in a factory setting.[66] Obtaining a high degree of quality assurance is essential for nuclear construction given the strict regulations surrounding nuclear safety components. For example, the nuclear island (including the containment and reactor vessel) is a highly sensitive aspect of the plant. The quality standards are high, the tolerances are tight, fabrication must abide by specific regulations, and fabrication methods must be thoroughly inspected.[67]

Module size and weight are critical parameters that may greatly influence project costs. Component size and weight drive fabrication costs.[68] These parameters also create ripple effects across almost every other project interface. For example, heavier modules increase shipping costs and require larger crane lifts for transport. In offshore oil and gas projects, large crane lifts can account for up to 10% of the cost.[69] If larger modules do not fit within the size and weight constraints of shipping containers, disassembly may be necessary for transport, which increases on-site or near-site assembly and, thus, labor costs.[70] SMR developers must carefully consider the size and weight of components and assemblies, balancing the economies of scale from higher-capacity reactors with the constraints during project execution that may limit modularity.

Precast concrete offers the possibility of significant reductions in capital cost, labor, schedules, and rework. Precast concrete, manufactured and cured off-site, would avoid high-volume, on-site concrete pours and instead allow for the assembly of modular, standardized concrete pieces. Use of precast concrete in other industries, like chemicals and oil and gas, have reduced construction costs for various facilities through shorter schedules and fewer delays.[71] The production of precast modules off-site also enables construction activity to occur simultaneously and increases flexibility, because damaged modules can be replaced with copies.[72,73] Limiting the use of traditional concrete mixes and opting for advanced, prefabricated modular concrete has been identified as a best practice for nuclear power plant delivery.[74]

The traditional nuclear industry uses a large amount of continuous volumetric pours of high-rebar-density concrete, which are prone to logistical challenges and costly errors.[vi,75] Many of the plants undergoing construction have experienced substantial schedule delays and cost overruns related to errors during the pouring and curing of concrete.[76] Nuclear concrete requires certification and testing for the entire supply chain, from raw materials to the trucks that carry concrete, as well as strict quality assurance standards that must be met before, during, and after the pour.[77] This requires considerable personnel, equipment procurement, and preparation.[78]

In transitioning from stick-built to modular construction, the costs associated with design and engineering are typically higher, especially for the first project. Modular projects require more upfront design than traditional projects, as more of the end-to-end manufacturing and construction processes must be detailed earlier in the project life cycle. Further, designers of FOAK projects must learn and adjust based on the manufacturing process.[79] Engineering costs for the first modular construction project are usually higher because of this inexperience. In some cases, first projects are 50% to 60% more expensive than conventional construction design.[80,vii] This illustrates the importance of high-quality front-end engineering and design (FEED).

Modularity places a greater emphasis on the interdependency of activities, the complexity of planning and interface handling, and lack of adaptability to variations.[81] Detailed FEED studies demonstrate the actual required space for certain project components, such as piping, in comparison with the early design assumptions.[82] A low-quality FEED study of an offshore oil and gas platform, for example, led to size and weight updates for the entire platform later in the project, impacting all the work that already had been completed.[83]

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vi For example, the AP1000 requires a 5,400 m3 41-hour continuous concrete pour that must meet strict quality assurance standards. Errors related to concrete during construction of Vogtle 3 lead to cost and time delays.

vii This illustrates the need for multiple builds of the same design. While relatively more effort is put into the design of the first builds, this is more than offset by subsequent builds where standardization and complete designs allow for much simpler “repeat” builds. This is the case for any manufactured product.

Policy Actions to Date Supporting SMRs

Over the last five years, Congress and the executive branch have taken actions to promote SMR investments by revising existing policies and introducing new ones.

The Inflation Reduction Act (IRA), which was signed into law in mid-August 2022, was the most important policy action. It significantly reduced the capital cost of new SMRs. The clean electricity investment tax credit—26 U.S. Code §48E (48E)—provides a technology-neutral tax credit for investment in facilities that generate clean electricity. Subject to labor and prevailing wage requirements, its base value is 30%. A 10% bonus for domestic content requirements is available, and so is an additional 10% for siting an SMR project within a defined energy community. Therefore, up to 50% of the capital cost of an SMR project can be reduced through the application of this tax credit.[viii,ix]

Congress has supported SMR technology demonstrations through several actions. The ARDP, which was authorized in the Energy Act of 2020 and funded in the Infrastructure Investment and Jobs Act (IIJA) and IRA, dedicates $5.6 billion to move 10 SMR designs of varying maturity toward demonstration.[x] Most notably, DOE awarded a combined $3.2 billion to demonstrate TerraPower's Natrium ($1.97 billion) and X-Energy's Xe-1000 ($1.23 billion) by 2028.[xi] These demonstrations are full-scale commercial reactors. Positive spillovers from the design work, licensing activities, supply chain development, construction, workforce development, and operation from these demonstrations are expected to reduce risks for future SMR projects.

The Consolidated Appropriations Act of 2024 repurposes $900 million of existing funds from the IIJA to support the demonstration of up to two Gen III+ SMRs.[84] Importantly, the Office of Clean Energy Demonstrations' recent Notice of Intent to award these funds indicates ambitions to incentivize not just one reactor build per award, but, ideally, an orderbook of SMRs.[85]

There is considerable congressional interest in securing and expanding the domestic nuclear fuel supply chain. The HALEU Availability Program (HAP) invests $700 million to support the buildout of a domestic supply chain for

viii Instead of a tax credit, tax-exempt organizations, states, political subdivisions, the Tennessee Valley Authority, Tribal governments, Alaska Native Corporations, and rural electricity co-ops are able to receive direct pay, or simply a cash refund.

ix While a 50% ITC is theoretically possible, it is far more likely that a 30% or 40% ITC would be achievable for a first orderbook of SMRs. The 30% ITC is the baseline value; the 40% ITC would be earned by achieving domestic content requirements on top of the baseline value.

x The ARDP allocated awards to the designers within three pathways: the Demonstrations Pathway, Risk Reduction Pathway, and Advanced Reactor Concepts Pathway.

xi Additionally, $600 million was awarded to five teams under the Risk Reduction Pathway, and $56 million was awarded to three teams for nuclear concept development.

HALEU, including $500 million to be used for procurement of HALEU enrichment and deconversion services and products.[xii] This $500 million may be further strengthened by the Nuclear Fuel Security Act of 2023 (NFSA), amended in the 2024 National Defense Authorization Act (NDAA).

NFSA (1) establishes a Nuclear Fuel Security Program that requires DOE to enter into at least two contracts to acquire at least 20 metric tons per year of HALEU by the end of 2027, (2) expands the American Assured Fuel Supply program, designed to ensure a reserve of nuclear fuel in the event of a supply chain disruption, and (3) establishes a program to ensure HALEU is available for the needs and schedules of developers within the ARDP.

The NFSA received $2.72 billion in appropriations in the 2024 Consolidated Appropriations Act, contingent upon the enactment of a law or administrative action to prohibit or limit importation of LEU and HALEU from the Russian Federation or by a Russian entity in the United States.[86] In May 2024, the Prohibiting Russian Uranium Imports Act was signed into law, banning the importation of uranium and LEU produced by the Russian Federation or Russian entities through December 2040. This law does offer a waiver option for domestic reactors or nuclear energy companies if the entity does not have near-term viable alternatives for Russian products. The waivers will expire, however, in January 2028 and are negated completely if Russia preemptively bans exports before that time.

Lastly, in July 2024 the Accelerating Deployment of Versatile, Advanced Nuclear Energy for Clean Energy (ADVANCE) Act was signed into law. The ADVANCE Act requires a number of regulatory reforms aimed at easing first-of-a-kind projects, improving international competitiveness, modernizing regulatory frameworks, and strengthening the regulatory workforce.

xii HAP was authorized in the Energy Act of 2020 and appropriated in the IRA. Funding is available through Sept. 30, 2026.

Challenges to SMR Bankability

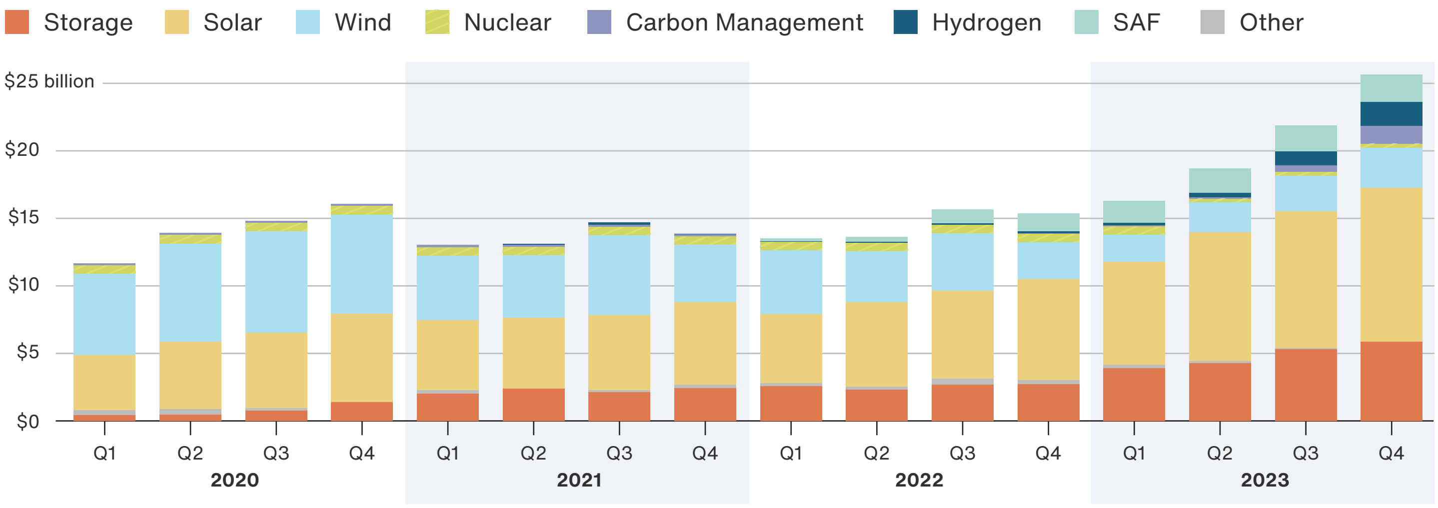
Despite all the pre-commercial activities and marketing announcements—as well as the research, development, demonstration, and deployment support through policy actions announced and implemented—a clear demand signal or material aggregation of project sponsors to begin the commercialization of SMRs in the United States has yet to emerge. There is a robust innovation landscape with more than 80 SMR concepts at various levels of maturity, but there are only four SMRs in advanced stages of construction, and none of them are in the United States. (Construction is happening in Argentina, China, and Russia.)[87] Even the Gen III+ reactors that are based on current technologies are considered FOAK, with no construction or operational heritage on which capital providers can base decisions, and strategic investors (e.g., data center operators, utilities, industrial companies) are wary of taking on these and other risks.

This lack of investment in nuclear energy in general and SMRs in particular puts it at odds with other forms of clean energy, namely solar, wind, and battery technologies. Of the total $72 billion in new actual investment in clean energy production and industrial decarbonization in 2023, utility-scale solar and storage investment accounted for $53 billion.[88]

Figure 2 throws into stark relief the level of investment in nuclear versus other forms of clean energy. Considering the state, federal, and corporate requirements

Figure 2: **ENERGY AND INDUSTRY INVESTMENT BY TECHNOLOGY IN BILLIONS OF DOLLARS, 2022**

Nuclear investment in general is much smaller than investments in other forms of clean energy. Moreover, almost all nuclear investment is focused on life extensions of existing reactors, rather than focused on development and construction of new capacity, including SMRs.



Source: See first figure mention in text for source.

for emissions-free energy and increasing demand for electricity, a strong investment case can be made for all forms of clean energy. [89] There is tremendous value in extending the life of existing nuclear power plants to provide clean firm power; this is the destination of most investment in nuclear energy in the United States. However, new nuclear energy, especially SMRs—which may be needed in the next decade to help address tremendous electricity load growth and decarbonization of hard-to-abate sectors—has yet to aggregate capital for at-scale deployment, despite the strong value proposition once they're built and operational.

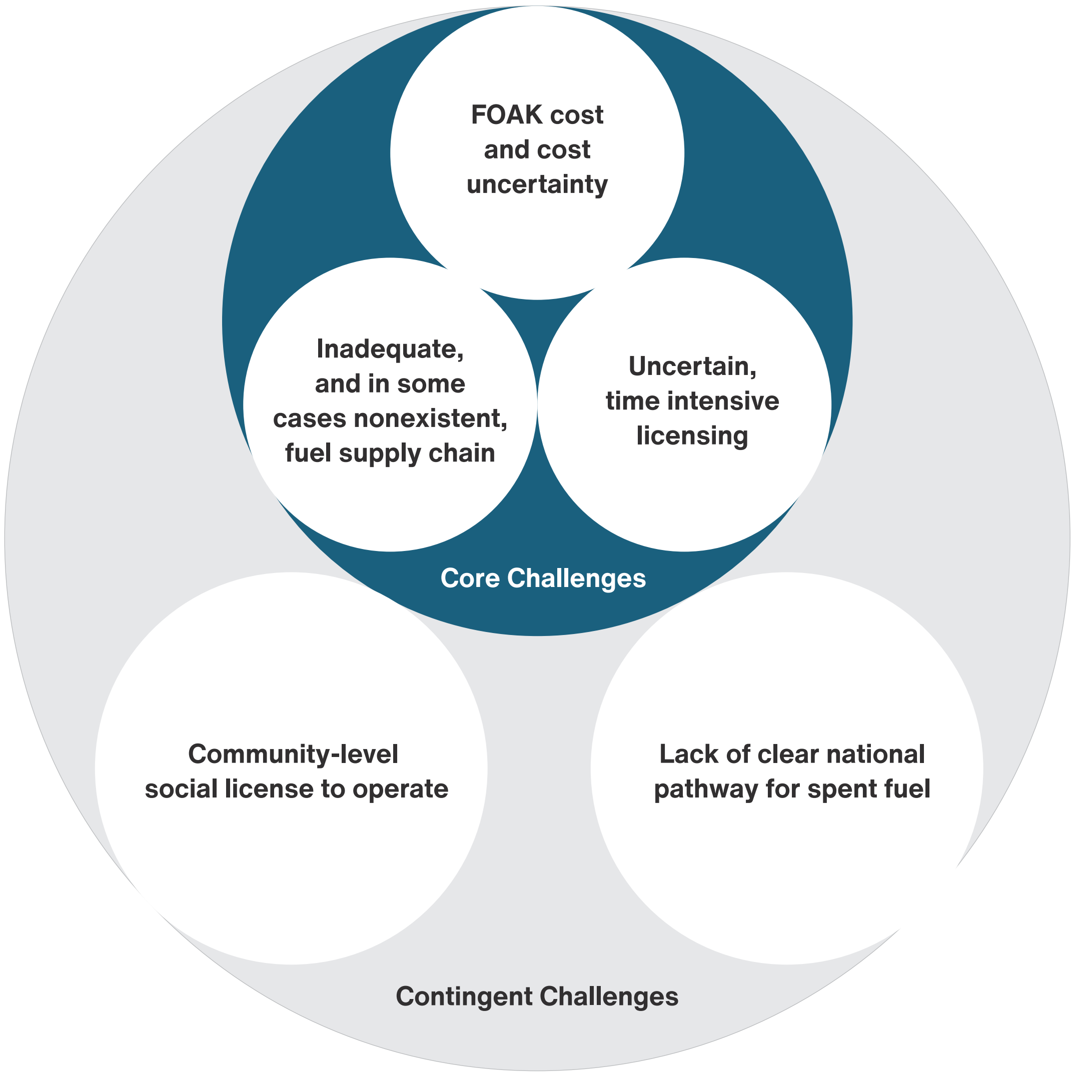
Indeed, it will take substantial capital provided by the private sector over a long time period to fund not only the construction of SMRs, but the investments needed in upstream supply chain and fuel resources. A workforce also will be needed to build the SMR industry alongside the existing large-scale nuclear ecosystem. However, there is reluctance among significant private sector capital providers such as project developers and strategic investors (e.g., electric utilities, large industrial loads, etc.) to fund SMR deployments because the technology class is currently not considered bankable. Specifically, there are significant risks associated with FOAK deployments. It is much the same with other energy technologies on the cusp of commercialization such as carbon capture, utilization, and storage; enhanced geothermal systems; and long-duration energy storage.

When assessing a decarbonization opportunity, the ultimate private capital decision-makers (e.g., capital commitment committees, investment committees, boards of directors) consider the project or investment itself, along with the interconnected upstream and downstream supply chain and customer base. These capital decision-makers use a broad set of criteria to determine the extent to which an investment strikes the right risk/reward balance according to their preferences and constraints. Central to this process is the identification and diagnosis of risks that exist along the entire value chain of an opportunity. If any one of these risks, wherever located in the value chain, is deemed too great given the expected returns, then the opportunity is rejected.[90]

This study identifies five challenges to SMR bankability; three core challenges and two contingent challenges. Core challenges constitute binary risks that if not addressed adequately will prevent commercial builds of a given SMR technology. While addressing the core challenges is necessary, doing only that is insufficient to make an SMR project bankable. Contingent challenges are those that may not be binding constraints for all SMR projects in the near team but must be addressed to attract sufficient capital to enable a thriving SMR industry longer term.

The core challenges include (1) FOAK cost coupled with cost uncertainty, (2) uncertainty surrounding new design licensing by the U.S. Nuclear Regulatory Commission (NRC), and (3) an inadequate, and in some cases nonexistent, fuel supply chain. The two contingent challenges are (1) the lack of a clear national pathway for spent fuel, and (2) difficulty in achieving a community-level social license to operate (Figure 3, next page).

Figure 3: **CHALLENGES TO SMR BANKABILITY**



Source: EFI Foundation.

The dual challenges of cost magnitude and cost uncertainty

The dual challenges of cost magnitude and cost uncertainty are the most salient impediments to FOAK SMR deployment.[xiii] The two concepts are interrelated. Despite their smaller size and modularity of certain standardized components and simpler design, FOAK SMRs are still capital intensive across Gen III+ and Gen IV designs.[91,92,93,94] At this stage, they are advanced concepts and prototypes on the cusp of commercialization.

xiii SMR designs generally have a power capacity of up to 300 MWe per unit (the "S" in SMR) and use standardized parts, thereby increasing manufacturing efficiency, and the finished reactors can be modularly configured into sets of installations to "right-size" a facility (the "M").

Given that there is little “real-world” validation of cost estimates, lenders and equity investors are wary of the economic viability of SMRs. Any lender, whether private or the federal government through DOE’s Loan Programs Office, is likely to require that project funding plans include some form of large and readily available financing reserves (e.g., cash, letters of credit, or funding availability) to cover unplanned costs. This adds meaningfully to the overall capital commitment. Even with such project cost buffers, there remains a material probability that FOAK costs will surpass engineering, construction, and procurement cost estimates, as experienced by Vogtle 3 and 4.

Even though the stick-built approach may ultimately be less competitive than the manufacturing-based approach envisioned for SMRs, there is a good chance that costs will exceed project budgets in the first few SMR installations because of their relative commercial immaturity. Indeed, developers, project sponsors, regulators, and shareholders have a legitimate worry that first-mover costs will be largely uncertain, which will strongly dissuade SMR development en masse. There is the specter of large, unforeseen FOAK project costs that could force abandonment if risks cannot be mitigated.

Experts and experience indicate that large cost reductions for SMRs of a particular design could occur both at construction sites and in the factory for 2OAK, 3OAK, and subsequent projects (collectively defined as “next-of-a-kind” or NXOAK)—but only if the first-mover disadvantage is addressed. That is, if nobody can be induced to accept the first-mover disadvantage, then there will be no NXOAK units.

If the FOAK is completed successfully, learning effects across manufacturing, procurement, and construction could begin to accumulate for subsequent builds. Presuming that the knowledge can flow from one developer to the next, developers of later units are in some sense getting a “free ride,” benefiting from, but not paying for, the first movers. The logical conclusion for would-be developers is to not be a first mover, thus leading to a holdup in which no development takes place because all developers hope to be “fast followers.”

Licensing challenges and regulatory uncertainty

Deployment of design, fuel, safety, and construction innovations depends on regulatory approval during licensing. Through the licensing process, the NRC evaluates new reactors to ensure an SMR design meets public safety, security, and environmental requirements. If a review is successful, the NRC authorizes an applicant to construct, operate, and decommission a commercial reactor.[95] Licensing involves a combination of permits, approvals, certifications, and the ultimate license to operate. To initiate and expedite a review, the NRC strongly recommends preliminary actions, referred to as pre-application engagements. These include white papers, topical reports, and meetings.

Domestic vendors are making steady progress in licensing and reducing regulatory risk. The NuScale VOYGR reactor (Gen III+) received its design certification in 2020, the first SMR to do so. In December 2023, Kairos received a construction permit for its Hermes Gen IV reactor, which is capable of high-temperature heat. This licensing action is notable not only because it is the first Gen IV SMR design to receive a construction permit, but also because its safety review was completed in 18 months, three months ahead of an already aggressive project schedule.[96]

In Canada, Terrestrial Energy's Integral Molten Salt Reactor has completed Phase 2 of the Canadian Nuclear Safety Commission's pre-licensing vendor design review, the first Gen IV reactor to complete a review of this type in either Canada or the United States.[xiv,97] The NRC is completing pre-application activities for 13 Gen IV designs and seven LWR-SMR designs or sites, but no commercial plant has obtained construction permission from the commission.[98]

Attempts to license new reactor designs have proven to be a challenge to the NRC. Investors, vendors, and utilities find the cost, time, and uncertainty associated with FOAK SMR licensing prohibitive. Generally, the process to license new reactors—from application submittal to license-to-operate approval—takes six to seven years. Considering pre-application engagements, permits, and the eventual license, costs to participate in a review can surpass $100 million.[xv] This does not include the design and engineering costs required to develop a robust NRC application in the first place. Those costs can run into the hundreds of millions of dollars as well.

An uncertain, and in some cases nonexistent, fuel supply chain

A reliable, secure nuclear fuel supply chain enables on-time deployments of nuclear reactors and uninterrupted operations over several decades. However, the current fuel supply chain is challenged by several factors. First, the United States relies on Russia for 24% of its low-enriched uranium (LEU) supply, making this a critical vulnerability in the nuclear fuel market. The Prohibiting Russian Uranium Imports Act of May 2024 bans Russian uranium products, with limited exemptions through 2028. With this ban, there is now even greater emphasis on bolstering the domestic fuel supply chain to ensure energy security. This ban unlocks $2.72 billion in appropriations (enabled by the Consolidated Appropriations Act of 2024) to support

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xiv Vendor design reviews (VDRs) are an optional service that enables the Canadian Nuclear Safety Commission's staff to provide feedback to a vendor early in the design process of an NPP. Over three phases, the objective of a VDR is to verify that Canada's nuclear regulatory requirements and expectations will be met. A VDR also identifies any fundamental barriers to licensing a new design in Canada. VDRs are not an application for any type of license.

xv "Costs to participate" include hourly service fees and the internal costs for applicants to complete reviews (e.g., responding to requests for additional information) as well as all of the licensing actions needed to reach regulatory approval (e.g., pre-application activities, permits, and the ultimate license). For example, in the case of NuScale's design certification, it cost $70 million in hourly service fees during the review and an additional $130 million to respond to requests for additional information, analyses, and audits. The NRC's fee estimates, based on the 2024 hourly rate ($321), for licensing actions are (from low effort to high effort): Design Certification, $34 million to $82 million; Early Site Permit, $4 million to $20 million; Combined Operating License, $14 million to $57 million.

new domestic low-enriched uranium (LEU) and/or high-assay LEU (HALEU) supply chain development. Deployment of new domestic LEU production will take time, leaving the U.S. at risk if Russia retaliates by accelerating a cutoff of supply.

The second challenge is the capital-intensive, new facilities needed to provide HALEU for some Gen IV designs, as there are currently no commercial suppliers outside of Russia and China. While Gen III+ and some Gen IV designs can rely on existing fuel supply chains, Gen IV designs that rely on HALEU are at an elevated risk. In the United States, Centrus Energy, which utilizes U.S. developed centrifuge technology thus making it eligible to supply nuclear fuel for national security purposes, has demonstrated successful HALEU production with its small scale pilot in Ohio. However, fuel suppliers such as Centrus still do not have sufficient market signals to invest in new capacity because the long-term demand for HALEU is unclear, which threatens the schedules of first demonstrations and customer confidence in new projects.

Finally, the U.S. needs a fully domestic fuel supply chain to support nuclear national security requirements, including LEU for tritium production, high enriched uranium (HEU) for naval reactors, and HALEU for research and demonstration reactors.[99] Current international agreements restrict the use of foreign-owned enrichment technologies to serve U.S. national security requirements. As a result, U.S. national security needs require milling, conversion, enrichment, and fabrication technologies, as well as uranium, that are U.S.-designed, manufactured, and sourced.[100] Currently, no U.S.-based enrichment facility operates at scale to meet these needs, posing medium-to-long term (2038 - 2060) national security nuclear fuel supplies risks.[101] Currently, there are two domestic centrifuge technology candidates that could meet enrichment requirements: Centrus' American Centrifuge technology, undergoing small scale commercial HALEU demonstration in Ohio, and the less mature Domestic Uranium Enrichment Centrifuge Experiment (DUECE) Program, developed and managed by Oak Ridge National Laboratory (ORNL). There are plans for DUECE to undergo an engineering-scale cascade testbed at ORNL to inform an eventual pilot plant, however this technology has yet to reach key technology milestones.[102,103]

Lack of a clear national pathway for spent nuclear fuel

As the demand for more electricity, clean energy, and energy security grows, support for nuclear energy facilities now outweighs opposition.[104] However, spent nuclear fuel (SNF) management continues to be a concern shared by the public, nuclear stakeholders, and county, state, and federal governments. This potentially adds uncertainty for SMR developers and investors over the longer term. Several states have restricted building new nuclear power facilities until the federal government identifies the means for permanent nuclear waste disposal.[105]

A survey conducted during this study found that the lack of a clear national pathway for nuclear waste management was a concern for all stakeholders interested in new nuclear development, including communities; federal, state, and local governments; and the nuclear industry.

SMRs of either Gen III+ or Gen IV reactor technologies would not eliminate the need for geological disposal of spent nuclear fuel because advanced reactors still require the disposal of radioactive fission products.[106] Additionally, some spent fuel stream generated by Gen IV designs might be significantly different from those generated by existing nuclear reactors, creating some uncertainty surrounding long-term storage approaches. Some Gen IV designs also incorporate spent fuel reprocessing as an integral part of a design that, in addition to triggering nonproliferation concerns, would necessitate a much more complex waste management system. Reprocessing creates both low-level and high-level waste streams that require sophisticated, expensive machinery to manage. Spent fuel management is not seen as an impediment to short-term SMR deployment because of existing protocols for interim on-site storage; however, longer-term solutions will be needed as the new nuclear designs scale up.

Community-level social license to operate

Project developers are keen to find communities that are amenable to hosting not only the plants themselves, but also the upstream and downstream infrastructure such as SMR component manufacturing, fuel fabrication, and spent nuclear fuel facilities (or “SMR facilities”). Aside from considerations of financial returns, capital providers (e.g., commercial lenders, private equity firms, etc.) are reluctant to put new nuclear in their portfolios if communities have a negative impression of SMRs. Many institutional investors have increasingly considered social impact as part of their portfolio screening criteria. Therefore, having a well-informed understanding of specific communities’ perceptions of hosting SMR facilities, rather than generalized public perceptions, is most salient from a bankability perspective. Realistically, facilities will not be deployed if communities are not interested in hosting.

Kick-starting the SMR Industry: Reducing Challenges to Increase Bankability Through Policy Action

This study provides policy recommendations in response to the listed challenges to bankability. The guiding principle for each set of policy recommendations is that progress must be made to increase the likelihood of orderbook formation by motivated strategic investors and affiliated capital providers. The orderbook is the appropriate area of focus to kick-start the SMR industry, given that SMRs' industrial design is predicated on cost efficiencies gained through economies of series. An orderbook signals the durable demand for a reactor design and enables knowledge to be accumulated through learning-by-doing and through repeated builds.

Foundational research and analysis on each challenge and detailed policy recommendations can be found in white papers developed for this project.

- *A Cost Stabilization Facility for Kickstarting the Commercialization of Small Modular Reactors*[107]
- *Making SMR Projects Blue Chip Investments: Supporting an Effective and Efficient Nuclear Licensing Process*[108]
- *Fuel Supply for Nuclear Energy Production*[109]
- *U.S. Spent Nuclear Fuel Policy: The Current Stalemate and Policies to Generate Momentum and Support Advanced Reactor Investment*[110]
- *Enhancing Community Acceptance of Small Modular Reactors*[111]

Table 1: **MAPPING SMR BANKABILITY CHALLENGES, RECOMMENDED POLICY ACTIONS, AND THE INTENDED EFFECTS ON SMR ORDERBOOK FORMATION**

Identified challenge	Recommended policy action	Orderbook implications
First-of-a-kind cost tied to cost uncertainty	Federal government provides a construction cost cap for eligible orderbook project proponents	Eliminates the first-mover disadvantage; induces learning effects through multiple builds
Uncertainty surrounding new design licensing	Increase the efficiency and predictability of licensing through fee reform and regulatory infrastructure buildout	Reduces licensing costs, timelines, and schedule unpredictability while enhancing design optimization and cost reductions by capitalizing on modularity
Inadequate or nonexistent fuel supply chain	Shore up and secure the LEU and HALEU fuel supply chain through domestic and allied strategies	Creates a long-term signal for orderbook formation
Lack of clear national pathway for spent fuel	Generate momentum to overcome the long-term SNF stalemate, focusing on interim storage solutions	Provides solutions to the overall increase in SNF from scale-up of domestic civil nuclear fleet
Need for community-level social license to operate	Develop trust and meaningfully share benefits to create an accepting SMR social environment	Leads to the identification of host communities interested and excited about hosting SMRs

Containing project costs and addressing unplanned construction costs

What is needed to tackle the challenges of cost magnitude and cost uncertainty of SMR deployment?

The dual challenges of cost magnitude and cost uncertainty are the most salient impediments to FOAK SMR deployment. To eliminate the first-mover disadvantage and address both high costs and tail risks, three critical elements are essential: demand pooling, knowledge sharing, and risk sharing.

Demand pooling: Cost reductions are predicated on an orderbook of a single design that is repeatedly deployed. It is likely that a coalition of utilities, large industrial users, or other project sponsors would be the source of the aggregate demand underpinning an orderbook. This "buyers club" also would be necessary to adequately share risks across multiple project sponsors.

Knowledge sharing: Implementing an integrated project delivery (IPD) model is an effective way to ensure that best practices are used in construction planning.[xvi] Some estimates indicate that FOAK costs can be reduced by as much as 30% to 40% if an IPD model is followed.[112] Beyond FOAK, unit costs will decrease and estimates will become more certain if existing nuclear construction knowledge is applied and if the knowledge gained through successive builds of SMRs within an orderbook

xvi IPD is a collaborative project delivery approach that involves a deliberate form of integration among project participants, emphasizing collaboration, information sharing, multiparty agreements, and pooled risk and reward structures.

is rigorously captured and shared. Rigorous knowledge sharing during the SMR construction design phase, coupled with applying accumulated knowledge to series of builds, holds the promise of reducing cost and cost uncertainty.

Risk sharing: Risk sharing mechanisms are legal and commercial arrangements that allocate the risks associated with FOAK/NXOAK installations among various entities that are best positioned to address such risks. Risk sharing mechanisms motivate the entities involved in a project to reach an amenable solution as cost- and time-efficiently as possible, given quality requirements. Within the project group (e.g., the project sponsors [i.e., the buyers club], developers, EPCs, and reactor technology vendors) the IPD model is used for risk sharing. The next risk sharing tier, outside the project group, expands participation to address residual risks that cannot be mitigated within the project group. For an orderbook that contains FOAK builds, the overrun risk should be born partially by an entity outside of the project team that has sufficient capacity to take on the cost—and that cost won't be well understood at the onset of the project. For at least the FOAK orderbooks, a government entity is uniquely positioned, and has sufficient capacity, to fulfill this role. For subsequent orderbooks of a design that is no longer considered FOAK, or one that is commercially unproven, the private sector (e.g. insurance companies) can increasingly fulfill this role.

These three elements can be pulled together through creation of a mechanism to address potential cost overruns. A cost stabilization facility (CSF) consisting of a special backstop loan facility provided by DOE's Loan Programs Office (LPO) could address project tail risks.

Recommendation: DOE's LPO shwould offer a cost stabilization facility to provide necessary liquidity in the event that an orderbook of SMRs exceeds its expected project cost.

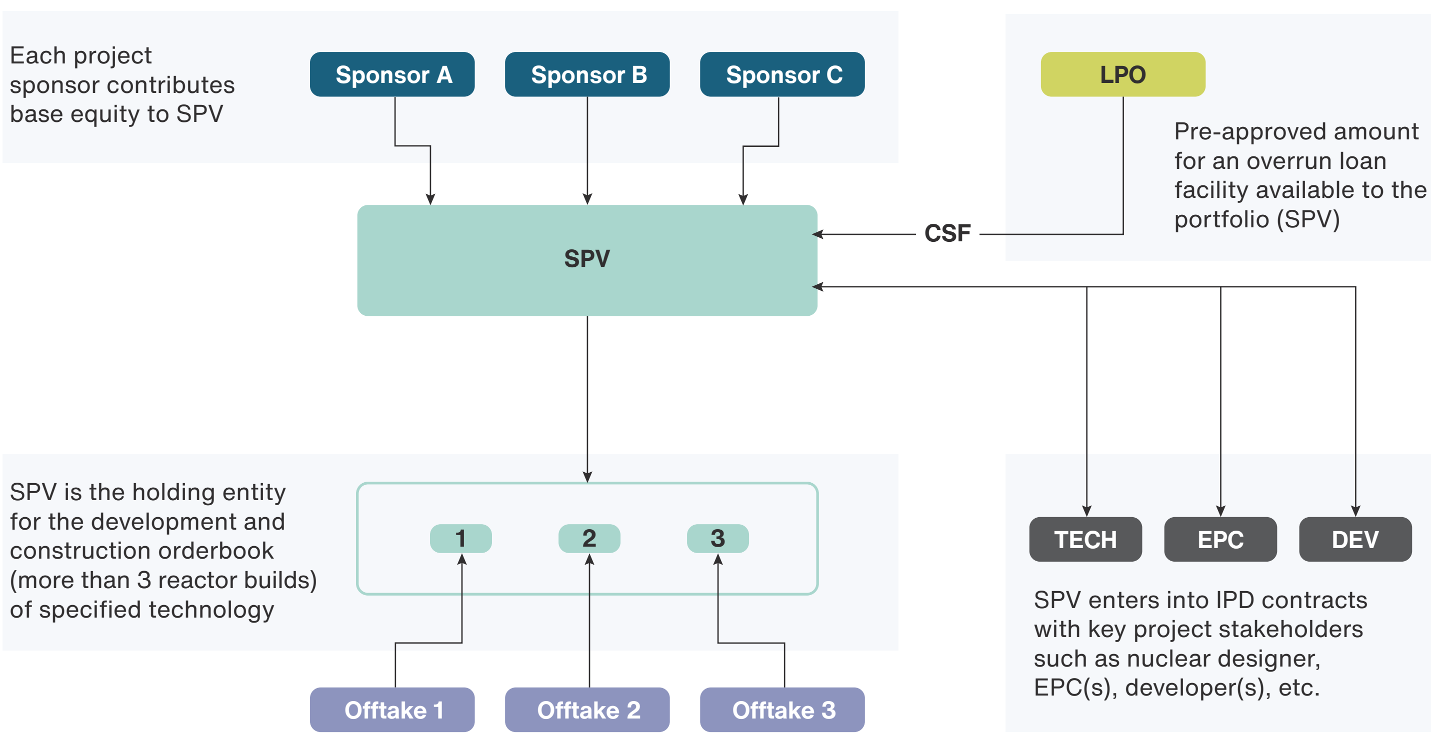
The CSF centers on a special credit mechanism provided by the federal government through the LPO. Employing existing LPO authorities, the CSF would be an augmented loan product with features specifically designed to significantly reduce the tail risk faced by pioneering SMR project proponents during the development and construction phases. The major components of the framework are as follows:

Orderbook. The CSF would be available only to FOAK orderbooks for multiple builds of a given SMR design. Project sponsors (i.e., the buyers club) would choose the design they wish to build. The minimum number of builds that would be sufficient to constitute an orderbook could vary by SMR design and would be a parameter negotiated upfront with the LPO. Nothing would preclude multiple orderbooks from being formed by additional project proponents, each focused on a specific Gen III+ or Gen IV design and supported in parallel.

Collective undivided ownership through a special purpose vehicle (SPV). The orderbook of SMRs would be placed within an SPV, a holding company that is a separate legal entity from the project sponsor(s). This is common practice within project finance that separates the economics (and risk) of the project from project sponsors. The SPV would own the orderbook and be capitalized by the project sponsors (Figure 4). Project sponsors would own pro rata shares in the SPV based on contributed capital. Via passthrough, each sponsor would own an undivided percentage of each of the plants constructed under this arrangement. Provided project sponsors have a noncontrolling investment in the SPV (i.e., less than 50%), any debt carried by the SPV would not be represented on the project sponsors' books. Management, structure, role of project sponsors, and operations of the SPV would be determined by the project proponents and codified within the SPV's bylaws.

SPV capitalization. Each sponsoring party would be responsible for arranging its own financing to support the SPV orderbook. The project sponsor would choose its form of capital injection (i.e., a mix of equity and debt, however sourced). Funds injected into the SPV by project sponsors would be on a callable basis as determined by milestones agreed to by the parties. Participation in the SPV would be designed to be open-ended, with additional project sponsors or investors joining the SPV and providing capital if agreed to by the parties. Effects on ownership shares in the SPV would be determined by the bylaws.

Figure 4: **SCHEMATIC OF A POLICY MECHANISM TO ELIMINATE THE FIRST-MOVER DISADVANTAGE, POOL RISKS, AND MITIGATE CONSTRUCTION COST UNCERTAINTY OF AN ORDERBOOK OF SMRS THROUGH A CSF OFFERED BY THE LPO**



Source: EFI Foundation.

Cost containment. The construction of the individual project plants within the orderbook would be governed by an IPD agreement. An IPD agreement would establish a shared incentive structure among key project stakeholders (e.g., major suppliers, engineering procurement, and construction, owners, operators, etc.) and would outline terms in which implementation risks and costs (and cost savings) are shared. The IPD model would create an incentive framework among the project proponents to share information and contain costs.

Tiered cost sharing. Cost risks would be allocated in tiers. In the first tier, project sponsors would be responsible for all project costs established in the baseline orderbook budget, excluding contingencies. The second tier would comprise funds to address reasonably estimated contingencies and also would be the responsibility of project sponsors. These contingencies would be pooled funds assembled by all project participants (e.g., the designer, EPC, and vendors) through the IPD agreement. In the third tier, the LPO would provide backstop financing to complete the orderbook through the proposed CSF. The CSF is a public-private liquidity mechanism where the project sponsors provide 20% of the total overrun and the federal government through the LPO provides the remaining 80%.

CSF design and implementation. The CSF would be enabled automatically in the event that the orderbook is not complete but the total budget (first and second tiers) for all builds has been exceeded. The trigger threshold for the CSF would be agreed to at the beginning of the project. The CSF is a credit facility provided by the LPO to the SPV. Importantly, the CSF loan would be granted to the SPV, not the individual project sponsors. Put another way, the SPV would become the debtor to the LPO.

Project offtake. Offtake agreements should generate sufficient revenue to cover all baseline orderbook EPC costs and contingencies (principal and interest).

Project operations. There would be multiple options for completed projects. One option is for the SPV to spin out the completed plants to the sponsors who provided the upfront investment in the SPV. Another option could allow the SPV to retain ownership while contracting for the operation of the completed plants. This option would most likely occur with experienced nuclear utilities where SMRs are built within their service territories. Finally, the SPV may retain ownership and operation of the completed plants by forming its own operating company.

CSF repayment. The CSF agreement between the LPO and the SPV would contain flexible repayment terms and conditions that could differ significantly from conventional loan and loan guarantee agreements. Repayment terms need to consider the possibility of an SPV default if the SPV fails to complete construction of the orderbook or if completed projects do not achieve their projected economic value over their operating life. In short, the CSF would be as flexible as feasible within current LPO authorities. Conversion of the CSF loan facility to a grant (i.e., a forgivable loan similar to what is offered by the U.S. Department of Agriculture's Rural Utilities Service) would require new legislation.

Exit provisions. The orderbook agreement to establish the SPV would include provisions that allow for an orderly exit by sponsors. Off-ramps would need to be constructed for when: (1) learning and/or cost advantages are not demonstrated in the first few builds, and the orderbook needs to be abandoned, and (2) the CSF is triggered and exhausted before the orderbook is completed.

Mitigating licensing challenges

The business case for SMRs is closely tied to the regulatory environment. Most reactor, construction, efficiency, and safety innovations require scrutiny and approval from the NRC. For example, passive safety technologies can enable simpler design requirements, fewer materials, less regulatory oversight, and less complex engineering, reducing direct and indirect project costs.[113] However, the deployment of novel safety systems requires successful NRC licensing.

The current licensing landscape reflects meaningful progress from first movers, but critical challenges remain. For first movers, licensing is an uncertain, time-intensive undertaking. The NRC is challenged by the need to license new reactors for the first time in decades, many of which contain novel features that have never been commercially demonstrated. Applicants must navigate licensing processes fit for large, complex light water reactors (LWRs) with a regulator that has limited flexibility in preparing for anticipated innovations. This results in decade-long interactions with the NRC, involving cost-intensive testing and engineering work to complete FOAK licensing.

Congress has recognized the need for comprehensive NRC reform through the passage the ADVANCE Act. The ADVANCE Act reforms NRC activities in several of ways. This includes reducing licensing costs for advanced nuclear reactor applicants and/or projects on DOE sites or critical infrastructure, improving international competitiveness, providing guidance on different SMR licensing issues, enhancing NRC efficiency, and strengthening the NRC workforce.

Actions from Congress and the NRC in recent years have improved the regulatory landscape, but further policy actions are needed to support FOAK applicants in the near term and, over the long term, foster a regulatory environment amenable to rapid SMR scale-up. This includes the regulatory capabilities and human capital to efficiently license multiple kinds of reactors and a significant volume of orderbooks, each building a specified reactor type.

The degree to which SMR facilities can quickly deploy innovations is dependent upon (1) high-quality applications from developers, and (2) a regulatory landscape that fosters, and ultimately reflects, new reactor innovations and construction methods. Without an amenable regulatory environment, developers may have to make design choices that reduce modularity and standardization, threatening promised cost reductions.

The Current Regulatory Landscape

The regulatory pathways to license a commercial reactor as described in Title 10 of the Code of Federal Regulations (10 CFR) under Part 50 and Part 52 assess reactors on design criteria that are prescriptive for large LWRs. The pathways impose broad requirements on all nuclear energy facilities, regardless of size, technology, or risk.[xvii] It is possible for designs to receive exemptions, but the process can be time intensive. For example, NuScale underwent a seven-year process to receive a modified emergency planning zone (EPZ).[xviii,114]

Similarly, regulations surrounding how nuclear plants are to be constructed reflect traditional nuclear construction practices, as opposed to construction practices for factory-built, standardized plants. For example, the American Society of Mechanical Engineers (ASME) currently stamps each nuclear containment vessel so it is tied to a specific site, reducing flexibility in the supply chain because stamped vessels cannot be redirected freely.[115] Microreactors, particularly those that require pre-loading of fuel, face several policy uncertainties given their novel nuclear fabrication model. Such issues include the licenses required to load fuel at the factory and transport it to the site, as well as the licensing approaches to enabling operational testing at a factory.[116] Globally, changes in the regulations surrounding supply chain oversight will be needed for rapid and efficient delivery of SMR projects.[117] This includes the ability to design and manufacture safety-significant items that sometimes require significant lead time before the establishment of a license.[118]

Advanced manufacturing and construction technologies that promise meaningful cost and schedule reductions for SMRs are not reflected in essential regulatory infrastructure. Despite the successful use of precast concrete in other industries, the standards that applicants must follow for proper design and construction of safety-related concrete structures—excluding containments—do not include precast concrete.[xix,119,120]

Seismic isolation technology also offers immense value to an SMR developer. Seismic risk differs at each nuclear site, requiring specific testing that affects the design, equipment qualification, and regulatory review of a plant.[121,122] Seismic isolation would enhance design standardization, reducing plant-specific engineering, review, licensing, and time to construction start for a nuclear project.[123] Application of seismic isolation in other industries has been shown to reduce seismic demands on structures, systems, and components by factors of up to 10 and seismic risk by orders of magnitude. However, it has never been applied to nuclear plants given the few new builds and a lack of technical guidance and standards.[xx,124]

xvii Each pathway contains a safety review and an environmental review.

xviii The emergency planning zone refers to a buffer area around nuclear power plants designated for implementing the necessary operational and protective measures in a nuclear emergency.

xix Nuclear safety-related concrete structures and foundations, other than concrete reactor vessels and containments, must follow ACI 349 code requirements. Concrete containments must follow ASME Boiler and Pressure Vessel Code Section III, Division 2 (also ACI 359) (ASME, 2001b) requirements. However, most SMR designs use steel containments.

xx The Rolls-Royce SMR design incorporates an aseismic bearing pad that neutralizes the seismic and thermal loads of the region, allowing for a higher degree of standardization (ETI, 2020).

Rather than approaching common SMR characteristics on a case-by-case basis with individual licensees, expeditious licensing can occur in an environment with regulatory standards of general applicability. While first movers will continue to modify existing regulations to their design, a regulatory environment that facilitates scale-up requires proactive improvement to regulatory infrastructure that applies broadly to designs. The NRC is making progress on a number of these actions.

Per congressional mandate, the NRC is developing a technology-inclusive and performance-based regulatory pathway, Part 53. While the original draft rulemaking received criticism from industry and nongovernmental organizations alike, the commission's direction for the final rule, released in March 2024, removes key challenges with the draft and requires staff to address additional areas of regulatory uncertainty in the final rule (e.g., fuel loading requirements for microreactors). While near-term deployments must use Part 50 and Part 52, successful implementation of Part 53 may avoid several inefficiencies surrounding broad SMR characteristics.

The NRC is also developing a rulemaking for an Advanced Nuclear Reactor Generic Environmental Impact Statement (ANR GEIS). This rule aims to streamline and reduce the environmental review process for SMRs, as the ANR GEIS would be used to determine the same impacts for different designs within a set of parameters.[125] In November 2023, the final rule for alternative emergency preparedness requirements for SMRs was published; it includes a scalable method to determine the size of EPZ around a facility. [126] The NRC also plans to publish guidance on the use of seismic isolation in NPPs in December 2024.[127] ADVANCE also requires the NRC to identify issues and release guidance and considerations for licensing microreactors, nuclear energy for non-electric applications, nuclear facilities on brownfield sites, and advanced nuclear fuels.[128]

Taken together, success in these efforts can prevent the inefficiency of conforming each design to prescriptive regulations. They also can facilitate rapid scale-up of new designs and construction innovations within a cohesive regulatory environment and promote regulation commensurate with reactor risk, all without sacrificing safety. Still, other factors impede the success of these modernization initiatives, leaving potential project developers, sponsors, and customers cautious about regulatory risk.

Common Challenges and Root Causes That Impact Review Schedules and Cost

The length of time required to complete licensing and obtain permission to operate—six to seven years, not including pre-application engagements—is not conducive to rapid expansion of deployments, and consequently it does not create favorable conditions for the scale of investment needed for an emerging industry. In addition to the challenges for novel designs in the regulatory framework, licensing experiences from the past 20 years reveal several factors that cause inefficiencies during reviews.

FOAK applicants struggle to provide sufficiently complete, durable, and quality application information that facilitates a successful review. Design development often causes unanticipated changes to application information after submittal, leading to rework and delays. The NRC workforce's performance can also be variable and unpredictable, which can lead to prolonged review schedules and unnecessary resource use. For example, staff have preemptively accepted applications for review, administered requests for additional information (RAI) in the wrong context, and lacked accountability in timely decision-making.[129,130,131,132,xxi]

Productive engagement between applicants and the NRC during licensing is a challenge across reviews. Disagreements and frictions between the NRC and applicants over complex issues often require weeks, if not months, to resolve.[xxii] Applicants might incorrectly assume the staff's familiarity with a new reactor design, while NRC staff may not know what answer or information they need to make a safety determination, resulting in back-and-forth with little resolution.[133] Finally, communication shortfalls between NRC staff and management, and across staff working on different applications, lead to delays, inconsistencies across reviews, or reopening of previously closed issues on a single review.[134,135]

These challenges not only create long regulatory timelines, but they also increase the costs and risks of licensing.[xxiii] Costs to complete licensing can be substantial, particularly when a reactor contains novel features. Hourly service fees typically total tens of millions of dollars, and costs to assemble the necessary tests, analyses, and documentation to support a license application reach into the hundreds of millions of dollars.[136]

Recurring delays indicate deeper challenges that hinder both the agency's and applicant's ability to license new designs efficiently. The inefficiencies that occur during reviews are attributed to three root causes: (1) FOAK, novel technologies, (2) fee structure, and (3) agency culture.

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xxi Requests for additional information (RAIs) are administered to obtain further information the staff deems necessary for resolving safety or environmental issues not adequately addressed in an application.

xxii For example, 30% of NuScale's RAI responses could not be met within the 60-day response period. These delays were associated with highly challenging issues that impacted the project schedule.

xxiii Costs to the developer for licensing include costs from application development, hourly fees for NRC services, and compliance with NRC information requests.

FOAK, Novel Technologies

Reaching confidence that novel features comply with the NRC's stringent standards can be time and resource intensive for the applicant and the regulator. While large LWR, and even Gen III+ SMRs, can build safety cases atop decades of operating experience, new reactor technologies must complete substantial testing and data collection to reach the same certainty. For example, in addition to NuScale's 12,000-page design certification application, the vendor also provided the NRC with 2 million additional pages to assist the commission's understanding of the information included in the application.[137]

Regulatory decision-making is complicated by a lack of institutional knowledge within the NRC on regulatory precedent and infrastructure on novel technologies.[138,139] The NRC must develop new review processes and acceptance criteria to interpret the new methods by which SMR developers comply with regulations. Further, technology uncertainties make it challenging for the agency to administer guidance. Regulatory guides inform licensees and applicants on how to implement regulations, how staff evaluates problems, and the data needed for permits or license.[140] Across the globe, regulatory bodies are struggling to create guidance for SMR applicants, as regulators themselves are in the process of learning.[141]

Agency Fee Structure

The NRC must recover a large portion of its annual budget from fees charged to the beneficiaries of regulatory services, including license holders and license applicants. While this may be a sound model for an established, largely stable industry, attempting to deploy new nuclear innovations under this structure is highly challenging and a critical challenge to SMR deployment.

User fees originated under the Atomic Energy Commission in 1968. But up until the late 1970s they covered just 20% of what licensing actually cost the NRC in terms of time and resources.[142] Sweeping efforts by the Reagan administration to reduce federal spending during the 1980s led to several budget actions that dramatically increased fee recovery across federal agencies, including the NRC. The Consolidated Omnibus Budget Reconciliation Act of 1985 (COBRA) authorized Congress to tie fee collection to a certain percentage of an agency's budget, requiring the NRC to recover 35% of its budget from fees. For scale, this increased the NRC's fee recovery from $37 million in FY1986 to $134 million in FY1987.[143] The Omnibus Budget Reconciliation Act of 1990 (OBRA-90) mandated 100% recovery of the commission's budget.[144]

Today, the NRC still must recover a majority of the annual budget, but certain activities are excluded from fee recovery and are funded by congressional appropriations.[145] Crucially, advanced reactor infrastructure is considered an excluded activity, thus congressional appropriations are used to complete general SMR activities, such as developing rulemakings.

While the growth of fee recovery in the '80s certainly inconvenienced the nuclear industry, two dynamics in this time period softened the impact of this new fee structure. First, new reactor builds, let alone reactor innovation, were broadly considered improbable. Flat electricity demand, high construction costs, and Three Mile Island in the 1970s dissipated demand for new nuclear construction by the mid-1980s.[146] Second, electricity markets remained centrally regulated until the mid-1990s, allowing vertically integrated nuclear utilities to pass the fees onto ratepayers.[147]

Despite a fee structure that's largely unchanged from the 1990s, the nuclear context today is quite different. There are many new developers undergoing extensive regulatory activities to commercialize new technologies, as well as customers working with the NRC to investigate site viability for potential projects.[148] At the same time, new projects are highly sensitive to the additional cost burdens of licensing given a majority of investor-owned utilities are in deregulated markets that do not value bulk, clean, firm power.

Given this new context, it is time to fundamentally rethink the NRC's fee structure. A budget that relies so heavily on such a fee recovery mechanism inadvertently discourages regulatory innovation, robust pre-application engagements, and technology innovation that can enable new nuclear deployment.

Regulatory Innovation

Though congressional appropriations provide some flexibility, the fee structure limits the activities the NRC can pursue. The NRC's activities are tied to certain categories depending on which entity pays. For example, fees collected from the operating fleet are used for regulatory services for the operating fleet only; the NRC cannot collect fees from the operating fleet to conduct broad SMR research and rulemakings. Even if the NRC anticipates novel technologies or a gap in regulatory infrastructure that will impact future applicants, the agency is limited in developing institutional knowledge and regulatory infrastructure in advance of reviews.

The NRC is also limited in making proactive budget requests for research activities or additional hiring. The agency can request appropriations only based on activities that it plans to recover fees from, or if it is mandated by Congress through legislation, such as with Part 53. Thus, hiring experts on anticipated reactor, fuel, or construction innovations is only permissible with limited congressional appropriations or if a developer pays directly for the NRC's efforts (e.g., staff time). Additionally, the NRC can only staff up significantly for high-volume licensing with foresight into the development of orderbook(s).[xxiv] Because of the delay that exists between recruiting, hiring, and training employees, the NRC may not be able to staff a review when an applicant needs it.[xxv]

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xxiv The NRC faces additional challenges hiring skilled workers and keeping up with attrition because of competition from industry and higher rates of retirement. However, the commission does have tools at its discretion to increase workforce competitiveness, including direct hiring authority, contracting authority for specialized expertise, and incentives for staff. The NRC must still use its direct hiring or contracting authority within the confines of its annual budget, highlighting the importance of accurate requests.

xxv For example, three years of training is necessary for a probabilistic risk assessment analyst.

High-Quality Engagements

Pre-application engagements are one method for reactor technology developers to provide the NRC with sufficient foresight to allocate adequate staff and acquire needed expertise. Yet the cost burden imposed by fees often dissuades these useful engagements. Pre-application activities are critical for the success of a FOAK review, as they increase regulatory certainty and allow for early resolution of complex issues for vendors.[149,150]

Most SMR vendors are not incumbent developers, but rather small, startup companies relying on some combination of seed investments and federal research, development, and demonstration (RD&D) dollars. Even SMR vendors tied to large legacy firms are resource-constrained given the uncertain market. The NRC's professional hourly rate in FY2024 is $321. Highly complex, topical reports can cost up to $1.2 million in fees for the NRC to review, and official license reviews may cost an additional tens of millions of dollars per step, depending on the pathway.[151] Thus, the high cost of design development paired with the anticipated fees from official licensing reviews may prevent robust pre-application engagement, creating the risk of rework and longer licensing schedules due to eventual NRC feedback.

Implications on SMR Commercialization and Technology Innovation

The current fee structure has created a lag in regulatory infrastructure and NRC preparedness. The NRC has been limited in its ability to acquire sufficient regulatory resources to be ready for the SMR designs being pursued by vendors today.

Measurable interest from industry and Congress in SMR deployment in the past several years, through legislation or pre-application activities, has been associated with notable increases in NRC appropriations generally and, advanced reactor (AR) infrastructure appropriations specifically. AR appropriations have grown from $5 million in 2017 to $34 million in 2024. While this progress is significant, there remains a gap in regulatory infrastructure perpetuated by the current fee structure, which hinders ongoing FOAK applications. Even with these gaps, developers are still responsible for high fees.

This is aggravated when considering that Gen IV reactor technologies require more time and resources—at least initially—for the NRC to fully understand, given their departure from the better-known LWR design. This is particularly salient for microreactors, as fee costs for licenses make up a much higher fraction of the overall project costs. Indeed, one Gen III+ SMR developer said that the use of LWR technology provides a strategic regulatory advantage.[152]

While ADVANCE certainly provides financial relief through reduction in fees, the foundational challenges with the fee structure remain—the NRC is still limited in the activities it can pursue with these funds, and applicants are not incentivized to engage unless they are financially capable of doing so.

The ADVANCE Act aims to remedy some of the barriers imposed by the fee structure. ADVANCE reduces the hourly fee rate for advanced reactor license applicants and pre-applicants by altering the professional hourly rate calculation. This will likely cut hourly service fees for these applicants in half.[xxvi,153,154,155] Additionally, to incentivize first movers, financial prizes are available to entities that receive an operating licensing from the NRC if it is the first advanced nuclear reactor to: 1) receive a license under Part 50 or 52, 2) receive a license with a design that uses isotopes derived from spent nuclear fuel, 3) receive a license using an integrated energy system, 4) receive a license for operating flexibly to generate electricity or process heat for industrial applications, and 5) receive a license to load nuclear fuel under Part 53. Prizes will equal the costs collected by the commission during the process of receiving the operating license and, if applicable, construction permit and early site permit.

While ADVANCE certainly provides financial relief through reduction in fees, the foundational challenges with the fee structure remain—the NRC is still limited in the activities it can pursue with these funds, and applicants are not incentivized to engage unless they are financially capable of doing so. The prize program does target first movers specifically but does not provide applicants with the funds to support engagements throughout.

Agency Culture

The NRC's thorough reviews and questioning attitude are essential to maintaining public trust and upholding the current fleet's high performance. However, an overly conservative culture may unnecessarily prolong the

xxvi The NRC's professional hourly rate is derived by adding budgeted resources for (1) mission-direct program salaries and benefits; (2) mission-indirect program support; and (3) agency support (corporate support and the Inspector General (IG), then subtracting certain offsetting receipts and then dividing this total by mission-direct full-time equivalents (FTE) converted to hours. Taking data from FY2019- FY2024, mission-direct costs typically account for ~46% of the costs, mission-indirect accounts for ~15% of costs, and agency support accounts for ~39% of costs.

timelines and engagements surrounding novel features, even when an adequate safety case with quality information is presented. The NRC has faced a number of cultural challenges in the past 20 years, including hierarchical decision-making, a lack of trust between management and staff, and a failure to value innovation and agility.[156,157] Indeed, the agency has also been slow to accept innovations within the operating fleet in the past, such as the transformation from analog instruments to digital instrumentation and control.[158]

Policy Recommendations

Actions are needed in the near term to enable successful FOAK applications and over the coming decades to ensure the NRC can support orderbook formation for SMR designs in a timely manner, while maintaining world-class safety standards and enabling continued innovation.

Recommendation 1: Congress should exempt FOAK SMR pre-application and licensing activities (irrespective of number of reactors in the first NRC review) from the mandatory fee base and offset the cost to the NRC with congressional appropriations to encourage robust pre-application activities. Exemptions from fees for early involvement can encourage robust pre-application activities. Early involvement supports successful FOAK reviews by (1) improving application and engagement quality, and (2) enhancing NRC workforce and agency preparedness by signaling to the NRC what core resources, competencies, and budget will be needed to support reviews. After a given design has successfully completed one licensing pathway (either Part 50, 52, or 53), fees should apply to the design, as most complex issues will be resolved.

As shown in Table 2, fee exemptions in the near term would likely require an additional $25 million to $40 million in appropriations per year, working in parallel with existing appropriations for advanced reactor infrastructure.[159,160,161]

Table 2: **NEW REACTOR LICENSING COSTS TO NRC COMPARED WITH AR INFRASTRUCTURE APPROPRIATIONS, 2021-2025**

New reactor licensing includes large reactors and SMRs; however, starting in FY2021, the number of SMR developers completing licensing activities with the NRC grew from three to 11, all of which are FOAK.

Budget line	FY2021	FY2022	FY2023	FY2024	FY2025
New reactor licensing (in millions)	$26.8	$35.2	$32.5	$32.5*	$36.3**
AR infrastructure activities (in millions)	$17.7	$23	$23.8	$23.8*	$19.2**

*Annualized Continuing Resolution as Enacted amount unavailable **Presidential budget request
Source: See first table mention in text for sources.

Recommendation 2: As the costs of licensing standardized designs are better understood, Congress should consider fixed application fees for licensing activities. Additionally, rather than a front-end service fee, back-end fees could enable vendors to repay the additional upfront appropriations funding over time as projects are successfully built and operated. Fixed licensing fees, similar to those used by the U.S. Food and Drug Administration, can provide certainty and transparency to applicants.[162] Providing certainty with fixed fees does not force the NRC to meet a fixed timeline, which maintains the agency's ability to make decisions when, and only when, an applicant demonstrates compliance with safety regulations. To accommodate longer, more complex reviews, the NRC could set up a contingency fund with appropriations to cover overruns beyond the fixed fee. This would also provide an incentive for NRC to complete its reviews within the cost ceiling associated with the fixed fee. Finally, the implementation of a back-end fee would allow vendors to pay when a steady revenue stream has been established, rather than needing the capital before operation. The back end fee concept, however, would require additional upfront appropriations to finance NRC budget costs that ultimately be repaid.

Recommendation 3: Based on the results from the advanced methods of manufacturing and construction report mandated by ADVANCE, DOE and the NRC should consider creation of a working group that is focused on SMR manufacturing. Included in ADVANCE, the manufacturing and construction report will examine the licensing issues related to advanced manufacturing and construction practices for SMRs and identify needed guidance or rulemakings. Additionally, the commission should investigate regulatory gaps in this area in relation to the use of artificial intelligence (AI) as a tool in the design and operation of SMRs. Use of artificial intelligence is expected to improve safety and operational efficiency in SMRs, in some cases using robotics to complete tasks. As AI is increasingly relied upon in the development, manufacturing, and operations of nuclear plants, the NRC must have the protocols to test and validate licensee claims.[163] SMRs create the potential for significant departures from the current methods of regulation for manufacturing, construction, and transportation of nuclear components. A newly formed office, with the necessary expertise, may be best equipped to implement new guidance, rules, and oversight and inspection activities.

Recommendation 4: The NRC and DOE should pursue several joint initiatives to create regulatory infrastructure and transfer knowledge via official reviews on cross-cutting technical uncertainties. Though the NRC and DOE have several memorandums of understanding to share knowledge, the joint-initiative model builds regulatory infrastructure by mimicking real licensing experiences on cross-cutting issues, with industry and public involvement throughout. This benefits workforce capacity through learning-by-doing and results in strong, well-informed guidance. This model was effective in developing guidance for principal design criteria for non-LWR reactors, as demonstrated by its ongoing use by Kairos, TerraPower, and X-energy in licensing activities.[164, 165, 166] This method could be used to identify the challenges and create the guidance mandated in ADVANCE, such as for advanced fuel concepts, microreactors, or non-electric applications of nuclear energy.

Shoring Up LEU and HALEU Fuel Supply Chains

Supporting nuclear scale-up requires secure and readily available fuel supplies for Gen III+ and Gen IV SMRs. Both the LEU and HALEU supply chains, however, face uncertainty. For LEU, domestic fuel suppliers require sufficient confidence that investments to expand capacity will not be undercut by cheaper supplies from international competitors (e.g., Russia) over time. For HALEU, fuel suppliers need sufficient confidence to invest in capital-intensive new facilities. HALEU is particularly challenged, as long-term demand for it is unclear, while the current scarcity of HALEU threatens the schedules of first demonstrations as well as customer confidence in some new Gen IV projects. Lastly, securing a national-security qualified nuclear fuel supply chain for the mid-2030s must be a consideration as well.

The United States recognizes these investment challenges, as well as the critical role Russia plays in the international fuel supply chain, and the threat to certain early SMR deployments. Therefore, the U.S. has taken several legislative actions to fill the current demand gap and support investments in new LEU and HALEU capacity, including the HALEU Availability Program (HAP), the Nuclear Fuel Security Act of 2023 (NFSA), and the Prohibiting Russian Uranium Imports Ban. Additionally, DOE and the National Nuclear Security Administration (NNSA) continue to support the development of two American enrichment centrifuge technology candidates; Centrus' American Centrifuge and the DUECE Program developed and managed by ORNL.

The United States must carefully consider next steps, however, to ensure fuel supplies for the operating fleet remain secure in the near term and that expanded, secure LEU and HALEU supplies are available for new nuclear deployments and national security needs.

The Current LEU Landscape

Russia provides a large portion of fuel services for domestic and global operating fleets. Russia owns 47% of global enrichment capacity (see Table 3) and 20% of conversion capacity.[xxvii,167,168,169,170,171,172]

Table 3: **ENRICHMENT CAPACITY BY COUNTRY**

Country	Company and plant	2020 capacity (1000s SWU per year)[xxviii]	Est. 2030 capacity (1000s SWU per year)	Capacity change 2020-2030
France	Orano, Georges Besse I & II	7,500	10,000	+33.33%
Germany-Netherlands-UK	Urenco: Gronau, Germany; Almelo, Netherlands; Capenhurst, UK.	13,700	13,950	+1.8%
USA	Urenco: New Mexico	4,900	5,100	+4%
Russia	Tenex: Angarsk, Novouralsk, Zelenogorsk, Seversk	27,700	24,800	-10.4%
China	CNNC, Hanzhun and Lanzhou	6,300	17,000	+169.8%
Other	Various: Argentina, Brazil, India, Pakistan, Iran	66	525	+695.4%
Total 1000s SWU per year		60,166	71,375	+18.6%
Total non-Russian 1000s SWU per year (%)		32,466 (53%)	46,575 (65%)	+43.4%
Total SWU requirements per year		50,205	±	±

Note: In projecting 2030 capacity, this included any announced capacity expansions as well as facility capacity reductions between 2020 and 2023, if available. ± Data not available.
Source: See first table mention in text for sources.

xxvii Conversion is a chemical process that changes mined uranium into uranium hexafluoride (UF6), which becomes a gas when heated, facilitating the enrichment process. Enrichment processes the UF6 gas through a series of gas centrifuges to achieve the desired concentration of the U-235 isotope in the fuel.

xxviii Enrichment production is measured in separative work units (SWUs). This unit defines the effort required to separate isotopes of uranium.

Nuclear plant operators outside Russia, including the United States, would face a shortage of LEU if Russian exports were to become immediately unavailable. Even though some suppliers have announced a limited expansion of LEU capacity, including Urenco and Orano, a gap between LEU demand and supply outside Russia will still exist.[173,174] A leading nuclear fuel consultant recently estimated the enrichment gap between supply and demand outside Russia, China, and a handful of countries technologically constrained to Russian services to be 3 million to 11 million SWUs per year.[xxix,175]

Further, solely excluding Russian supply and demand, Constellation estimated a "potential gap" of up to 15 million SWUs per year globally.[xxx,176] For scale, this global gap is equivalent to current U.S. enrichment requirements; U.S. utilities required 15 million SWUs to supply the entire 93-reactor operating fleet in 2022.[177] While enrichment capacity needs can be reduced by a technique called overfeeding, this will add to raw material demand and also constrain uranium conversion capacity, which is also in deficit without Russian supply.[xxxi, 178]

The United States remains reliant on Russian enrichment and, to some extent, conversion services. In 2022, Russia accounted for 24% of total enrichment services purchased by U.S. owners and operators of civilian NPPs.[179] More broadly, imports satisfy the large majority of U.S. demand, accounting for 73% of enrichment services in 2022.

The war in Ukraine has strengthened congressional and executive branch interest in phasing out Russian nuclear fuel in non-Russian markets, but actions taken may sacrifice near-term fuel security for the operating fleet while still failing to provide LEU suppliers with the confidence to make sufficient investments in capacity expansion.

The Prohibiting Russian Uranium Imports Act (H.R. 1042) became law in May 2024, banning the imports of Russian enrichment products in the United States 90 days after enactment. Exceptions may be granted through waivers until 2028 if the secretaries of energy, state, and commerce determine there are no viable fuel alternatives for continued reactor operations at an NPP or a nuclear energy company. Even with waivers, a significant effort will be necessary to completely replace Russian imports by 2028. As such, this ban unlocks $2.72 billion in appropriations (enabled by the Consolidated Appropriations Act of 2024) for the NFSA, which can support LEU and/or HALEU supply chain development.

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xxix Several Eastern European countries have Soviet- or Russian-designed reactors that operate on Russian fuel.

xxx According to the World Nuclear Association's 2019 fuel market report, total non-Russian enrichment capacity is 33 million SWUs/year, whereas total non-Russian enrichment requirements are 48 million SWUs, leaving a potentially 15 million-SWU supply gap.

xxxi To a limited extent, fuel suppliers can vary the amount of UF6 feedstock versus SWU effort needed to reach the same desired enrichment amount. When UF6 feedstock is more expensive than the use of SWU, suppliers can "underfeed" by inputting less UF6 and obtaining a higher percent of the naturally occurring U-235 within that batch. When SWUs are in higher demand, suppliers can "overfeed" by supplying more feedstock and leaving behind a higher proportion of U-235 in the excess, or the "tails." Overfeeding requires less SWUs because, the higher proportion of U-235 present in the feedstock and/or tails, the less effort (or SWU) is required to extract the U-235.

Soon after the ban was passed into law, a DOE pre-solicitation indicated that the agency could spend up to $3.4 billion to procure LEU from new domestic enrichment capacity via task orders under an indefinite delivery-indefinite quantity (IDIQ) contract.[180] This $3.4 billion represents all of the enrichment funding available and appropriated between HAP and NFSA. While it is unlikely DOE will use all of this funding on LEU, the urgency to replace Russian fuel by 2028 suggests a near-term priority for LEU procurement over HALEU.

In the lead-up to this ban, many U.S. nuclear power plant operators have proactively sought alternative fuel suppliers, enabling some domestic enrichment capacity extensions.[181] As mentioned, Urenco announced a limited expansion at its U.S. enrichment plant (an increase of about 15%), to be completed in 2027. In Europe, Orano has approved an expansion of its enrichment capacity by 33%, with the full expansion complete by 2031.[182, 183] Centrus' American Centrifuge Plant could produce domestic LEU to help close the gap but would require three years to build out LEU capacity after an investment decision is made, thereby starting production no earlier than mid-2027.[184] But sanctions do not provide LEU suppliers with sufficient confidence that these restrictions will persist long enough to recover capital on invested capacity.[xxxii] If sanctions are lifted in several years because of a shift in the geopolitical landscape, investments in capacity expansions will likely be uneconomic sunk costs.

Even with these expansions, though, a gap in LEU supply outside Russia will remain in the short to medium term, threatening the potential expansion of nuclear energy. Given the United States' current reliance on Russian enriched uranium, some suppliers will require waivers to meet customer demands between August 2024 and 2028. Even during the waiver period, Russia may still cut off supplies and immediately negate these waivers, potentially threatening nuclear operators that have not secured a non-Russian fuel supply until 2028. Given the size of Russia's share of the market, this deadline is likely unrealistic; financial analysts have pointed out that the ban could increase exposure to fuel shortfalls for plant owners as fuel needed in the mid-term (3-5 years) may not be able to be sourced outside Russia. [185]

In 2023, the International Atomic Energy Agency estimated that the United States' combined supply chain (including utility and fuel supplier uranium inventories) holds little excess—about 12 months of existing requirements at each stage of the cycle.[xxxiii,186] If Russia were to retaliate, the United States and/or private industry would not be able to expand capacity quickly enough to address the immediate gap created by Russia's absence. As a last resort, the American Assured Fuel Supply (AFS) could be pulled from domestic and foreign customers to cushion

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xxxii Uranium enrichment facilities typically have a 25- to 30-year economic life. Optimistically assuming new domestic capacity can come online by 2026, this leaves only 14 years of operations before the ban is expected to be lifted.

xxxiii Inventories include uranium products in several forms, including U3O8, UF6, enriched uranium products, and fabricated fuel.

supply chain disruptions.[xxxiv] This supply is designed to provide a backup source of fuel in the event of an unexpected supply disruption that threatens normal operations of a country's civilian nuclear program. The reserve is modest in size, however, and has never been used. Thus, uncertainties remain regarding the conditions for extraction, the price of fuel at the time of extraction, and how long that process might take.[xxxv,187,188] International collaboration can also mitigate fuel supply exposure. In April 2023, the Sapporo 5—the U.S., Canada, France, Japan, and the United Kingdom—announced their collective intent to leverage each country's civilian nuclear resources and capabilities to undermine Russia's dominance on civilian nuclear supply chains and enhance the stability of LEU and HALEU supplies.[189,190] At COP28, this same group announced plans to mobilize $4.2 billion in government-led investments for the global nuclear energy supply chain; combined commitments from the Sapporo 5 already surpass this $4.2 billion target.[191]

Lastly, Rosatom, the Russian state atomic energy corporation, may attempt to access U.S. customers through displacement—increasing deliveries of Russian enriched uranium to countries that are willing or obligated to accept, and who then export this enriched uranium to global markets undetected.[192] Given the leakage, attempts to cut off the Russian flow of fuel products into the United States and other Western markets could fail, leaving Rosatom largely unaffected by sanctions, again making it difficult for new LEU capacity to compete.

Ultimately, nuclear fuel is a global business requiring international coordination to develop new, non-Russian supply in order to truly phase out Russian fuel for commercial operators and ensure LEU capacity expansions are recovered over the long term.[xxxvi] An increase in enrichment supply outside Russia will require agreement from other importers to exclude Russian LEU, even if it becomes economically attractive not to do so. This will require global cooperation, which remains a challenge.

Countries with Russian-designed water-water energy reactors (VVER) face technological barriers to diversifying fuel assembly fabrication.[193] The European Union has 18 Russian-designed VVER reactors, and Ukraine has 15.[194,195] However, there are some signals that cooperation is in progress. The 2024 G7 communiqué reflects a collective intent to reduce reliance on civilian nuclear goods from Russia and commits to supporting multilateral efforts to strengthen nuclear supply chains.[196] While the $4.2 billion in fuel investment commitments from Sapporo 5 is a start, more concrete efforts will be required.

xxxiv The AFS is drawn upon only in the event of demonstrated need and is not intended to act as a market formation mechanism.

xxxv Initiated in 2007 and completed in 2012, DOE downblended 17.4 metric tons HEU into 290 metric tons of LEU, and 230 metric tons was placed in the AFS.

xxxvi Excluding Russia and China, the U.S. represents less than 40% of the demand for enriched uranium.

The Current HALEU Landscape

Some but not all Gen IV reactors require HALEU; about 75% of Gen IV reactor designs call for a HALEU fuel type.[xxxvii,197] Original DOE estimates that a total of 22 metric tons of HALEU will be needed by the mid-2020s for initial core loadings to support reactor demonstrations, research, and test reactors, though this estimate far exceeds actual HALEU available in the U.S. This demand will grow to between 8 and 12 metric tons annually into the early 2030s, increasing to more than 50 metric tons annually by 2035, with an ultimate projection of more than 500 metric tons annually by 2050.[198] Currently, the United States has limited demonstration capacity to produce HALEU (0.9 metric tons per year), while Russia and China have the infrastructure to produce HALEU at commercial scale.[xxxviii] One DOE awardee has already announced a project delay due to a lack of fuel.[199]

Meaningful progress in establishing a HALEU supply chain in Europe and the United States is underway. In May 2024, the U.K. government announced a £196 million ($245 million) award to Urenco to build a new uranium HALEU facility at its Capenhurst site in northwest England.[200] This facility, which would be the first HALEU facility in Europe, is anticipated to commence operations in 2031, with a capacity of 10 metric tons per year.[201] In the United States, HAP makes available $500 million to acquire HALEU for Gen IV reactors. Some additional funding may also be available from the NFSA; however, the ultimate amount will depend on competing, near-term needs for LEU procurement.

Thus, the total available for HALEU production remains uncertain.

Despite this progress, fuel suppliers outside Russia and China remain in an uncertain position and cannot yet invest in new time- and capital-intensive facilities. In the United States, fuel suppliers lack a durable demand signal for HALEU given the uncertainty surrounding NFSA funds and the nascency of Gen IV designs that use this fuel.

Despite the $500 million commitment from HAP, this funding alone is insufficient to meet projected demand. Assuming that (1) the minimum practical single facility capacity is 12.5 metric tons per year, (2) six to 10 years of production at high throughput utilization is needed to recover capital, and (3) the cost of HALEU is roughly $20 million per metric ton, a practical bank would likely require on the order of $1.5 billion to $2.5 billion to support one facility and $3 billion to $5 billion for two facilities.[202,203,xxxix] The current HAP funding

xxxvii Certain Gen IV designs with high temperatures, such as Terrestrial Energy's ISMR reactor, use LEU to minimize enrichment supply chain risk.

xxxviii It should be noted that, of the two U.S.-origin technologies for HALEU production, one is currently under demonstration and the other remains under development at Oak Ridge National Laboratory.

xxxix Calculation: 12.5 metric tons/y * $20M/metric ton = $250M/year per facility; $1.5 billion for six years or $2.5 billion for 10 years; double for a second facility.

could support perhaps a total of 25 metric tons, which is below DOE's estimate of the cumulative demand by the early 2030s.[xl,204]

The HAP request for procurement (RFP), released in January 2024, will select recipients under IDIQ contracts, with the work conducted under various task orders. HALEU enrichment contracts will have a maximum duration of 10 years with a minimum order value of $2 million. Absent additional appropriations, the combination of the IDIQ structure and the low minimum order value falls short of supporting capital formation to build necessary HALEU production capacity. If and how much of the NFSA appropriations will ultimately flow to HALEU remain unknown, creating significant market uncertainty that fuel suppliers cannot make investment decisions upon.

NFSA aims to address this funding shortfall by establishing a revolving fund, so proceeds from sales of DOE's acquired fuel could subsequently be used to purchase additional fuel. However, this fund will not revolve fast enough given the long runway expected before sufficient HALEU demand materializes from Gen IV operation, constraining the utility of the revolving fund. If HALEU demand is slow to build early on, additional public funding will need to be injected into the program to bolster fuel supplier confidence to build and operate enrichment facilities.

National Security Considerations

Several national security activities in the U.S. require enriched uranium at various assays and forms. In 2017, NNSA outlined the particular assays, forms, estimated timelines when enrichment will be needed for, shown in Table 4.[205]

Table 4: **NATIONAL SECURITY ENRICHMENT REQUIREMENTS AND ESTIMATED TIMELINES**

Assay	Requirement	Estimated Timeline until Enrichment Need Arises	Estimated Magnitude of Enrichment Need *(metric tons of uranium per year)*
HALEU LEU (19.75%)	Research Reactors	2030	N/A
	Test Reactors	2025	N/A
	Demonstration Reactors	2030	N/A
LEU (4.75%)	Tritium Production	2038	54.6*
HEU (>93%)	Nuclear Naval Fleet	2060	N/A

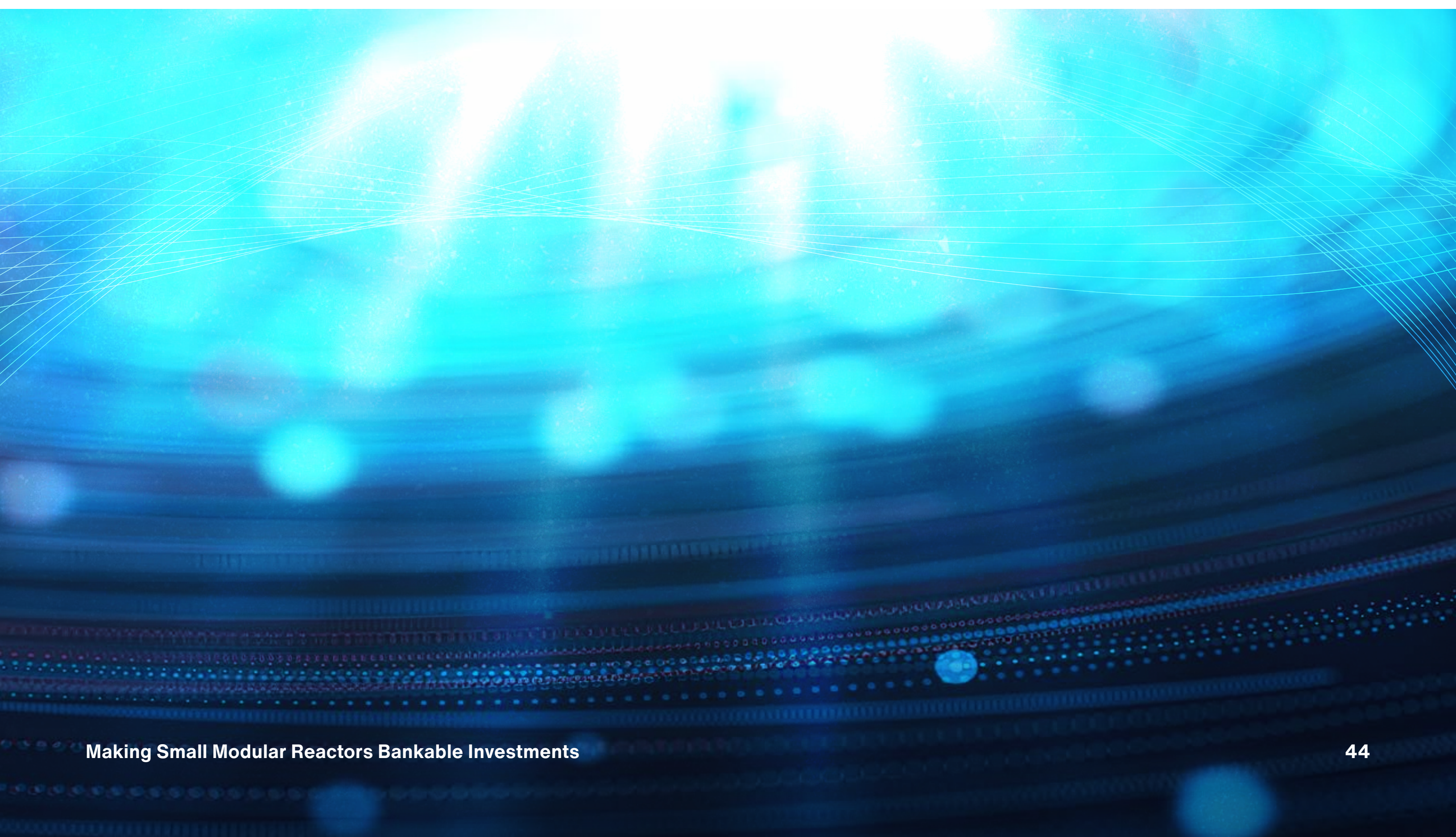
*To supply one pressurized water reactor reload (approximately 42.3 metric tons uranium) every year for two years and two reactor reloads every third year (84.6 metric tons uranium), for an average of 54.6 metric tons uranium per year.
Source: Department of Energy, 2017

xl As of May 2023, the cost of LEU was over $2,900 per kilogram (kg)—at the high end of historical prices, due to the dynamics around the Ukraine war. Thus, the LEU feedstock alone will cost about $13,000 per kg of HALEU produced. Given the cost of the LEU feedstock, the operating costs, and the potentially accelerated capital recovery that might be sought for an enrichment plant under a contract of limited length, the full cost of HALEU production could easily reach $20,000 per kg (i.e., $20 million/metric tons) or more.

Foreign-owned enrichers are currently operating under an international agreement that restricts the use of their enrichment technology to serve U.S. national security needs.[206,207] As a result, U.S. national security requirements must be entirely supported from a domestic supply chain, from uranium feed to fuel fabrication. While the U.S. has limited domestic uranium mining, milling, conversion, and fuel fabrication services, there is not an active enrichment facility utilizing domestic technology.

The absence of a domestic nuclear fuel enrichment facility using U.S.-developed technology presents a national security risk, potentially undermining national security objectives and nuclear deterrence.[208] To address this, the U.S., alongside substantial private investment, has supported the development of two centrifuge technologies. After more than 15 years of development, $2.5 billion in private investment, and several cooperative agreements with the DOE, Centrus' American Centrifuge technology successfully completed a full-scale LEU cascade demonstration in 2016 and is now conducting a small-scale HALEU demonstration.[209,210] Commercial deployment of the American Centrifuge technology is ready for scale; however, doing so will be dependent upon further government policy and program actions.

DUECE, a newer technology with a smaller footprint, has been under development at ORNL since 2016 as part of NNSA's Domestic Uranium Enrichment (DUE) program. While still a less mature option for meeting NNSA's requirements, the program aims to leverage DUECE for future national security requirements.[211] The next steps include an engineering-scale cascade testbed at ORNL, followed by a LEU pilot plant to demonstrate performance, reliability, and cost.[212]



Policy Recommendations

Recommendation 1: Congress should mandate that all new nuclear fuel supply contracts post-2028 contain a portion of fuel that would be eligible for national security purposes (unobligated fuel) pairing additional appropriations to cover any incurred premiums.

The United States has a strategic interest in opting for a portion of its fuel to serve both civilian and national security purposes. While allied and domestic supply of fuel enriched using foreign technologies can eventually address a significant portion of civilian nuclear needs, only U.S. facilities using enrichment technologies of U.S. origin, with U.S. sourced uranium, can serve national security requirements. As shown in Table 5, 14.9 million LEU SWU capacity is already licensed in the United States but has not been built, including 3.5 million LEU SWUs based on U.S. technology the latter of which is has the potential to be national security qualified (i.e., 23% of unbuilt SWU capacity could be made national security qualified).[213,214,215]

Table 5: **BUILT VS. LICENSED LEU CAPACITY IN THE UNITED STATES**

In addition to these facilities, the planned Eagle Rock Enrichment Facility (Orano) in Idaho Falls had obtained a license for an LEU facility with a capacity of 6.6 million SWU/yr. in 2011; however, it terminated the license in 2018, and the plant was never built. Orano recently expressed that it is reconsidering plans to build this facility.[216]

Facility	Current LEU SWU capacity *(million SWU/yr.)*	Licensed LEU SWU capacity *(million SWU/yr.)*	Licensed LEU SWU capacity not built *(million SWU/yr.)*	Licensed LEU SWU capacity which is national security eligible *(million SWU/yr.)*
Louisiana Energy Services facility, New Mexico (Urenco)	4.6	10	5.4	0
Global Laser Enrichment facility, North Carolina (SILEX Systems Limited)	0	6	6	0
American Centrifuge Plant, Ohio (Centrus)	0	3.5	3.5	3.5
Total	**4.6**	**19.5**	**14.9**	**3.5**

Data from: See first table mention in text for sources.

Congress and the administration should look to bolster civilian and national security enrichment supply chains holistically. A mandate to include some portion of national security-eligible uranium in supply contracts would act as a forcing mechanism to establish a domestic civilian nuclear fuel supply chain using U.S. technology. While this would fulfill a national security need, in the short term there may be a cost premium because of the need to restart or rebuild dormant operations and use domestic technologies. Moreover, this mandate would come into effect post-2028, acknowledging the time needed to replace Russian uranium products in the domestic market.

To kick-start this supply chain without passing along the premiums to customers, federal appropriations, perhaps from the Defense Production Act, should cover the difference from market price for a period of time. A contract-for-difference mechanism may be an appropriate model for this purpose. At the same time, domestic enrichment technologies should be cost competitive in the long term; a robust research, development, demonstration, and deployment (RDD&D) program to enable this should also be expanded. It is acknowledged that there is only one viable supplier that can provide the enrichment for these products in the near term; however, it is in the national interest to have at least two suppliers.

Recommendation 2a: DOE's Office of Nuclear Energy should consider a contract-for-difference option for HAP, paired with a domestic supply mandate, to better leverage limited federal dollars and encourage further private investment.

Recommendation 2b: HAP should include a termination option in its agreements to preserve capital should HALEU markets not materialize as projected.

With the limited appropriations available in HAP, the buy-and-sell model under the IDIQ is insufficient to establish a HALEU market. If HALEU production capacity were to receive all of the appropriations within the Consolidated Appropriations Act of 2024 ($2.7 billion) plus HAP ($500 million), totaling $3.2 billion, it could be sufficient to support two facilities. However, as mentioned, the revolving door likely will not revolve fast enough. Competing demand for these appropriations also is likely given the Russia ban.

A contract for differences under HAP would allow the current limited number of customers with HALEU demand to purchase at market rate, with appropriations covering any cost premium. Similar to Recommendation 1, there could be a mandate that a portion of produced HALEU be national security eligible. In recognition that this market is still quite small, the federal government could purchase a notional amount of HALEU now to support near-term demand, with the remaining Consolidated Appropriations Act funds to serve as premium coverage. An additional premium coverage for the national security portion could come from Defense Production Act funds.

Purchases made by the federal government can be resold later at the market rate. This contract for differences approach would still accomplish the goals of HAP: (1) to create a market that supports domestic investments in HALEU production facilities given the current small market and (2) to be a creditworthy intermediary, making commitments to buy the fuel before future buyers have sufficient credit or willingness to deploy.

If future demand for advanced reactors does not materialize sufficiently to absorb

HALEU commitments created by HAP, one approach is a termination option coupled with a termination payment in the purchase agreements. A termination option would allow HALEU producers to save the cost of procuring the LEU feed (saving on operational expenses). A complementary termination payment could be used to compensate producers for capital recovery embedded in foregone purchases. For example, if the HAP bank committed to supporting 10 years of purchases, and the LEU feed represents 65% of the cost of the HALEU, then a termination option after the fifth year of production would save about a third of the anticipated outlays of the bank, even after making a termination payment to cover the capital recovery in foregone purchases.[xli]

Even if the government were to terminate the program, production assets would be paid for so producers could sell HALEU to other potential customers.

Clear National Pathways of Spent Nuclear Fuel Management and Disposal

The Nuclear Waste Policy Act (NWPA) of 1982 set the ultimate strategy for commercial spent fuel as disposal in a deep geological repository, and the 1987 amendments to that act (Public Law 100-203, Part E) selected Yucca Mountain in Nevada as the only site to be examined for disposal.[217] This set off decades of pushback from Nevada, and ultimately the project was terminated.[xlii] While there have been multiple high-level efforts to set a comprehensive SNF strategy in the United States, like the 2012 Blue Ribbon Commission (BRC) on America's Nuclear Future, there is no clear path forward for the siting, licensing, and construction of a geological repository for the disposal of commercial spent nuclear fuel.[218] This is a long-term issue that far predates the current commercial interest in SMRs and has a long runway before it is comprehensively resolved.

The lack of a clear path forward in the current federal nuclear waste management program, if not addressed, could eventually emerge as a significant impediment to large scale SMR deployment. Findings from a survey conducted during this study[219] demonstrate the hesitancy surrounding new development amid an uncertain future for waste, even for stakeholders already interested in SMR development:

- Lack of a clear national pathway for nuclear waste management was a top concern of all stakeholders interested in new nuclear development, including communities; federal, state, and local governments; and the nuclear industry.

xli In the above example, for each facility the full cost for 10 years would be $2.5 billion, but the savings in feed costs available through a termination option after the fifth year would be $13 million/metric ton * 12.5 metric tons/yr. * 5 years or about $0.8 billion of that amount (32%). Additional savings could result if the enrichment facility's annual operating costs are also eliminated through termination.

xlii For a useful summary of the history of the NWPA, the debates over the Yucca Mountain site, and its ultimate termination, please refer to Matt Bowen, "U.S. Spent Nuclear Fuel Policy: The Current Stalemate and Policies to Generate Momentum and Support Advanced Reactor Investment," EFI Foundation, February 2024.

- Communities with existing nuclear power plants expressed concern about storing accumulated nuclear waste with no path forward.

- Of the communities interested in hosting nuclear facilities broadly, a spent fuel facility was the least preferred.

The waste problem persists amid new nuclear innovations. SMRs do not eliminate the need for geological disposal of spent nuclear fuel, and many of the advanced reactors under development would generate waste streams for which there is little experience in the United States and potentially anywhere in the world.[xliii,220,221] As such, actions must be taken now to lay the groundwork for successful SMR deployment and create public confidence on this long-stalled issue.

Following one of the BRC's recommendations, DOE has laid out a nuclear waste management plan that features a consent-based siting process to pinpoint consolidated interim storage facilities. These facilities would temporarily store spent fuel before geological disposal. While creating interim storage facilities is a step forward, the future of a permanent geological disposal facility is still uncertain. Some stakeholders disagree with interim storage and would prefer to send the waste directly to geological repositories or deep boreholes.[222] Questions surround implementation of consent-based siting, namely because of the difficulty of reaching consensus for all stakeholders (e.g., local, state, federal, and Tribal governments; communities; and regulatory authorities).

Recommendations: Creating Momentum for Nuclear Waste Management

In 2012, the BRC provided eight high-level recommendations on a way forward for the U.S. nuclear waste program, and since then modest progress has been made. Congress appropriated money in FY2021 and directed DOE to begin a consent-based siting process for a consolidated interim storage facility (CISF), but not for disposal facilities. DOE awarded money in 2023 to groups to provide engagement and training resources for communities interested in learning more about interim storage, though it is not currently soliciting volunteer communities.[223] However, Congress has not amended the Nuclear Waste Policy Act and its amendments to allow for any CISF, and the act still precludes DOE from constructing such a facility until a repository developed under the NWPA has been issued a construction license by the NRC.[224]

However, building on BRC recommendations as well as those made by other prominent reports such as the National Academies' *Merits and Viability of Different Nuclear Fuel Cycles and Technology Options and the Waste Aspects of Advanced Nuclear Reactors*, steps can be taken to create momentum for the national nuclear waste management program.[225]

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xliii Some advanced fuels could result in changes of the amounts of spent nuclear fuel to be disposed of, its chemical compositions, and the specific radionuclide inventories.

Recommendation 1: Congress should amend the NWPA to allow interim storage before a permanent geological waste disposal site is licensed.

To instill confidence in DOE's consent-based CISF process, the NWPA must be amended to allow for interim storage. Current law restricts the siting and construction (but not planning) of both federally and privately owned consolidated interim storage facilities. As was supported by the BRC report, interim storage is a logical next step in managing spent nuclear fuel by removing it from NPP sites nationwide and reducing the number of locations with SNF. In May 2024, DOE determined that a federal consolidated interim storage facility is needed to help manage the nation's commercial spent nuclear fuel.[226] With this determination, DOE can begin work on research and development, conceptual design, management plans, and cost and schedule estimates.[227] However, without congressional approval for a CISF, DOE's work will be limited to community engagement and activities aligned with interim site identification, which perpetuates the uncertainty in the national SNF strategy. Congressional action that decouples interim storage from permanent geological waste disposal will reduce the complexity of managing SNF as well as enable critical work to occur now in service of downstream permanent disposal (see Recommendation 4).

Recommendation 2: Create Company-held dedicated escrow or trust accounts instead of payments to the Nuclear Waste Fund.

The NWPA authorized DOE to enter contracts with nuclear power plant owners for acceptance of spent nuclear fuel, subsequent transportation, and disposal. In exchange for the federal government taking responsibility for the spent fuel, the utilities would begin paying 0.1 cent per kilowatt-hour of electricity generated by the reactors into a new Nuclear Waste Fund (NWF), which was intended to cover the costs of the program. In 2014, the U.S. courts shut off the fees that nuclear power plant owners were paying into the NWF because of the partial break of contract by DOE in implementing the federal nuclear waste management program.

The standard contract could be restructured to address this issue by allowing NPP owners to establish company-held dedicated escrow or trust accounts for SNF disposition, similar to the NRC's current requirement for NPP owners to set aside funds for decommissioning (and not use it for any other purposes). At the same time, the standard contract would need to state that adequate interim storage is available at or near the reactor site for all SNF generated during the operation of the SMR. While the NRC does not explicitly require plants to store all SNF for the entirety of their operation, it does mandate that they have sufficient storage capacity to manage the spent fuel they produce during their operational lifespan. This is a new approach to managing SNF; treating it as an NPP-level requirement from both a business and policy standpoint while ensuring adequate resources are available for its successful management.

Recommendation 3: DOE should establish a dedicated office for waste management within the Department and work with Congress to authorize establishment of quasi-government spent nuclear fuel management corporation

Establishing a dedicated office at DOE would improve the current organizational structure by removing competing priorities (e.g., other programs in the Office of Nuclear Energy) as well as layers of bureaucracy in the reporting relationships within the Department. A dedicated office staffed by professional experts could enable greater continuity of measures that could span multiple Administrations and Congresses. The idea appears to have broad support. For instance, a 2021 letter from eight organizations to Secretary of Energy Jennifer Granholm requested that she establish a dedicated office for implementing U.S. nuclear waste management.[228]

In addition, Congress could consider legislation to charter a new federal corporation which would be less prone to political interference, more adaptable to changing conditions, and better able to manage costs and schedules.[229] The board of directors would be selected by the President and approved by the Senate and would oversee management and operations. An advisory group would provide broader perspective and advice. The mission, structure, responsibilities, and powers of the corporation would be clearly delineated in the legislation.

In a 2022 letter from U.S. Rep. Mike Levin (D-Calif.) to the House Appropriations Committee's Subcommittee on Energy and Water Development and Related Agencies, Levin called for a joint National Academies of Science, Engineering and Medicine, and National Academy of Public Administration study on the structure of a new single-purpose agency to implement the SNF management program.

Recommendation 4: Regional approaches to consolidating interim storage paired with an expanded SNF RDD&D program.

A regional approach to consolidating interim storage would reduce the transportation burden and perhaps enhance the political feasibility of interim storage efforts. Regional sites would lower the number of interstate shipments and involve a smaller number of cask-miles[xliv] for a given transportation campaign. Regional SNF shipments, rather than from shutdown sites nationwide, might be more acceptable to state officials. In some cases, consolidation of sites within a state may be the best path forward. The hosting state would at least have a smaller number of storage sites inside its borders, and local communities could reclaim the land associated with the other sites. International lessons learned are available from countries further along in comprehensive storage models, countries such as Canada, Finland, and Sweden.

At the same time, to increase the confidence and capability of SNF management in light of the expansion of nuclear developments across the United States, a major new program focused on the safety of spent fuel storage and innovation

xliv A cask-mile is a unit of measurement that represents the transportation of one cask containing radioactive material over a distance of one mile.

in transport, processing and storage technologies is recommended. This would expand upon existing research, development and demonstration efforts such as full-scale storage cask demonstration; spent nuclear fuel railcar transportation; and long-term performance of disposal systems in three main geological rock types: clay/shale, salt, and crystalline rock.

Enhancing Community Acceptance of SMR Facilities

Social acceptance of SMR facilities is necessary to encourage investment in SMR projects in communities. If there is a negative impression of SMRs among important local stakeholders, then it will be quite challenging to gather the broad-based social and political support needed to obtain licensing and other entitlements. Moreover, proceeding with any project that does not have community support would be a reputational risk to any project sponsor, creating substantial headwinds and reducing the impetus to continue to pursue the opportunity.

One of the ways to increase the prospects of social acceptance is by creating and sharing information across multiple stakeholders so high-quality decisions can be made very early in the development process. This allows project sponsors to understand the development needs and wants of a community and to reflect them in the project design. It also allows the community to understand the costs and benefits of the development and actively shape outcomes.

This is a community-level activity. Public perceptions of nuclear in general, or SMRs in particular, may be of use. However, a well-informed understanding of specific communities' perceptions of hosting SMR facilities, rather than generalized public perceptions of nuclear, is most salient from a bankability perspective.

How to enhance community acceptance of SMR facilities?

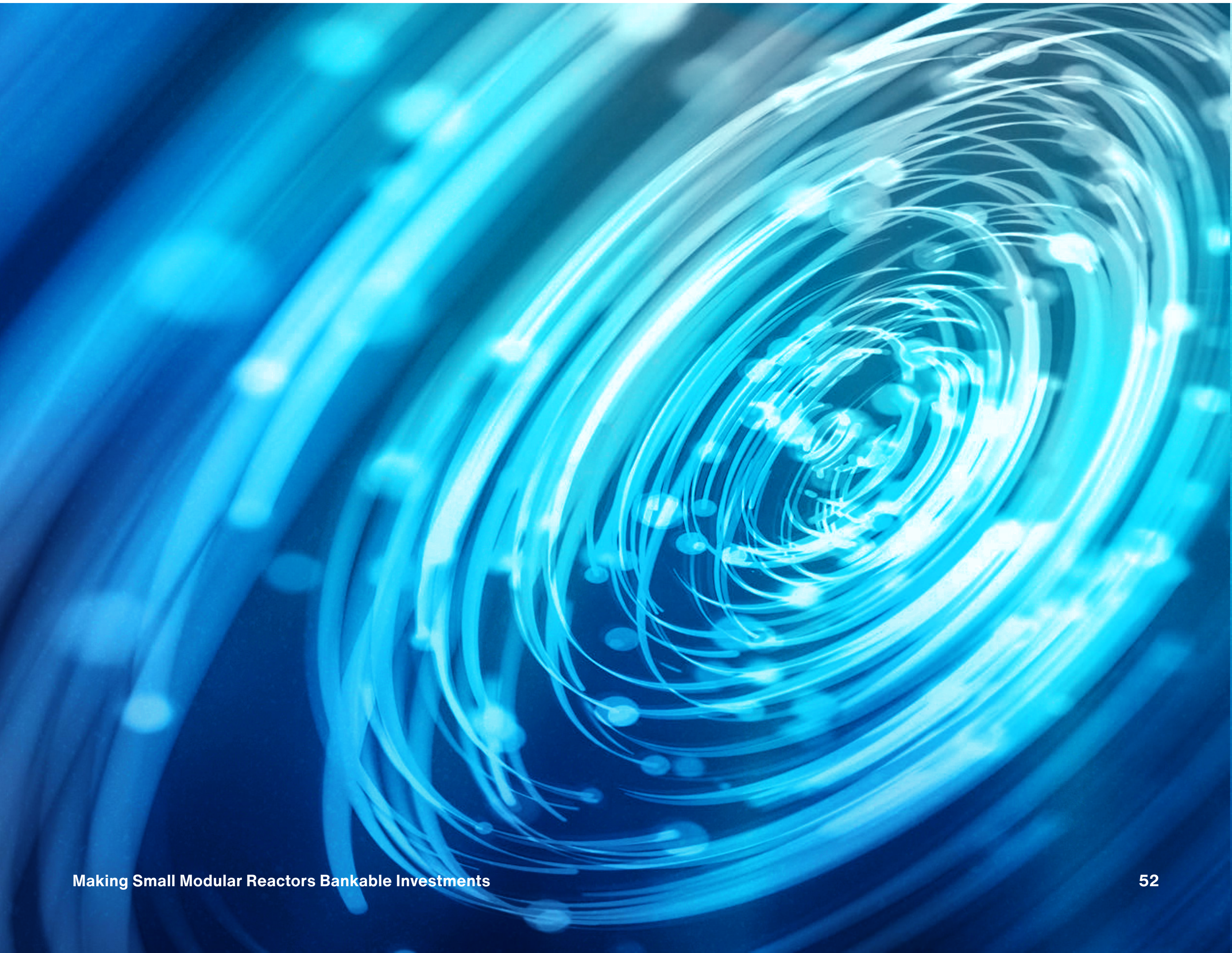
To examine the forces that determine community perceptions of SMR facilities, a primary analysis using a survey approach, paired with semi-structured interviews, was conducted with representatives of the communities notionally interested in SMRs. Their interest was indicated by their participation at the second annual Nuclear Development Forum of the Energy Communities Alliance (ECA) in May 2023. [xlv] The survey and semi-structured interviews were conducted in the lead-up to and at the ECA Forum.[230]

Results indicate that communities' willingness to host SMR facilities is driven significantly by economic and social benefits, such as creating new jobs, attracting new industries, and securing reliable energy sources. Communities also want to be fully informed about the impact of SMR facilities from an unbiased group that they

xlv The Energy Communities Alliance (ECA) is a membership organization of local governments adjacent to or impacted by U.S. Department of Energy activities. In 2020, ECA established the New Nuclear Initiative to help define the role of local governments in supporting the development of new nuclear technologies, for both DOE and non-DOE legacy communities alike. ECA's annual New Nuclear Forum is held under the auspices of the New Nuclear Initiative.

trust. Community members were concerned that pushback from state stakeholders (i.e., legislators, governors, anti-nuclear groups, or state citizens) against SMR facilities could impede or eventually stop a project, even if the community wanted to host it. Moreover, the lack of a clear and implementable national pathway for nuclear waste management was a material concern of all stakeholders, including state and community members.

These findings suggest that gaining community acceptance for SMRs requires a number of actions from a variety of stakeholders. The project developer must seek a clear articulation of the needs and wants from the host community and reflect an acceptable level of these into the project. What constitutes an acceptable level is a negotiation among the stakeholders. It is predicated on a well-informed community that receives information in a way that is understandable to them from (real and perceived) unbiased and credible sources. It is also predicated on a wider set of informed and engaged stakeholders, in particular state-level authorities, given their ability to influence community-level decisions.



Recommended actions

The most holistic path to foster community acceptance requires a number of actions, methods, and participation from a variety of stakeholder groups, each considered critical in shaping community perception and acceptance.[xlvi] Project developers in particular have an interest in identifying who these stakeholders are and facilitating collaboration. Developers must take the lead and build relationships based on trust, transparency, benefit-sharing, and shared participation in decision-making processes. [231,232]

For SMR projects, especially if it is FOAK and/or the first nuclear deployment for a community, project developers should engage early with diverse and small groups of local stakeholders to understand community-level concerns and development priorities. Developers should aim to provide long-term and recurring benefits to the host communities that alleviate potential concerns and align with the preferred development path. This may require creating a portfolio of benefits through partnerships (e.g., industries in need of emissions-free heat and power) or include binding agreements. In parallel, local educator groups and the nuclear industry could support project developers by building and disseminating transparent information about SMRs.

To create the conditions necessary for longer-term scale-up of SMR deployments in the United States, the federal government, state governments, and the nuclear industry should continue to work together to enhance public education, knowledge, and capacity-building. The outreach programs under DOE's Gateway for Accelerated Innovation in Nuclear (GAIN), Office of Nuclear Energy's Consent-Based Siting Consortia coupled with its Nuclear Energy University Program, NARUC-NASEO's Advanced Nuclear State Collaborative, and the ECA are examples of efforts focused on community education and engagement, though these efforts ought to be scaled up.

Recommendation 1: Project developers should place SMRs within a larger economic development narrative, working with potentially new and existing industries to ensure long-term and recurring economic and social benefits to the host communities.

Bringing industrial facilities together with SMRs would help enhance community acceptance since it increases economic and social benefits to the host community, such as providing jobs and expanding the community's tax base. Providing clean power and heat to existing industrial facilities in the host community could also increase the benefits because securing energy sources for industrial facilities is a concern, especially in circumstances where there is a retiring fossil fuel-fired power plant. Project developers should collaborate with and defer to communities to define their chosen vision.

xlvi Many of these general best practices are contained within DOE's Consent-based Siting for CISF initiatives.

Recommendation 2: Project developers should reach out to diverse and small groups of local stakeholders in the potential host community before any public announcement of the project to understand and be aligned on SMR facilities' contributions to the community's preferred development path.

The impacts of SMR facilities should be aligned with the host community's development pathway because energy facilities are and will become a critical part of the community's identity, especially in nuclear legacy communities and coal communities. In the early phases of project development, in advance of any public announcement of the project, project developers should understand the priorities and concerns of the potential host community and start a conversation on SMR facilities' potential contributions to community development.

Recommendation 3: The Secretary of Energy should create a new office within the department focused on gathering, producing, and conveying accessible, accurate, and reliable information to the public. This office can likely be established without an act of Congress.

To provide communities with transparent information that empowers informed engagements and supports trust building, The Secretary of Energy should create a new office within the department focused on gathering, producing, and, conveying (or supporting other trusted stakeholders conveying) accessible, accurate, and reliable information to the public. This office can likely be established without an act of Congress, and would involve coordination with relevant national laboratories, the Office of Energy Justice and Equity, the Office of Nuclear Energy, OCED, the NRC, the White House Office of Science and Technology Policy, and the Environmental Protection Agency.

Expanding upon the current efforts of GAIN at the Idaho National Laboratory, this office should be staffed to support energy communities, existing nuclear communities, and those interested in hosting new nuclear facilities. Importantly, the office would collaborate with impartial nuclear experts, project developers, academia, and communities to create a comprehensive SMR community engagement database. This database should build on existing GAIN materials and provide accessible information on sites, costs, risks, benefits, reactor technologies, safety, and environmental data for a lay audience. Integrating DOE resources, international sources of information and credible NGOs (e.g., ONE, NRC, OCED-NEA SMR Dashboard, EIA Energy Atlas, ThirdWay's Advanced Nuclear Map, etc.) inputs into this user-friendly platform will enhance transparency.

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