Pathways to Commercial Liftoff: Advanced Nuclear

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Comments

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Executive Summary

These D&D Pathways reports aim to establish a common fact base with the private sector around the path to commercial liftoff for critical clean energy technologies. Their goal is to catalyze more rapid and coordinated action across the full technology value chain.

U.S. domestic nuclear capacity has the potential to scale from ~100 GW in 2023 to ~300 GW by 2050—driven by deployment of advanced nuclear technologies. Power system decarbonization modeling, regardless of level of renewables deployment, suggests that the U.S. will need ~550–770 GW of additional clean, firm capacity to reach net-zero; nuclear power is one of the few proven options that could deliver this at scale, while creating high-paying jobs with concentrated economic benefits for communities most impacted by the energy transition.

Advanced nuclear includes a range of proven and innovative technologies. There are two major categories of advanced nuclear reactors: Generation III+ (Gen III+) and Generation IV (Gen IV). Gen III+ reactors are similar to the conventional reactors operating in the U.S.—they use water as a coolant and low-enriched uranium (LEU) as fuel. Gen IV reactors will use novel fuels, e.g., high-assay, low-enriched uranium (HALEU), and coolants that have not been used by the conventional U.S. nuclear fleet; these technologies offer some advantages over water-cooled reactors, in particular for non-electric applications. Advanced nuclear is also generally grouped into three main size categories: large reactors (~1 GW), small modular reactors (~50-300 MW), and microreactors (50 MW or less). Small modular reactors (SMRs) can provide more certainty of hitting a predicted cost target and are likely to play an important role in the early scale-up of nuclear power; scaling the industry to a full 200 GW of new nuclear capacity may require large nuclear reactors as well.

Advanced nuclear provides a differentiated value proposition for a decarbonized grid. Nuclear energy generates carbon-free electricity, provides firm power that complements renewables, has low land-use requirements, and has lower transmission requirements than distributed or site-constrained generation sources. It also offers significant regional economic benefits, can aid in an equitable transition to a net-zero grid, and has a wide variety of use cases that enable grid flexibility and decarbonization beyond the grid.

To unlock deployment at scale, Nth-of-a-kind (NOAK) advanced nuclear overnight capital costs may need to approach ~$3,600 per kW. While the estimated first of a kind (FOAK) cost of a well-executed nuclear construction project is ~$6,200 per kW, recent nuclear construction projects in the U.S. have had overnight capital costs over $10,000 per kW. Delivering FOAK projects without cost overrun would require investment in extensive upfront planning to ensure the lessons learned from recent nuclear project overruns are incorporated. Subsequent nuclear projects would be expected to come down the cost curve to ~$3,600 per kW after 10-20 deployments depending on learning rate; this cost reduction would largely be driven by workforce learnings and industrial base scale-up.

However, the nuclear industry today is at a commercial stalemate between potential customers and investments in the nuclear industrial base needed for deployment—putting decarbonization goals at risk. Utilities and other potential customers recognize the need for nuclear power, but perceived risks of uncontrolled cost overrun and project abandonment have limited committed orders for new reactors.

Waiting until the mid-2030s to deploy at scale could lead to missing decarbonization targets and/or significant supply chain overbuild. Rapidly scaling the nuclear industrial base would enable nearer-term decarbonization and increase capital efficiency. If deployment starts by 2030, ramping annual deployment to 13 GW by 2040 would provide 200 GW by 2050; a five-year delay in scaling the industrial base would require 20+ GW per year to achieve the same 200 GW deployment and could result in as much as a 50% increase in the capital required.

New nuclear deployment starting in 2030
Annual deployment (GW/yr) built and Cumulative GW online

New nuclear deployment starting in 2035
Annual deployment (GW/yr) built and Cumulative GW online

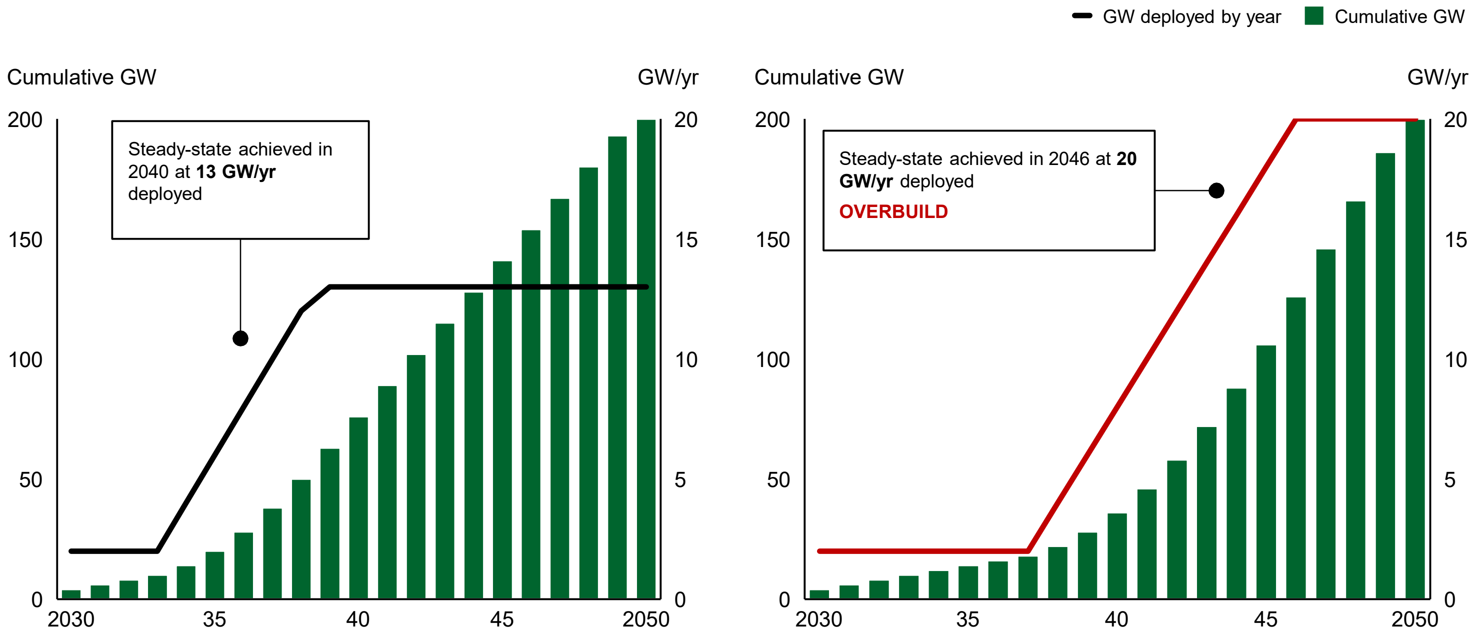


Figure 1: New nuclear build-out scenarios and implications for industrial base capacity requirements

The path to commercial scale for U.S. advanced nuclear requires three overlapping stages to realize the industry's potential to support the energy transition: (1) committed orderbook generation, (2) project delivery, and (3) industrialization

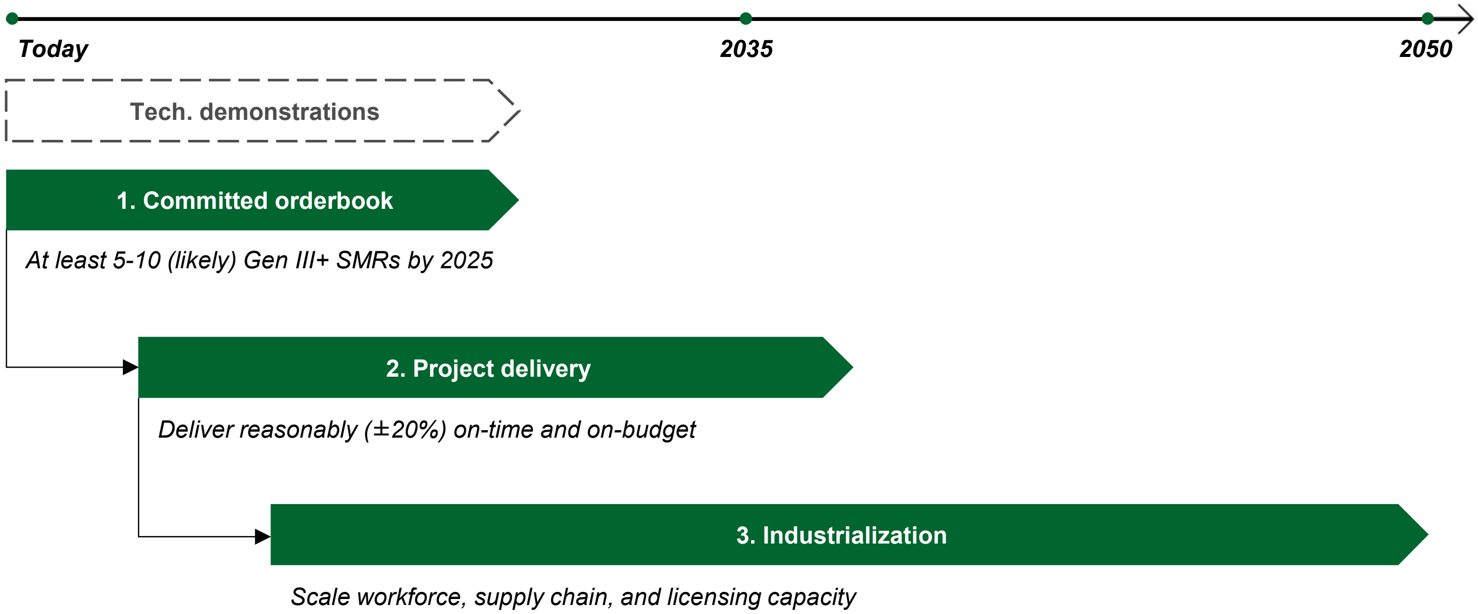


Figure 2: Path to the scale-up of the advanced nuclear industry to meet 2050 decarbonization targets

- **Committed orderbook:** A committed orderbook, e.g., signed contracts, for 5–10 deployments of at least one reactor design by 2025 is required to catalyze commercial liftoff in the U.S. Given expressed U.S. utility risk tolerances, it is likely that the first design to reach a critical mass of orders may be a Gen III+ SMR, which could be followed in parallel or sequence by Gen IV reactors.

- **Project delivery:** Once the orderbook for the first deployments is established, delivering the first projects reasonably on-time and on-budget (i.e., ± 20%) will be essential for generating sustained demand and commercial momentum.

- **Industrialization:** Once the industry has gained momentum and new projects are being delivered with significantly reduced government support, the industrial base, including workforce, supply chain, and licensing, will need to be scaled up with sufficient lead time.

Reaching 200 GW of new nuclear capacity in the U.S. by 2050 will require deliberate action by both the public and private sectors. Potential solutions identified by industry and investors to support to the development of a committed orderbook include:

Developing a committed orderbook could be facilitated by pooling demand, e.g., with a consortium of utilities. Participation in such a model could be accelerated with some form of financial support (either public or private) to help de-risk the first 5-10 projects and could take advantage of opportunities to transition retiring fossil assets with new nuclear assets. Cost overrun insurance, financial assistance, the government acting as an owner, and the government acting as off-taker are four possible approaches to accelerating orders.

Delivery of projects on-time and on-budget (± 20%) could be enabled by incorporating lessons learned from Units 3 and 4 at Vogtle around investment in upfront planning and scheduling. It could also be supported by the development of an institutionalized project management and development entity. Commitments to some of these principles could be included as contingencies for receiving the financial support for the orderbook.

Full scale industrialization of advanced nuclear power through 2050 would require advancements in the following areas across the value chain:

- **Workforce:** The U.S. would need ~375,000 additional workers with technical and non-technical skillsets to construct and operate 200 GW of advanced nuclear.

- **Fuel supply chain:** The U.S. would need an additional ~5,000 MT per year of additional fuel fabrication capacity. To fabricate this much fuel, the U.S. would also need to mill an additional ~50,000 MT per year of U_3O_8, to produce ~65,000 MT per year of UF6 through conversion, and have an additional ~30M separative work units (SWU) per year of enrichment capacity, including HALEU enrichment capacity, which currently does not exist in the U.S.

- **Component supply chain:** The U.S. would need to substantially grow the component supply chain to support 200 GW of advanced nuclear; the largest gap is in large forgings.

- **Licensing:** The NRC would need to scale its license-application capacity from ~0.5 GW per year to 13-GW-per-year to meet projected demand. This would likely require significant additional resources for the NRC. The licensing process could be streamlined through deliberate actions from both the NRC and the industry.

- **Spent nuclear fuel:** The U.S. should continue efforts to identify sites for consolidated interim storage and permanent disposal of spent nuclear fuel. New legislation would be required to build a federal consolidated interim storage facility and allow development of geologic repositories for permanent disposal at sites other than Yucca Mountain, Nevada.

Advanced nuclear can play a critical role in strengthening energy security, reliability, and affordability while generating high-quality, high-paying jobs and facilitating an equitable energy transition. Industry, investors, government, and the broader stakeholder ecosystem each has a role to play in ensuring advanced nuclear achieves commercial liftoff and rises to meet the challenge in time.

Chapter 1: Introduction and Objectives

This report outlines pathways to commercialization for advanced nuclear power, with the objective of identifying the critical unlocks needed for advanced nuclear to achieve commercial liftoff.[1] This report also describes DOE and USG actions aimed at overcoming industry challenges and clearing the way for large-scale, near-term private investment.

Critical to this effort is the ongoing engagement of stakeholders across the advanced nuclear value chain, including reactor designers, utilities, alternative off-takers, fuel suppliers, component suppliers, regulators, investors, and more. This report builds on earlier research from the Department of Energy, National Laboratories, research institutions, and other organizations. Prior DOE publications[2] leveraged include, but are not limited to:

- Examining Supply-Side Options to Achieve 100% Clean Electricity by 2035
- Nuclear Energy—Supply Chain Deep Dive Assessment
- Factors Impacting Nuclear Energy Share in U.S. Energy Markets
- Capital Cost and Performance Characteristic Estimates for Utility Scale Electric Power Generating Technologies
- Investigating Benefits and Challenges of Converting Retiring Coal Plants into Nuclear Plants
- United States Nuclear Manufacturing Infrastructure Assessment
- Advanced Fuel Cycle Cost Basis Report
- Annual Energy Outlook 2022
- Cost Sensitivity Analysis for Consolidated Interim Storage of Spent Fuel

This report focuses on the pathways required for advanced nuclear to scale commercially and achieve U.S. decarbonization goals. For purposes of this report, advanced nuclear technologies include Gen III+ and Gen IV reactors in three categories: large reactors, small modular reactors (SMRs), and microreactors. This report examines the nuclear value chain—from design to operations—and considers the critical challenges that must be addressed for advanced nuclear to accelerate and support the U.S. achieving its decarbonization goals. Note that nuclear fusion is not covered in this report given it will follow different pathways to demonstration and deployment.

This report is technology and business-model agnostic. It is not meant to be a comprehensive evaluation of all potential technologies and business models that could be deployed. This report uses analyses and stakeholder engagement to identify and evaluate the actions most likely to impede or support acceleration of advanced nuclear commercialization, including what industry, government, and other stakeholders can do to accelerate advanced nuclear deployment. It should be considered a working document and will be refreshed on a regular basis to incorporate the latest developments in advanced nuclear technologies and business models.

1 For purposes of this report, “liftoff” refers to the economic and technical state at which the industry becomes self-sustaining in service of meeting U.S. decarbonization goals.
2 Many additional publications from non-DOE sources were also consulted.

Chapter 2: Current State – Advanced Nuclear Technologies and Markets

Section 2.a: Advanced nuclear and its role in the energy transition

Key takeaways

- Modeling results indicate achieving net-zero in the U.S. by 2050 would require adding ~550–770 GW of additional clean, firm power; ~550 GW with higher renewables buildout and ~770 GW with renewables buildout bounded by limitations from transmission, land use, regional characteristics, etc.
- Advanced nuclear could provide ~200 GW of this capacity addition, comparing favorably with other clean, firm options (e.g., renewables paired with long duration energy storage, fossil with carbon capture, geothermal)
- Six features contribute to advanced nuclear's value proposition in a decarbonized grid: clean generation, firmness, low land-use, low transmission requirements, regional economic benefits, and supplementary use cases
- For more on the energy and environmental justice value proposition and considerations for advanced nuclear, see Section 3.a

Achieving net-zero in the U.S. by 2050 would require ~550–770 GW of additional clean, firm capacity; modeling results indicate demand for 200+ GW of new nuclear capacity

System level decarbonization modeling, regardless of renewables deployment, suggests that the U.S. would need significantly more clean, firm capacity to reach net-zero (Figure 3). There are only a few options for clean, firm power, and nuclear power is one of the most viable options proven at large scale, with ~100 GW [3] of nuclear reactors currently operating across the U.S., beginning in the 1950s.

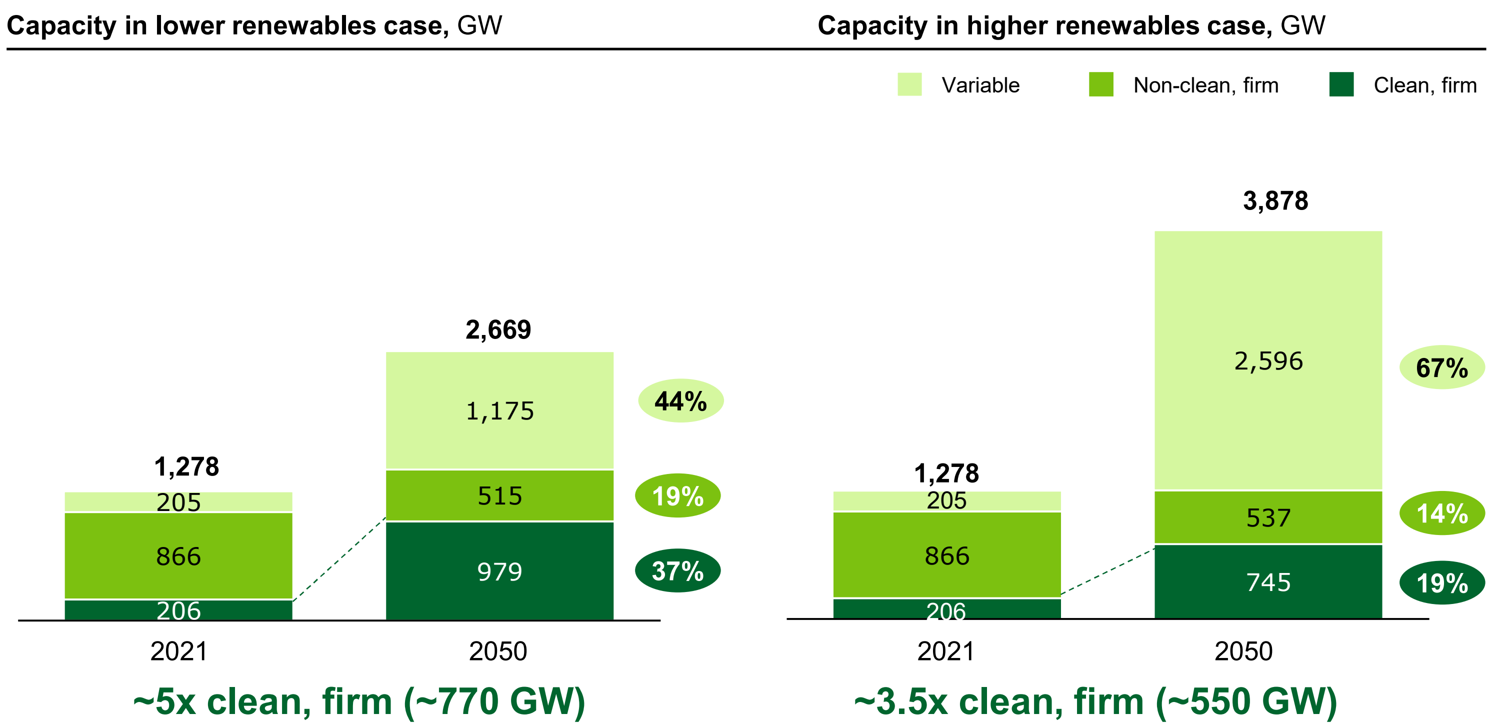
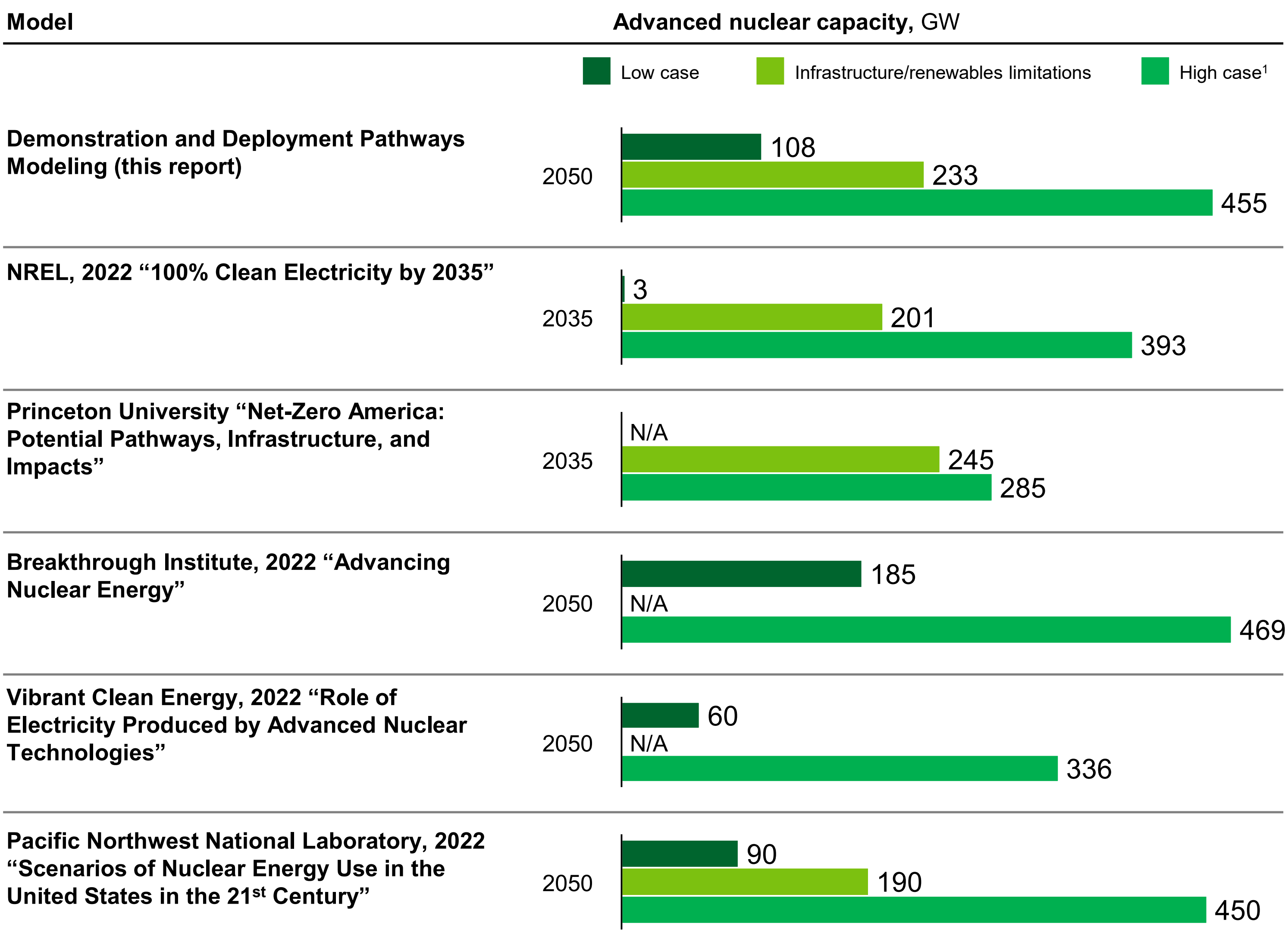


Figure 3: Additional capacity sources in a decarbonized grid in renewables scenarios

3 Note: throughout this report, GW and MW refer to gigawatts and megawatts of electric capacity.

Multiple system level decarbonization modeling exercises over the last two years have concluded that, especially with estimates for renewables buildout that account for limitations from transmission expansion and land use, significant new nuclear power would be required by 2050 (Figure 4). These estimates for limitations on renewables buildout come from current understanding of land-use intensity, regional siting requirements, supply chain, transmission, and interconnection difficulties that increasingly impact utility-scale deployment. Throughout this report, 200 GW of new advanced nuclear power capacity is used as a benchmark for substantiating what it would take to deploy at scale, a mid-point from modeling exercises that appears ambitious yet achievable.

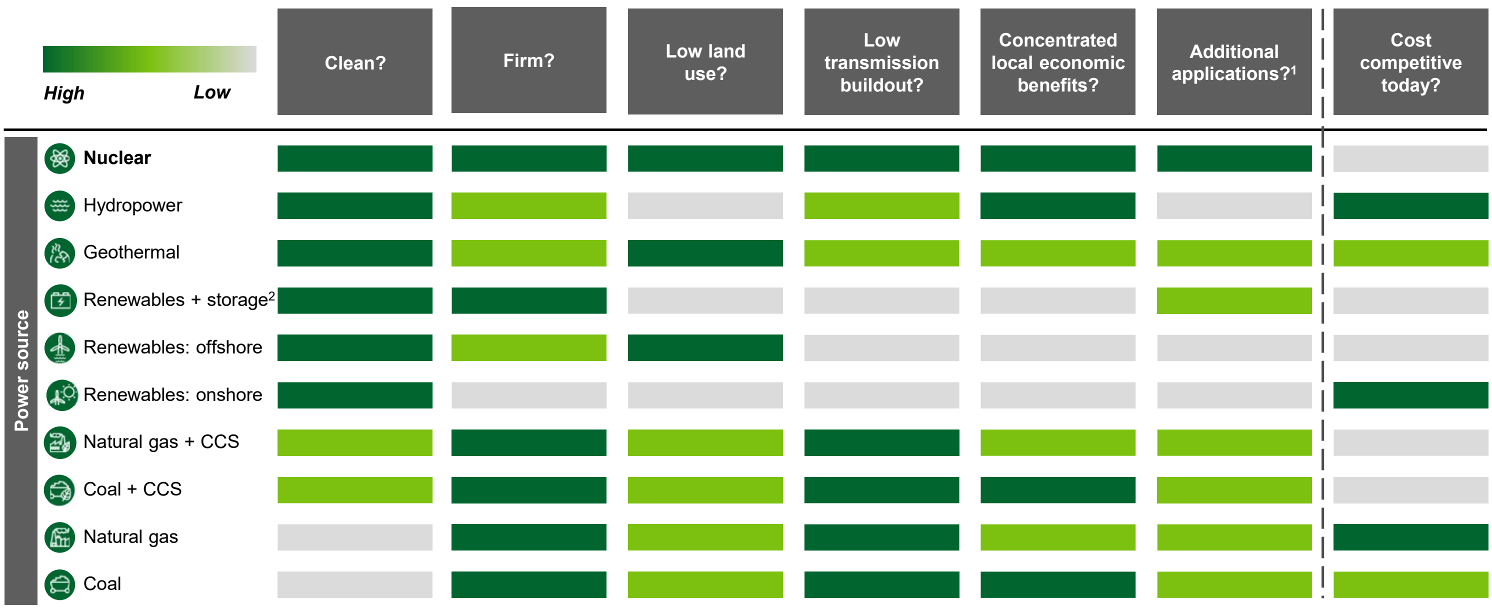
This level of deployment is consistent with The Long-Term Strategy of the United States: Pathways to Net-Zero Greenhouse Gas Emissions by 2050, which includes scenarios with substantial increases in U.S. nuclear capacity and electricity generation.[i]



1.“Low” and “high” refer to the level of nuclear build out; methodology for “low” and “high” nuclear build-out cases differ report to report

Figure 4: New nuclear capacity in a net-zero grid, based on various modeling efforts

Six features contribute to advanced nuclear power's differentiated value proposition for a decarbonized grid (Figure 5)



1. Additional applications include clean hydrogen generation, industrial process heat, desalination of water, district heating, off-grid power, and craft propulsion and power
2. Renewables + storage includes renewables coupled with long duration energy storage or renewables coupled with hydrogen storage

Figure 5: Select elements of nuclear's value proposition as compared to other power sources

1. Nuclear energy generates clean, carbon-free electricity

Nuclear power has the lowest lifecycle emissions of any major generating energy source,[ii] providing electricity to the grid with the lowest CO2 emissions per megawatt-hour of any currently available technology.

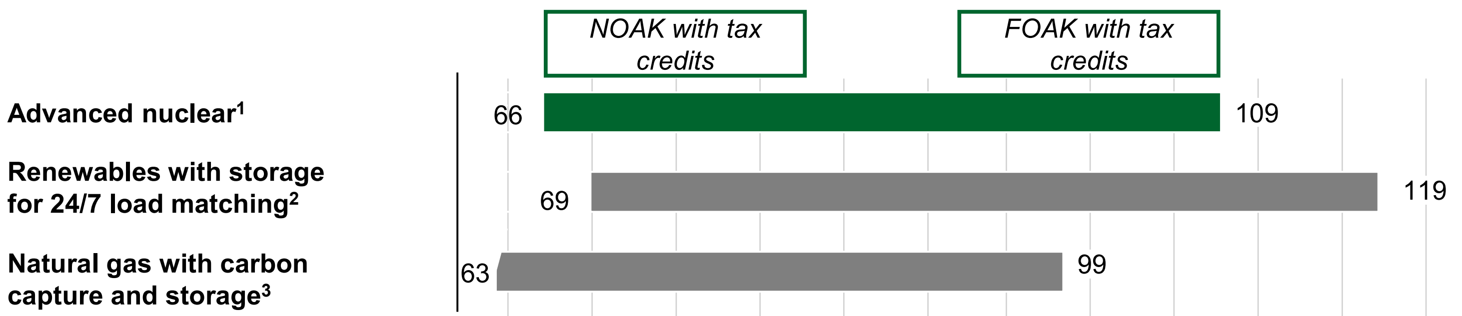
This carbon-free characteristic also means that utilities can replace more carbon-intensive generation (e.g., coal) with nuclear to achieve federal, state-, local-, or company-level emissions targets. This is especially important for players that are used to operating a system with a large amount of baseload power (e.g., coal)—deploying nuclear as a replacement for bulk power generation will require less change across the rest of the grid to accommodate high levels of variable renewables. By reducing air pollution from other health-harming emissions, nuclear generation also introduces the potential for significant social and health benefits for frontline energy communities hosting high-emitting energy sources.[iii]

2. Nuclear provides firm power that complements renewables in a deeply decarbonized system

System modeling shows that while renewables will play an essential role, decarbonizing the last ~20% of the grid would be very difficult and expensive without firm power.[iv] Firm power refers to generation sources that can provide stable energy supply during all seasons and during periods of weeks up to months. With an increasing portion of the grid supported by renewables, the value of grid stability provided by firm power increases.

As a clean, firm power source, nuclear complements variable renewable generation and is expected to be cost competitive with other sources of clean, firm power (e.g., renewables with long duration energy storage, natural gas with carbon capture) as each of these technologies is demonstrated at scale and moves down the cost curve (Figure 6).

Estimated LCOE of clean firm energy resources, $/MWh

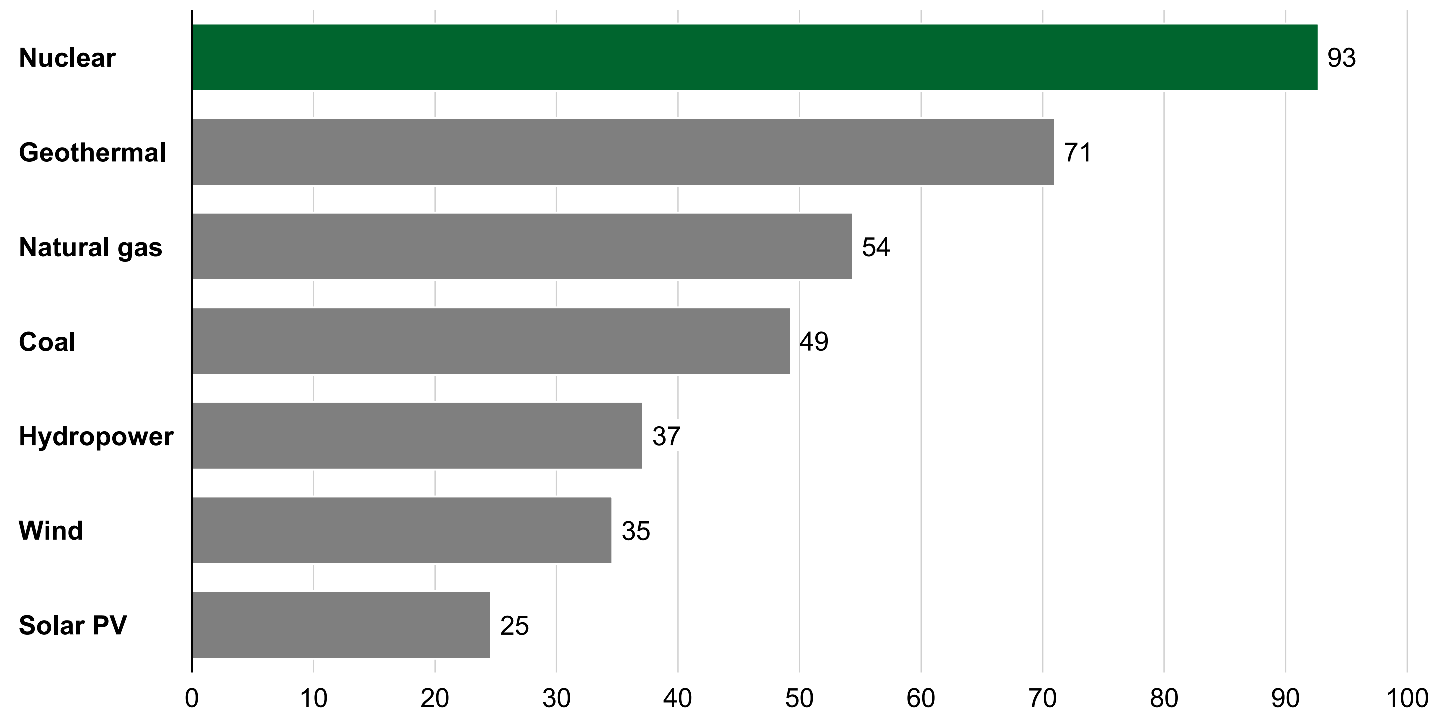


1. Advanced nuclear estimated LCOE from $3,600/kW (NOAK) and $9,000/kW (FOAK) overnight capital cost and includes 30% 48E ITC (without either 10% adder) 2. Renewables with storage for 24/7 load matching from LDES Council's "A path towards full grid decarbonization with 24/7 clean Power Purchase Agreements" and the LCOE is calculated as (annualized cost of renewable generation + storage capacity) / clean energy delivered to the off-taker excluding additional costs or revenues that would impact final PPA price and includes the ITC under section 48 for the full investment cost of the facility 3. Natural gas with carbon capture and storage numbers from the McKinsey Power Model and include the 45Q tax credit

Figure 6: Estimated first-of-a-kind (FOAK) to Nth-of-a-kind (NOAK) LCOE ranges of clean firm energy resources incorporating relevant tax credits;[v] note each technology's LCOE would be expected to move to the lower end of the range over time as learning curve benefits are realized.

Nuclear provides a firm resource (Figure 7) and system benefits that ensure reliability and stability across the grid.[vi] Nuclear power can help prevent blackouts in a future grid, which will be increasingly reliant on variable power sources. Firm power helps utilities provide a reasonable reserve margin through all hours of the year—especially during summer and winter peaks in demand—and across weather conditions. Access to reliable and resilient clean energy resources is not equitably distributed across the U.S.; increasing grid reliability and resilience for underserved, overburdened communities can support improved health outcomes, public safety, economic security, and overall quality of life.

U.S. capacity factor by energy source – 2021, %



Source: https://www.energy.gov/ne/articles/what-generation-capacity

Figure 7: Capacity factor by electricity generation source [iv, vii]

iv Coal and natural gas could operate at a higher capacity factor, if necessary, but on the grid tend to be load-following while nuclear is used as baseload.

3. Nuclear power provides electricity with low land-use requirements

Nuclear power has the lowest land-use of any electricity production source, generating the most electrical capacity per acre (Figure 8).[5]

Land use efficiency of energy for different energy sources,
MWh/year per acre, direct and indirect land use

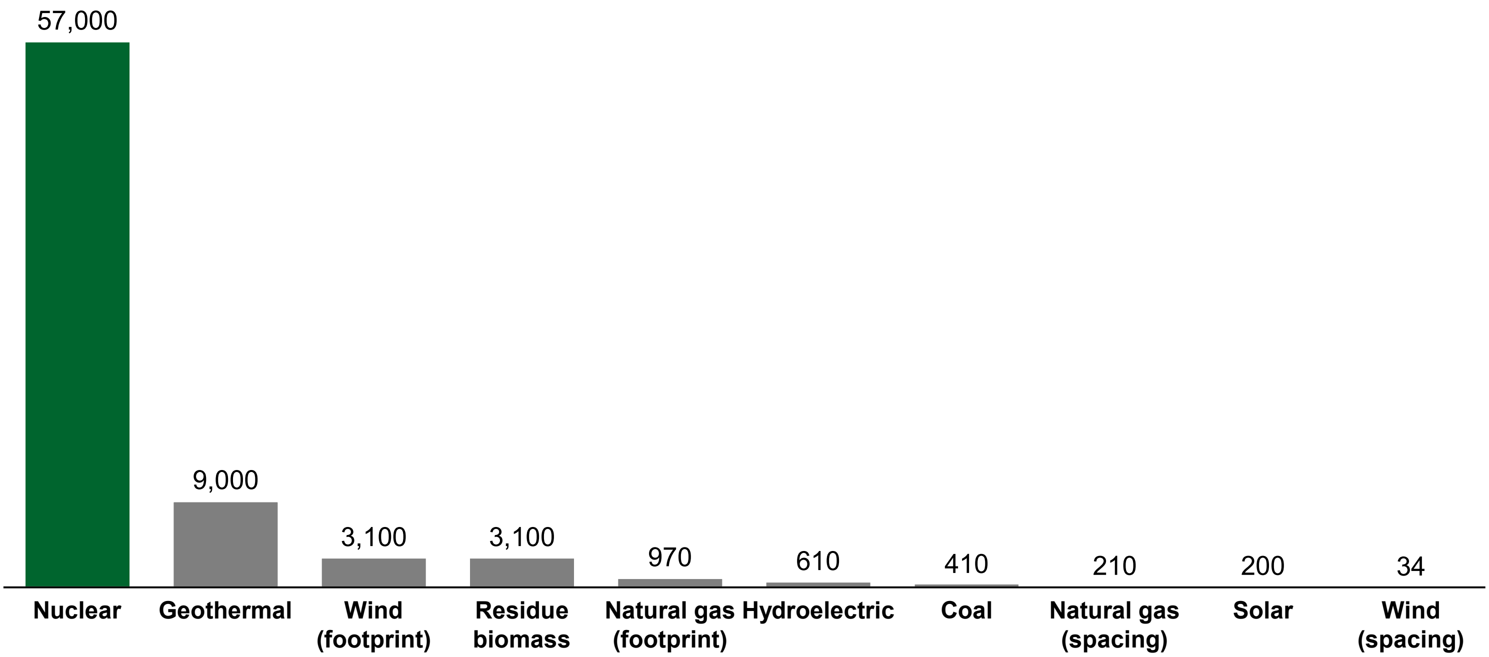


Figure 8: Land-use efficiency of electricity sources as determined by the inverse of total land-use required [viii]

Lower land-use also addresses the challenge of high land-cost in specific regions of the U.S. (e.g., coastal regions). To meet 2050 decarbonization targets using unconstrained renewables, an area of 600,000 sq-km would be required to supply power for the U.S. (i.e., roughly the size of New Mexico and Arizona, combined).[ix]

Lower land-use power sources allow utilities to leverage their existing footprint and therefore mitigate the siting, permitting, and political challenges of new land acquisition and development.

5 Land use includes land occupied by the electricity-producing facility (direct) and, when applicable, the land needed to source fuel for plant operations (indirect).

4. Nuclear power has lower transmission requirements than distributed or site-constrained generation sources and can leverage existing transmission infrastructure as fossil assets are retired

Nuclear power has lower transmission requirements than many other generation sources because of two factors: (1) it faces fewer technical limits for siting closer to demand;[6] (2) it has higher power density coupled with a high-capacity factor. As a result, less transmission must be built out to deliver the same amount of energy.

Location constraints are critical when considering regional deployment of clean energy technologies. Regions with low solar incidence or low sustained wind would require transmission to bring in power from outside of the region. Siting nuclear does not generally depend on technical geographic constraints to the same degree (though may depend on public acceptance, which is addressed separately in Section 3.e). This may mean that fewer miles of transmission infrastructure would have to be built out to link power from the area it is generated to where it is used.

Nuclear power's high-power density means that transmission lines connected to nuclear power plants can carry more total energy per mile. This results in lower transmission peak capacity required for nuclear power than for other lower capacity factor sources of power for a given amount of energy production. Thus, the inclusion of nuclear power in the grid reduces the amount of capital investment required in the inter-regional, regional, and local transmission infrastructure to supply and provide stability to the grid (a conclusion supported by system-level modeling).[x] This may support greater parity in access to clean, reliable energy for underserved, overburdened communities.

For utilities, the ability to leverage the same transmission infrastructure as retiring fossil generation could yield $100M in savings for a new plant; Idaho National Laboratory estimates additional overnight-capital cost-savings from coal-to-nuclear conversions could range from 15–35%.[xi]

[6] Siting is both a matter of technical feasibility and public acceptance; technical feasibility and access to transmission infrastructure is addressed here, though there are also public acceptance reasons for siting nuclear close to demand to consider. See Section 3.e Equity and environmental justice.

5. Nuclear power has significant regional economic benefits and can aid in an equitable transition to a net-zero grid

Nuclear power has the highest economic impact of any power generation source.[7] Nuclear power plants have ~300% of the jobs per GW when compared to wind power, and the pay of nuclear workers is ~50% higher than that in the wind or solar sectors (Figure 9).[xii] Nuclear is also one of few power generation sources that can preserve the volume of high-paying jobs from retiring coal plants

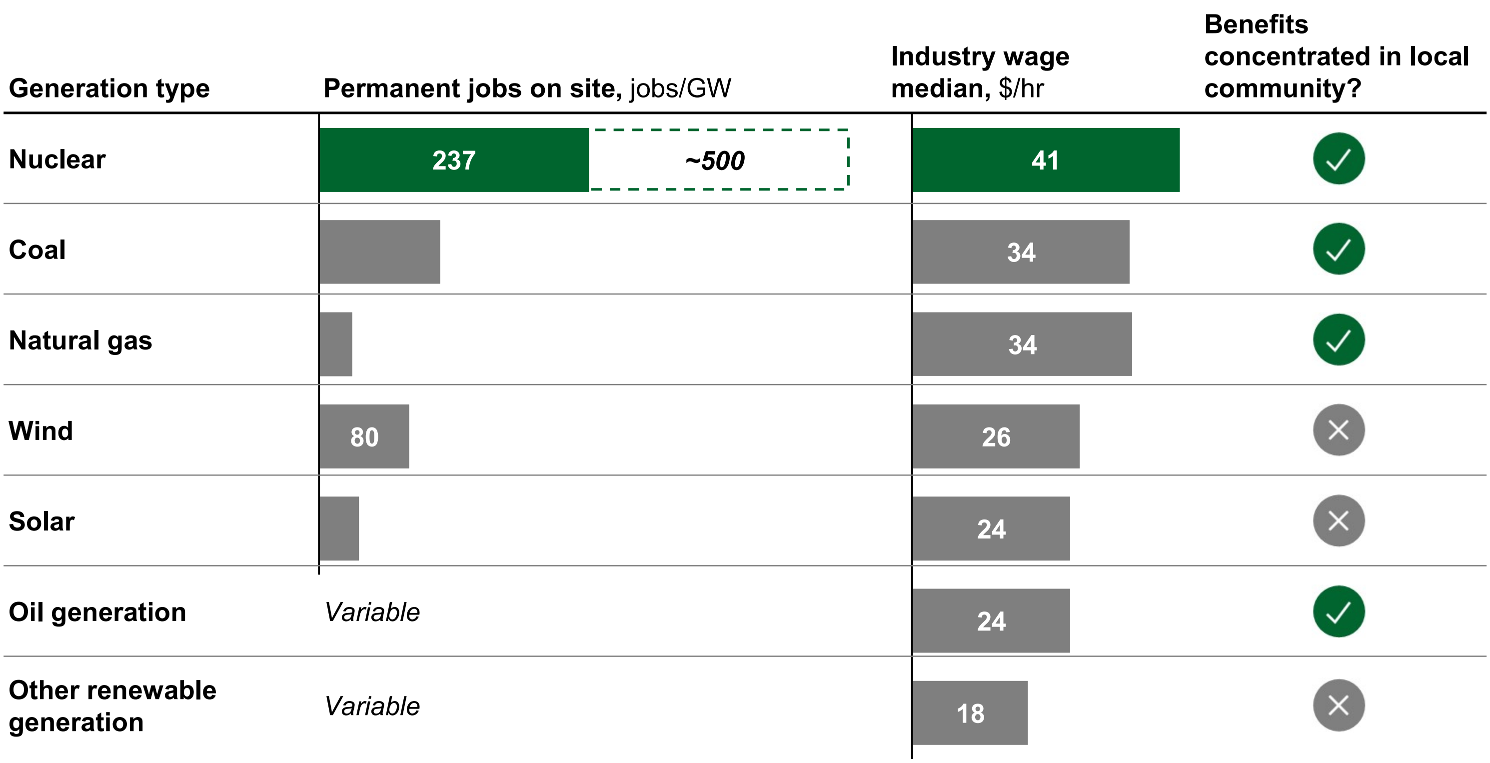
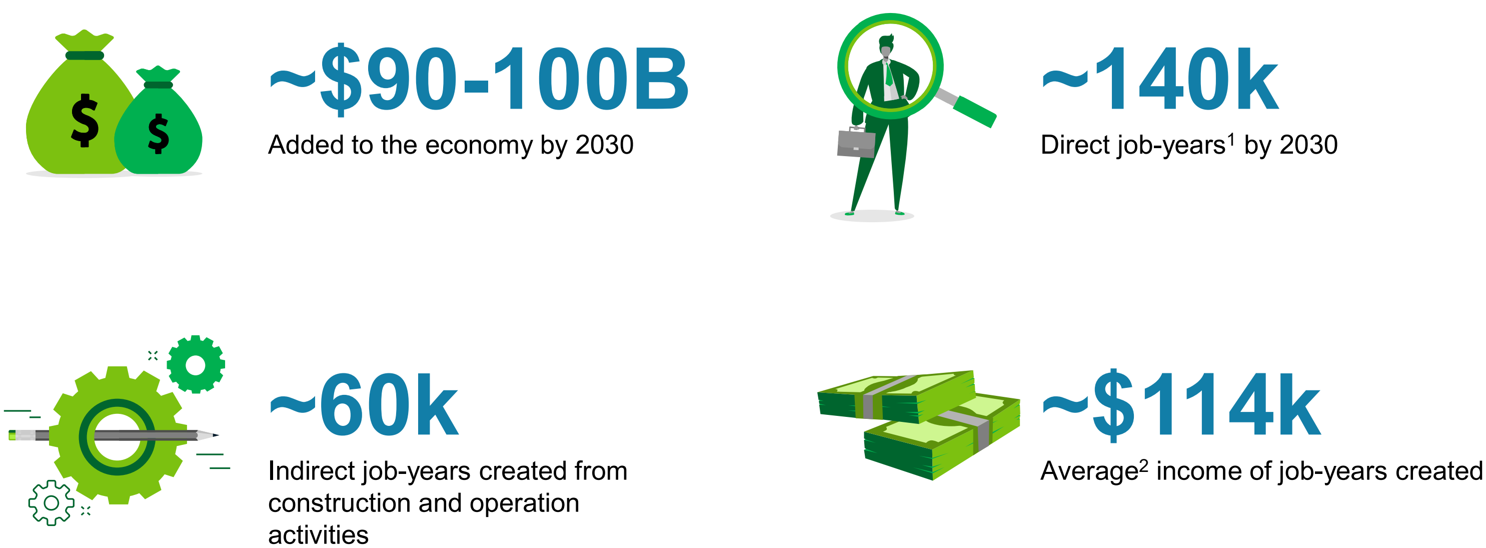


Figure 9: Electric power generation job and wage comparison; note the 237 jobs is an estimate for an SMR; ~500 represents the current operating fleet of large reactors[xiii]

[7] As measured in GDP increase per dollar invested

An effective energy transition is one that preserves the viability and livelihood of the communities impacted by the shift to clean energy sources. Up to 80% of existing coal power plant sites may be eligible for advanced nuclear plants, allowing utilities to invest in a new plant to repurpose the existing footprint—while preserving and expanding high-paying jobs in local communities.[xiv] Coal-to-nuclear transitions present critical opportunities to ensure an equitable transition to a decarbonized grid while increasing the domestic base and manufacturing capabilities. Nuclear power is also highly compatible with unionized labor; jobs tend to require more training and include both roles requiring college degrees and roles needing a wide variety of trade labor skills.[xv] Additionally, the manufacturing, construction, operation, and maintenance of power plants are a key enabler of both scale-up and reshoring the domestic industrial base (Figure 10).



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

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

6. Nuclear power has a wide variety of use cases that enable grid flexibility and decarbonization beyond the grid

The flexibility of nuclear reactors to address additional use cases beyond electricity production enables them to support other global energy demands and deep decarbonization (Figure 11). Many of these use cases stem from nuclear power's thermal-generation capabilities.

Use case	Example off-taker
Electricity production	• Utilities • Technology companies with data centers
Hydrogen generation	• H2 electrical generation • Heavy industry • Trucking / transport companies
Process heat for industry	• Industrials: chemical plants, refineries, smelters
Desalination of water	• Municipalities • Local governments
District heating	• Cities/areas with existing district heating infrastructure
Off-grid power	• Military bases • Remote communities/municipalities
Craft propulsion and power	• Commercial ship builders/operators • NASA / commercial space contracts

Figure 11: Potential use cases for nuclear power beyond electricity production

While direct electricity production is the primary use case at a system-level for new nuclear reactors, the additional use cases may be attractive to supply energy full-time, even when electricity supply is high from high renewable generation (e.g., windy and/or sunny days) or when demand is low (e.g., shoulder months and evenings). For example, the ability to switch between electricity supplied directly to the grid and electricity used for hydrogen production allows for dispatchability, load following, and increased aggregate system efficiency.

At a utility or end-user level, some new advanced nuclear technologies have the potential to decarbonize heavy industries such as chemical plants and refineries—including the direct replacement of fossil fuels for process heat—or increase total plant efficiency by using waste heat for desalination.[xvii]

Section 2.b: Advanced nuclear technologies, projects, and cost profiles

Key takeaways

- In this report, advanced nuclear covers five major technology categories: Gen III+ large, Gen III+ SMRs, Gen IV HTGRs, Gen IV metal/salt cooled, and microreactors
- Government funded demonstration projects are underway to demonstrate the technological viability of novel nuclear technologies: the Advanced Reactor Demonstration Program and the Carbon Free Power Project
- Advanced nuclear capital cost reductions could lead to a significantly reduced LCOE of nuclear power—reduction from FOAK to NOAK overnight costs of $6,200 per kW to $3,600 per kW would reduce LCOE by ~25%

Advanced nuclear includes five major technology types across two generations

Advanced nuclear, as considered in this report, includes two generations of reactors: Gen III+ and Gen IV. Gen III+ reactors are similar to the reactors currently operating in the U.S.—they use water as a coolant and low-enriched uranium (LEU) as fuel. Because of these shared characteristics with the current operating nuclear fleet in the U.S., deployment of most Gen III+ reactors is likely to be nearer-term than other, more innovative, reactor types. Gen IV reactors offer additional use cases and supplemental safety features. They will use novel coolants, and many will use HALEU as fuel, which has not been used by the existing U.S. commercial nuclear fleet.

Advanced nuclear reactors are categorized into three size groups: large, small modular reactors (SMRs), or microreactors. For the purposes of this report, large nuclear plants are defined as having ~1,000 MW capacity, SMRs as having ~50-300 MW capacity, and microreactors as having less than ~50 MW. For reference, 1 MW of nuclear capacity can power about 800 homes per year.

The current U.S. nuclear capacity is ~95 GW,[xviii] coming from large nuclear plants. The most recent builds in the U.S. are Units 3 and 4 at the Alvin W. Vogtle Electric Generating Plant in Georgia, two Westinghouse AP1000 pressurized water reactors; globally, ~50 large light water reactors are under construction.

	Gen III+		Gen IV		
	Large Light Water	**Light Water SMRs**	**High Temperature Gas Reactors**	**Metal/Salt Cooled**	**Micro**
Power output	~1+ GW	~70–300 MW	~80–270 MW	~200–800 MW	~1–50 MW
Typical fuel	LEU	LEU	HALEU	HALEU	HALEU
Coolant	Water	Water	Gas, e.g., helium	Metal or salt	Various
Select programs (reactor developer)	LPO loan guarantees for Vogtle Units 3 and 4 (Westinghouse)	Carbon Free Power Project (NuScale)	Advanced Reactor Demo. Program (X-energy)	Advanced Reactor Demo. Program (TerraPower)	DOD Project Pele (BWXT), Eielson Air Force Base RFP (TBD)

Figure 12: Categories of advanced nuclear reactors as referenced in this report; note this is non-exhaustive

Demonstration programs are underway to de-risk the technological viability of innovative nuclear technologies

The U.S. is supporting advanced nuclear technology demonstration and de-risking through multiple cost-sharing programs. DOE has made awards totaling $4.6 billion to support the demonstration of a Gen III+ SMR and two Gen IV SMRs (Figure 13).

Program	Reactor developer	Reactor type	Years of award	Awardee cost-share	DOE cost-share	DOE cost-share (%)
Advanced Reactor Demonstration Program (ARDP)	TerraPower	Sodium fast reactor	2021-2028	**$2.0B**	**$2.0B**	**50%**
ARDP	X-energy	High temperature gas reactor	2021-2027	**$1.2B**	**$1.2B**	**50%**
Carbon Free Power Project (CFPP)	NuScale	Light water reactor	2020-2030	**$3.6B**	**$1.4B**	**28%**

Figure 13: Summary of DOE financial support programs for new reactor demonstrations[xix]

The Department of Defense is also supporting the development and deployment of microreactor technologies: Project Pele is a program with the intent to design, build, and demonstrate a prototype mobile nuclear reactor and Eielson Air Force Base has released a request for proposals for a microreactor pilot project with a proposed timeline to enter commercial operation by 2027.

These demonstration projects are powerful tools enabling the technological de-risking of innovative reactor designs, but based on utility and other potential customer feedback, do not appear to be sufficient to unlock a wave of full-scale commercial deployments before the mid-2030s.

At estimated Nth-of-a-kind (NOAK) costs, new nuclear power is expected to play a critical role in a deeply decarbonized system

The projected levelized cost of electricity (LCOE) of NOAK nuclear reactors is estimated to be near ~$66 per MWh after the application of the 48E Investment Tax Credit (ITC) (see Figure 17 for a range of LCOE figures based on overnight capital costs). Even if this LCOE remains higher than other sources, nuclear will likely have a role as an economic option for utilities and other potential customers.

LCOE is an imperfect metric with which to compare firm resources to variable resources because it does not reflect total system costs. LCOE measures only generating costs and excludes delivery system costs such as interconnection and transmission, so nuclear compares more favorably when accounting for full |costs of provision. Renewable electricity sources can have high system costs because of their variability, limited dispatchability, and forced curtailment.[xx] As a result, they require either overbuilding or storage to meet load. A resilient grid is likely to include a variety of generating assets, not just those with the lowest marginal LCOE. However, cost reductions and predictability improvements will be critical for nuclear power projects, and LCOE will be a useful metric for tracking progress.

While FOAK reactors may be expensive, repeat deployments are expected to drive substantial cost reductions

Overnight capital cost is the cost required to construct a nuclear plant without the impact of interest accrued during construction. Overnight costs for nuclear plants are primarily driven by construction cost, as capital cost makes up around 70–80% of nuclear power's LCOE.[xxi] As of 2023, overnight capital costs of FOAK advanced nuclear power plants are estimated to range from ~$6,000–10,000 per kW.[xxii] Within a specific reactor design, repeat deployments are expected to result in an overall decline in overnight capital cost.

Best practices FOAK cost breakdown, $/kW

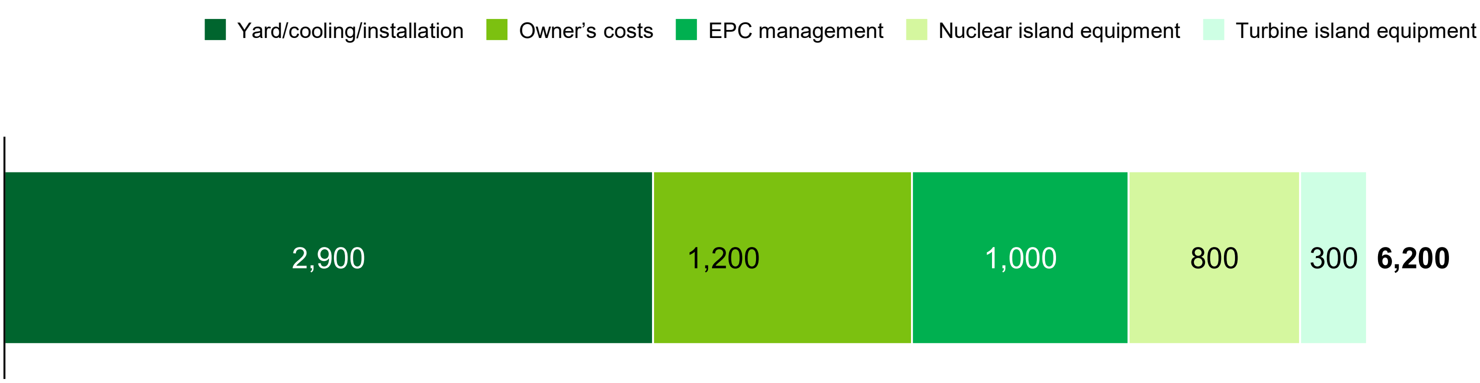


Figure 14: Breakdown of the capital cost of a genericized FOAK nuclear power plant [8, xxiii]

8 Original cost breakdown scaled up to the $6,200 per kW overnight capital cost used by NREL in "Examining Supply-Side Options to Achieve 100% Clean Electricity by 2035"

While the expected FOAK of a well-executed nuclear construction project is $6,200 per kW, recent nuclear construction projects in the U.S. have exceeded this figure, with overnight capital costs exceeding $10,000 per kW. Stakeholder interviews and top-down estimates suggest that a 30–40% reduction in cost is reasonable given that recent projects have taken roughly twice as long as necessary and experienced a high failure rate of components. These major issues led to higher-than-necessary direct and indirect labor and materials costs—the two key drivers of overnight capital cost. These issues can be avoided by investing heavily in upfront project planning and scheduling. For more information on a recent project at Vogtle, see Section 3.b; for a list of best practices to avoid these overruns, see Section 4.b.

Future deployment of nuclear power could see overnight capital cost come down from a best practice FOAK overnight cost of ~$6,200 per kW to an NOAK overnight cost of ~$3,600 per kW[xxiv]; for reference, South Korea has achieved overnight costs of ~$2,300 per kW on 7 large light water reactors built over the last 20 years and a ~50% overall reduction in capital costs of nuclear reactors over the same time period.[xxv]

The estimated ~40% overnight capital cost reduction from FOAK to NOAK is spread across five cost categories (Figure 15).

Potential advanced nuclear FOAK to NOAK overnight capital costs, $/kW

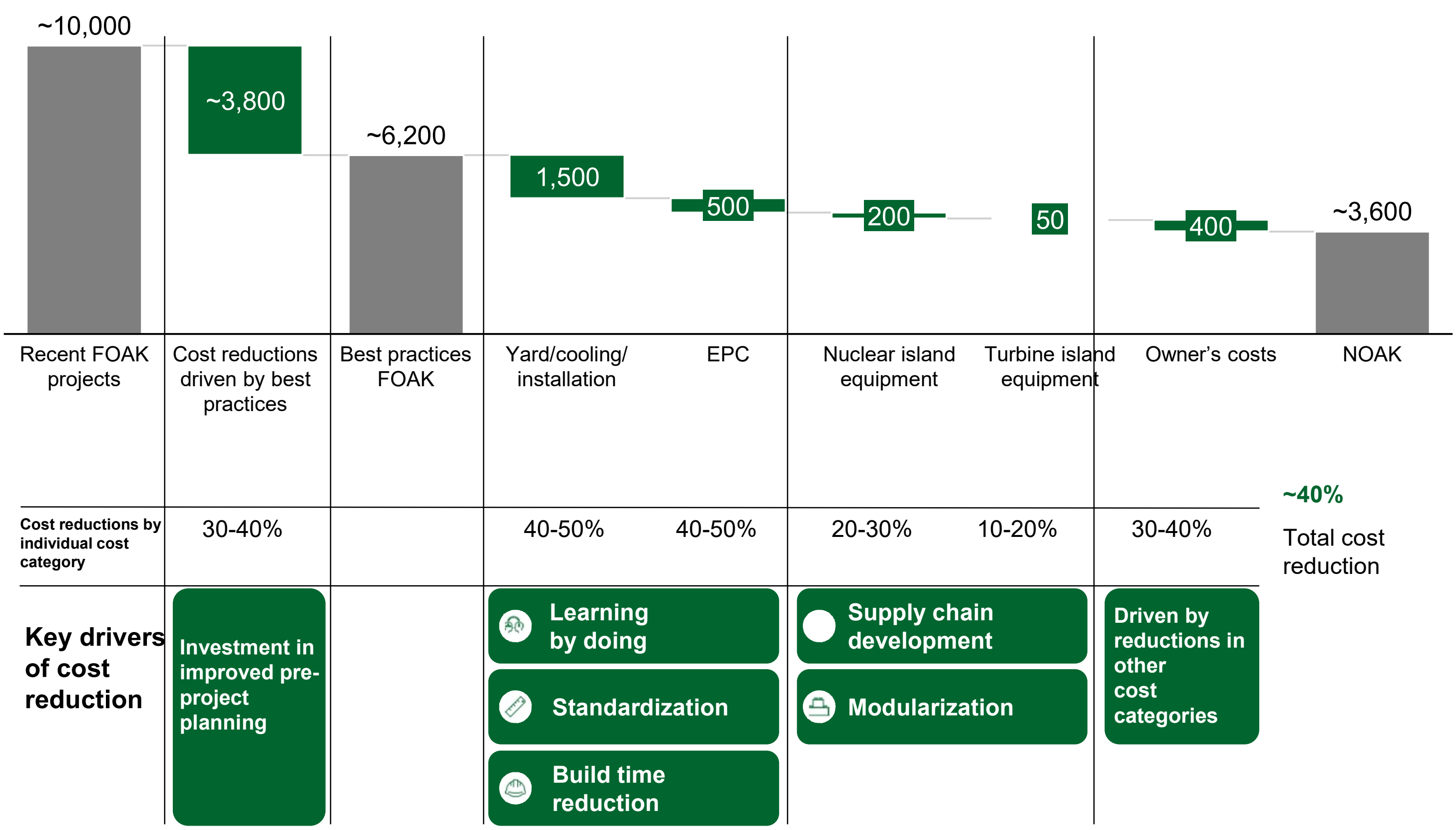


Figure 15: Categorizations for how advanced nuclear costs could decrease from FOAK to NOAK deployments[xxvi]

When working down the learning curve, the greatest reduction opportunity is likely to come from yard/cooling/installation and EPC (engineering, procurement, and construction) costs, as these cost categories primarily represent labor costs. The reduction in labor cost will be driven by:

- **Learning by doing:** Experience built across the labor force as it is carried from one project to the next.
- **Standardization:** Codified construction processes or process management that create a “playbook” for project construction.
- **Build-time reduction:** Co-processing of tasks and proper hand-offs reduce total construction time while maintaining safety.

The cost categories that will see a smaller reduction over deployments include nuclear island equipment and turbine island equipment (e.g., the materials and components that go into construction); however, savings in these categories are expected as the supply chain matures, driven by:

- **Supply chain development:** As new manufacturing facilities are built, forward bulk orders of materials (e.g., procurement for five units as opposed to one) will lead to procurement discounts.
- **Modularization:** Component standardization will lead to faster manufacturing, thus lowering costs; this component standardization will also benefit process standardization, potentially reducing labor costs.

Across the construction of multiple projects, owner’s costs will also reduce due to lower risk—leading to lower costs related to project financing.

This level of cost reduction implies 10–20 reactors may be necessary to reach NOAK targets, given a reactor-to-reactor learning rate of 12–15% (Figure 16). Twelve percent is similar to the learning rate observed among nuclear power plants built in South Korea from 1978–2017.[xxvii] Fifteen percent is similar to combined cycle gas turbine plant learning rates from 1980–1998.[xxviii] Learning rates will be mostly design-specific—learnings achieved on one design may not benefit other designs. Learning rates will also be dependent on how projects are executed—projects executed in rapid succession using the same workforce will achieve better learning rates than those with significant time between builds and that use a new workforce.

Project NOAK overnight capital cost by learning rate, $/kW

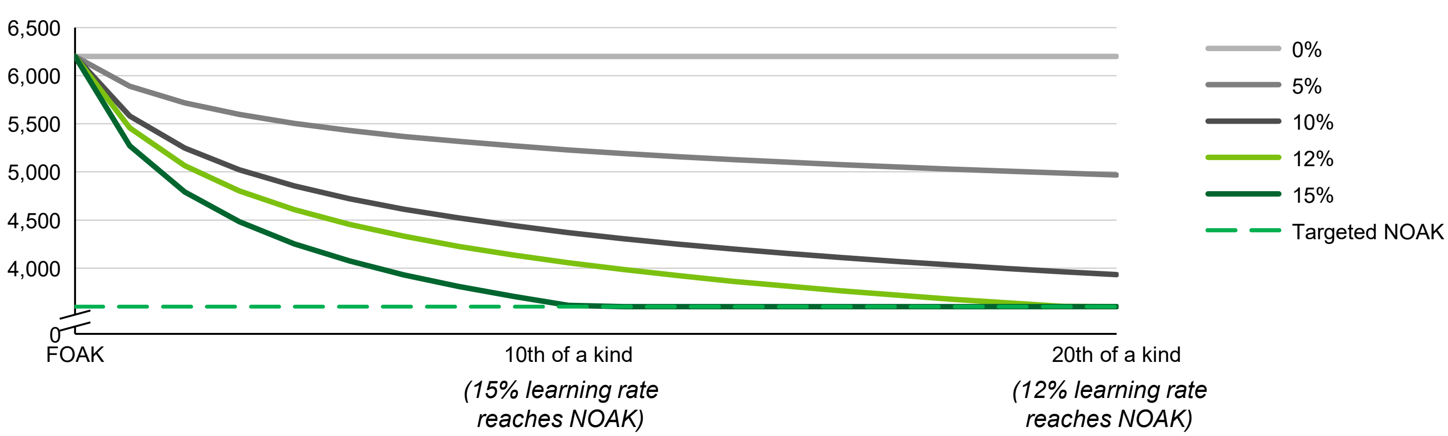
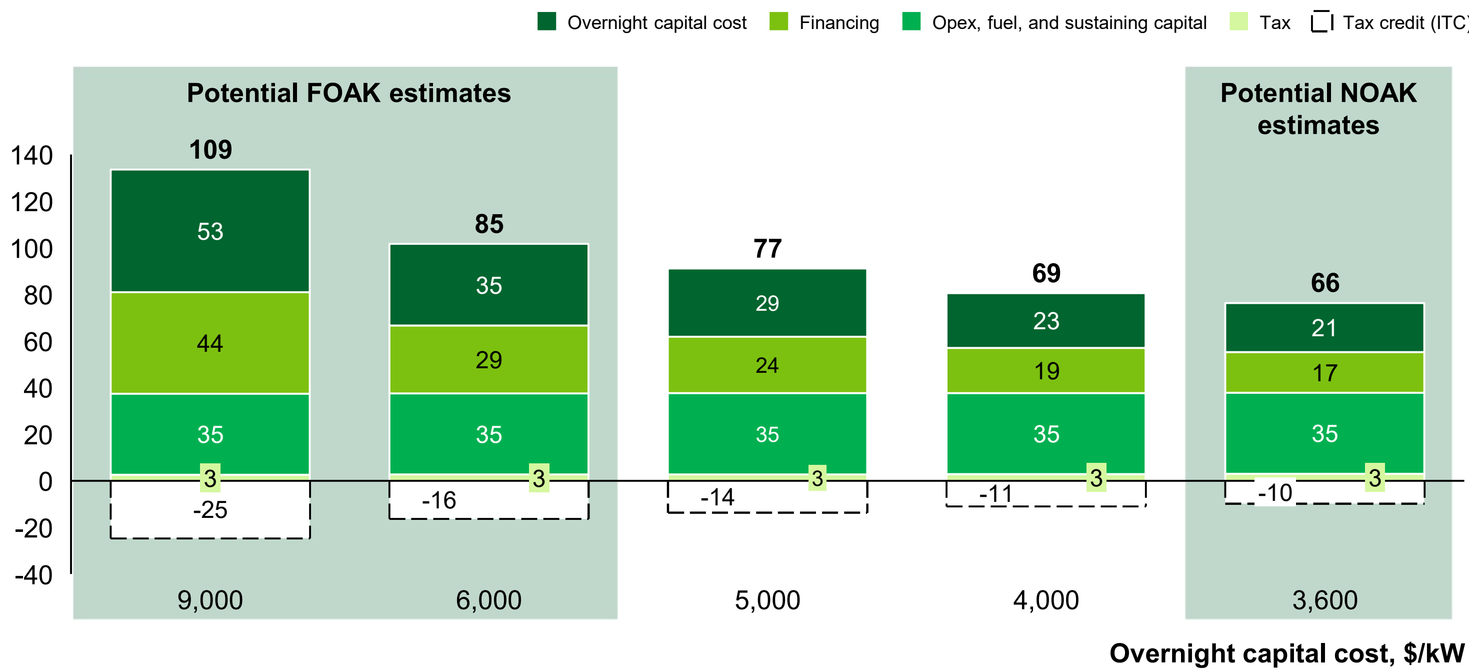


Figure 16: The number of reactors it would take to reach NOAK overnight capital costs depends on the learning rate achieved by the nuclear program

If advanced nuclear can successfully decrease costs from projected FOAK costs to NOAK costs, its LCOE would decrease by ~25%—from ~$87 per MWh to ~$66 per MWh. This reduction in LCOE over 10–20 successive site builds would enable advanced nuclear to strongly compete with other clean, firm electricity generation sources on a cost basis.

LCOE of advanced nuclear given varying overnight capital costs, $/MWh



Source: NREL "Examining Supply Side Options to Achieve 100% Clean Electricity by 2035," Inflation Reduction Act, EIA Annual Energy Outlook 2022

Figure 17: Estimated LCOE from FOAK to NOAK ranges assuming 60-year plant lifetime, including the 30% Investment Tax Credit from the IRA (48E) (note this does not include either 10% adder, which would create an effective 50% ITC)

Advanced nuclear reactors have the potential to improve the economics of nuclear power; large and small reactors have different roles to play

The U.S. nuclear industry historically relied on economies of scale to drive down costs, but many of these expected cost savings were not realized in the construction of large nuclear plants. Increased regulatory requirements and the inability to construct many of the same design in series meant that costs of conventional nuclear reactors rose, rather than fell, over time.

Both large reactors and SMRs could be expected to achieve similar capital costs of construction in dollars per kilowatt as they move down the learning curve. A recent MIT report outlines a bottom-up Nuclear Cost Estimation Tool (NCET);[xxix] note this work was limited to Gen III+ reactors, as there is not enough data on Gen IV designs to replicate this analysis for Gen IV reactors.

The cost overruns of large nuclear construction projects have led to the consideration of SMRs as an alternative. SMRs offer the potential for lowering the risk bands for construction due to smaller, simpler scale; SMRs also offer the potential to drive more quickly down the learning curve because more reactors can be built for a given amount of MW capacity.

Early SMR projects are likely to have a critical role in building the momentum and infrastructure for deploying nuclear at scale. Ultimately, to reach 200 GW of new nuclear capacity, large reactors may play a key role in adding capacity in larger increments. The effects of economies of scale mean that, in many modeling efforts, large reactors tend to have lower median costs per MW than SMRs; e.g., certain cost categories that are similar for both large and small reactors are spread across 1 GW of capacity versus 300 MW.

Three considerations contribute to the SMR value proposition for potential customers, regardless of economies of scale:

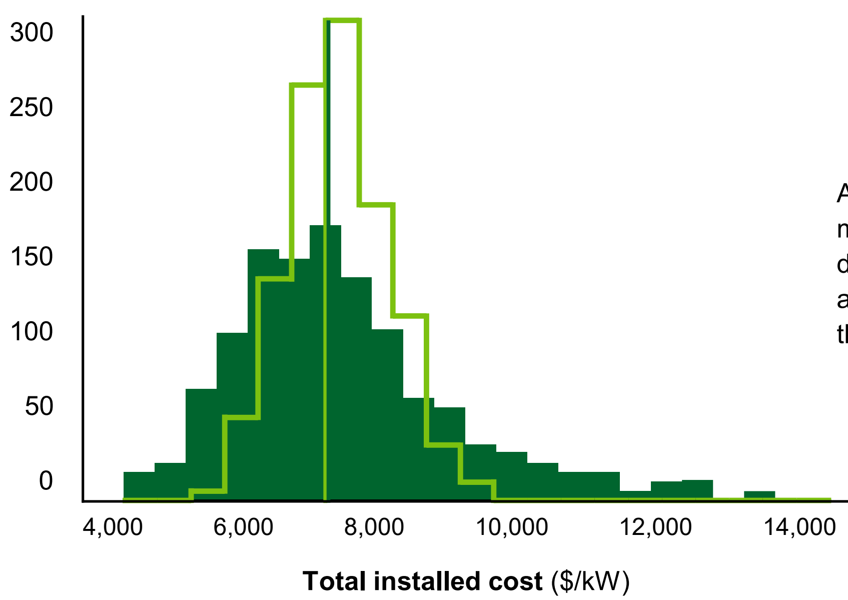
1. SMRs provide smaller and less time-consuming investments

Because each individual SMR project comes at a lower overall price tag and a shorter time to construct, deployment of SMRs involves less risk than large reactor construction. As an example, a $2B SMR with a 150% cost overrun would result in completed FOAK cost of $3B; a $10B large reactor with the same 150% cost overrun will result in a completed FOAK cost of $15B. Accordingly, with less time and less money, an SMR can complete FOAK construction and implement cost-saving learnings on the second-of-a-kind reactor. This shorter timeline and lower price should enable SMRs to move down the learning curve faster and with less risk. This accelerated de-risking for SMRs may make them more attractive to potential project owners who are skeptical of the quoted capital costs. These lower costs could also lower the barriers to entry for potential customers who are not able to easily make a $6B+ commitment.

2. SMRs provide more certainty of achieving a predicted cost with reduced risk of overrun

While large and small reactors could result in similar median costs per kW, SMRs can provide greater certainty in achieving that median cost. The MIT NCET report demonstrates this effect as well (Figure 18). A shorter construction timeline and smaller number of individual tasks provide less room for error in a smaller project than a larger one. This increased cost certainty can lower barriers to entry for potential project owners who are wary of severe cost overruns.

Probability distribution of cost of advanced nuclear



A 200-GW-by-2050 scenario would likely require multiple types of nuclear reactors to reach deployment at scale. These cost characteristics are likely to heavily inform which reactors provide the best profile for an individual customer.

Figure 18: Overnight capital cost estimations for a large reactor and SMR of similar design (boiling water reactors)[xxx]

3. SMRs can be more cost-effective in constrained labor environments, e.g., U.S., Western Europe

Recent successes in large reactor construction at a low capital cost can be found in China, U.A.E., and South Korea. At the same time, large reactor projects in the U.S. and Europe have been struggling with severe cost overruns of up to ~2X. One major driver of the different experience between these regions is that large reactor construction is more suited to unconstrained labor environments. Labor constraints may include quantity of labor available, quantity of labor certified, quantity of labor with prior experience in nuclear, and rates of pay for labor.

The MIT NCET report finds that labor constraints tend to impact large reactor costs much more than SMR costs. This correlation is mostly due to large reactors' need for a greater quantity of labor at any one time, which becomes an issue in constrained labor markets.

Because of this constrained labor effect, SMRs may be more attractive in the U.S. market as the current labor market for nuclear construction employees is highly constrained.

Overnight capital costs of large and small reactors by labor environment, $/kW

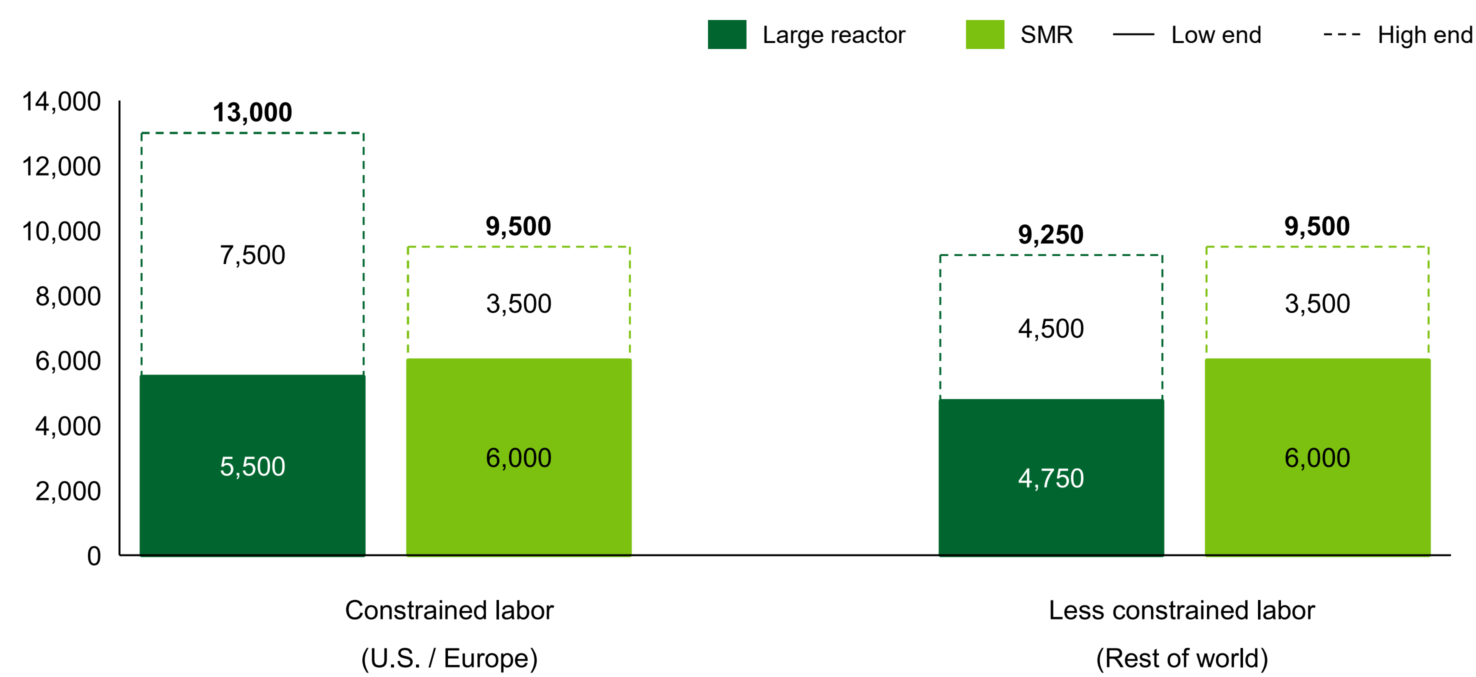


Figure 19: Overnight capital costs of large and small reactors by labor environment[xxxi]

The IRA provides a powerful boost to nuclear power economics, but may not be sufficient to accelerate commitments for deployment at scale

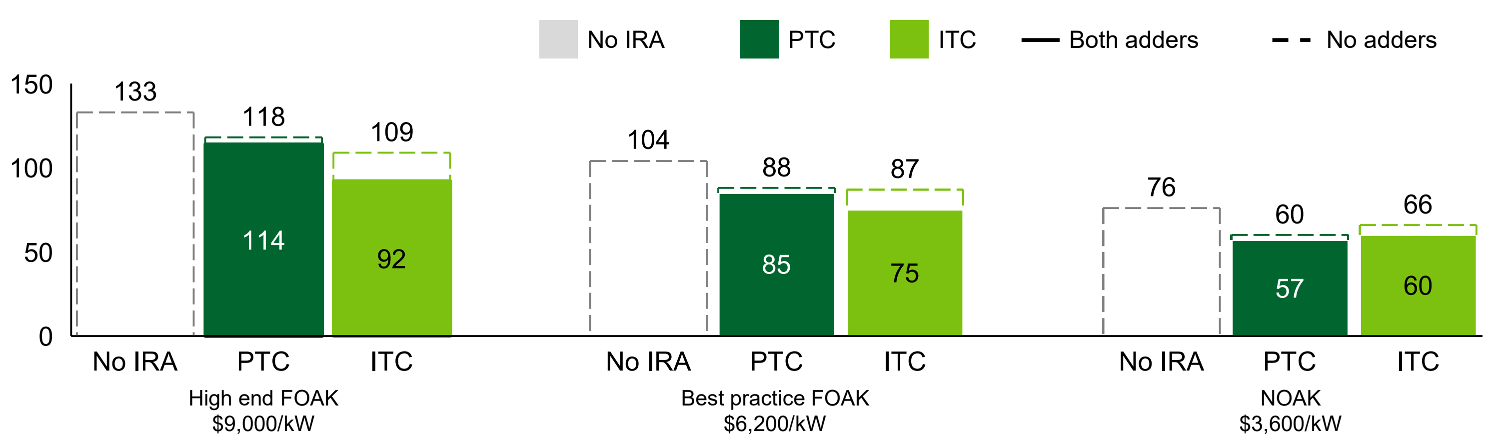
The recent passage of the Inflation Reduction Act introduced two technology-neutral clean energy tax credits that have the potential to improve LCOE: the Clean Energy Production Tax Credit (PTC) and the Clean Energy Investment Tax Credit (ITC).[xxxii] The PTC provides an inflation adjusted $25 per MWh in tax credits for every MWh of power produced by a nuclear plant, while the ITC provides 30% of the capital cost for a nuclear plant back in tax credits in year 1 of operation if prevailing wage and apprenticeship requirements are met. Both incentives have two possible 10% adders for siting in energy communities and for the use of domestic content (Figure 20). Note the ITC bonus adders are 10 percentage points, so a facility eligible for both adders would have an effective 50% ITC.

IRA provision	Description	Adders	Notes
48E: investment tax credit (ITC)	Provides 30% of the capital cost for a nuclear plant back in tax credits	+10% for siting in energy communities +10% for use of domestic content	**Facility eligible for both adders would get 50% effective ITC**
45Y: production tax credit (PTC)	Provides an inflation adjusted $25/MWh in tax credits for every MWh of power produced by a nuclear plant	+10% for siting in energy communities +10% for use of domestic content	**Must choose ITC or PTC (not both)**
Section 50173 Availability of High-Assay Low-Enriched Uranium	Provides $500M for development of HALEU production capacity, including research, development and demonstration	N/A	

Figure 20: Summary of benefits of the Inflation Reduction Act to advanced nuclear power

Every project developer/owner will have a unique set of considerations when determining how to leverage the IRA. If choosing between the ITC and PTC—based on dollar-for-dollar comparison of LCOE alone—the ITC is likely to be more attractive in cases where capex exceeds ~$6,000 per kW (Figure 21). The PTC is likely to be more attractive where capex is lower than ~$6,000 per kW

Advanced nuclear FOAK LCOE before and after IRA impact, $/MWh



1. "Both adders" represents the ITC / PTC with the addition of both 10% adders for energy communities and domestic content

Figure 21: IRA impact on LCOE of advanced nuclear power, comparing PTC and ITC with and without 10% adders for energy communities and domestic content

Chapter 3: Pathways to Commercial Scale

Key takeaways

- Waiting until the mid-2030s to deploy at scale could lead to missing decarbonization targets and/or significant supply chain overbuild
- A committed orderbook of at least 5–10 reactors of at least one design is required to catalyze commercial liftoff in the U.S.
- Once a critical mass of demand is established, delivering the first commercial projects reasonably on time and on budget (±20%) will become the most important challenge
- As the industry gains momentum, the industrial base, supply chain, and workforce will need to scale up accordingly
- The buildout would necessitate ~$700B+ from private (e.g., utilities, off-takers, debt investors, private equity, venture capitalists) and public sources

Waiting until the mid-2030s to deploy at scale could lead to missing decarbonization targets and/or significant supply chain overbuild

Committing to rapidly scaling the nuclear industrial base will increase capital efficiency and enable nearer-term decarbonization. If deployment at scale begins in 2030 and throughput is ramped up to 13 GW per year over the next 15 years, 200+ GW of new nuclear capacity can be achieved by 2050; however, a five-year delay in scaling the industrial base would require 20+ GW per year of throughput to achieve the same target. Delivering projects at that rate and scaling a supply chain to 20+ GW could come at significantly higher capital costs, both overall and for the marginal unit (Figure 22).

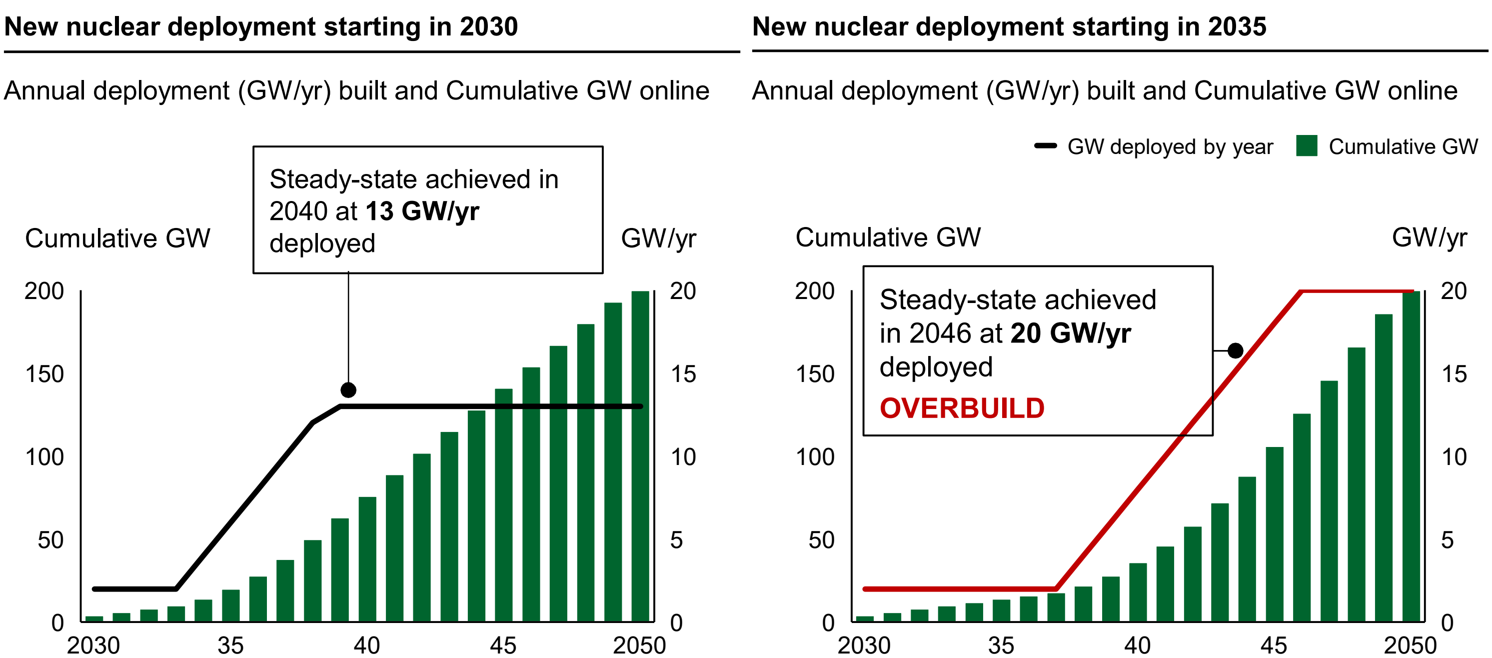


Figure 22: Build-out scenarios and implications for maximum industrial-base capacity requirements

To avoid the cost of a delay in advanced nuclear deployment, the industry will need to begin deploying advanced nuclear by 2030. Full-scale advanced nuclear deployment will proceed in three overlapping phases: (1) committed orderbook, (2) project delivery, and (3) industrialization. This chapter details, by phase, what would be required to reach 200 GW of new nuclear capacity by 2050 (Figure 23).

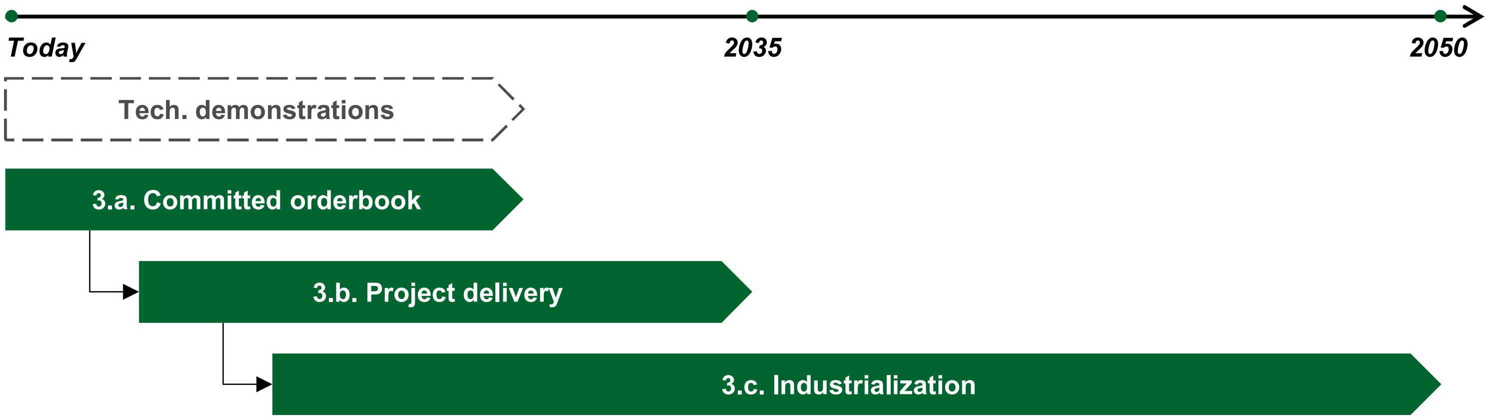


Figure 23: Path to the scale-up of the advanced nuclear industry to meet 2050 decarbonization targets

Section 3.a: Committed orderbook

A committed orderbook of at least 5–10 deployments of a single reactor design is the first essential step for catalyzing commercial liftoff in the U.S. An initial mass of 5-10 reactors is required for suppliers to make capital investment decisions, e.g., for new manufacturing capacity, and to show the benefits of learning curve impacts on overnight capital cost reductions. Note that a critical mass of orders for single design is necessary, but not sufficient, and the market will likely support multiple designs at scale. For scale, 10 SMRs of 300 MW capacity would contribute 3 GW to 200 GW.

These first orders would need to be placed by ~2025 to allow enough time for the industry to ramp up to meet demand and reach steady state by ~2040 without requiring a significant overbuild of supply chain or nearly doubling the required workforce. Waiting until 2030 to generate this demand signal would result in a five-year delay of the nuclear industry scale-up, a total buildout cost increase of >50%, and/or failing to meet 2050 decarbonization targets.

As of January 2023, there are no committed orders, e.g., signed contracts, for new nuclear reactors in the U.S.[9] While customers have indicated their interest in building nuclear (e.g., via memoranda of understanding or letters of intent), they have not committed contractually. Catalyzing the industrial base would require legally-binding commitments for the first 5–10 reactors.

9 Note there is a signed contract between GE Hitachi Nuclear Energy and Ontario Power Generation for a BWRX-300 SMR in Canada as of January 2023

These 5–10 deployments need to be of the same design as overnight costs are largely expected to decline based on repeat building and learning by doing. Different reactor designs are likely too distinct for learnings to transfer well from one design to another. Additionally, many investments to stand up supply chain elements specific by reactor design will benefit from scale.

While the two Gen IV reactors being demonstrated through the Advanced Reactor Demonstration Program are powerful tools in a portfolio of advanced nuclear technologies, Gen III+ reactors will likely generate the early demand signal. Interviews with utilities and supply chain players suggest they currently feel most comfortable with the Gen III+ designs. Generating this demand signal for Gen III+ reactors would benefit the entire industry, including Gen IV, by building the momentum and industrial base required for deploying all designs at scale.

Between 2023 and 2050, ~200 GW of coal assets are expected to retire.[xxxiii] As utilities begin to retire these fossil assets, advanced nuclear is uniquely positioned to replace retiring assets with a similar electricity generation profile. Leveraging the same transmission infrastructure as retiring fossil generation can yield $100M in savings for a new plant, and Idaho National Laboratory estimates additional overnight capital cost savings from coal-to-nuclear conversions could range from 15–35%.[xxxiv] Communities aiming to preserve the high-paying jobs that fossil plants provide would benefit from transitioning to nuclear for provide similarly concentrated local economic benefits. Additionally, the Inflation Reduction Act (IRA) offers a 10% addition to the ITC (e.g., 30% ITC with 10% adder would be 40%) and a 10% increase to the PTC (e.g., $25.00/MWh with 10% adder would be $27.50/MWh) in “energy communities” (including those at or near former coal plants). The IRA also established the Energy Infrastructure Reinvestment Program (Section 1706), administered by the Loan Programs Office, which can be used to finance nuclear projects at energy infrastructure sites that have ceased operations.

Customers for new nuclear outside of existing nuclear utilities, e.g., technology companies powering data centers or industrial companies requiring process heat, would likely pursue a non-traditional development and operating model. There are a few options that these non-traditional off-takers may pursue, including aligning with an existing nuclear operator for a non-owner operator construct or creating a 24/7 PPA with an existing nuclear operator or developer.

Section 3.b: Project delivery

Once a critical mass of demand is established, delivering the first commercial projects reasonably on time and on budget (±20%) will become the most important challenge. To build confidence that subsequent units (e.g., beyond the first 5–10) can be built on-time and on-budget, each step of the construction process needs to be executed in a timely and cost-effective manner.

Five major steps to building a nuclear power plant must be executed with high quality to build confidence in the nuclear industry's ability to scale (Figure 24):

1. Design: Reactor designer develops plans/layouts used to construct a power plant
2. Site selection / early site permit: Operator evaluates location for suitability
3. Construction: Plant is built on the selected site based on the initial design
4. Supply chain: Components are manufactured and shipped to the site to support construction
5. Licensing: Throughout the process, all applicable parties work with the NRC and other regulators to ensure the plant is built in a safe and high-quality manner

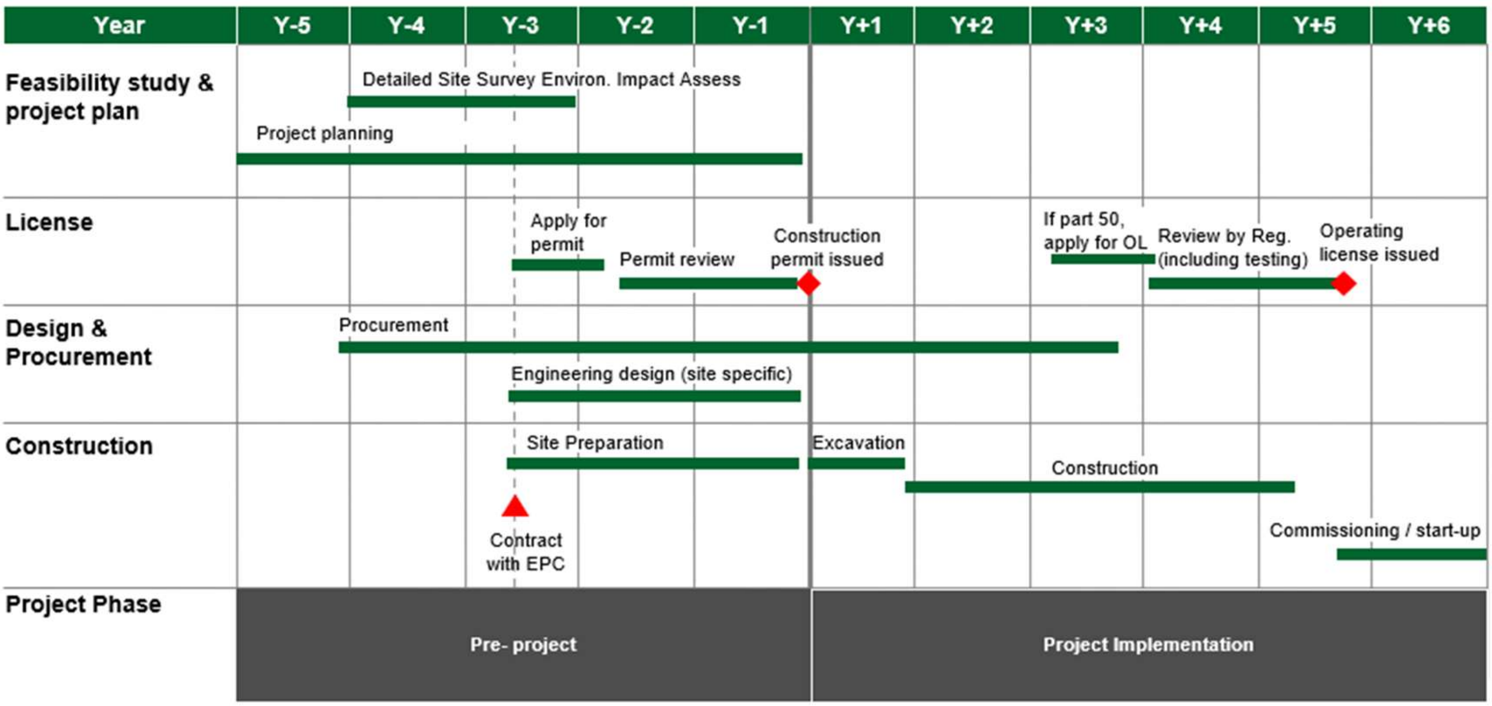


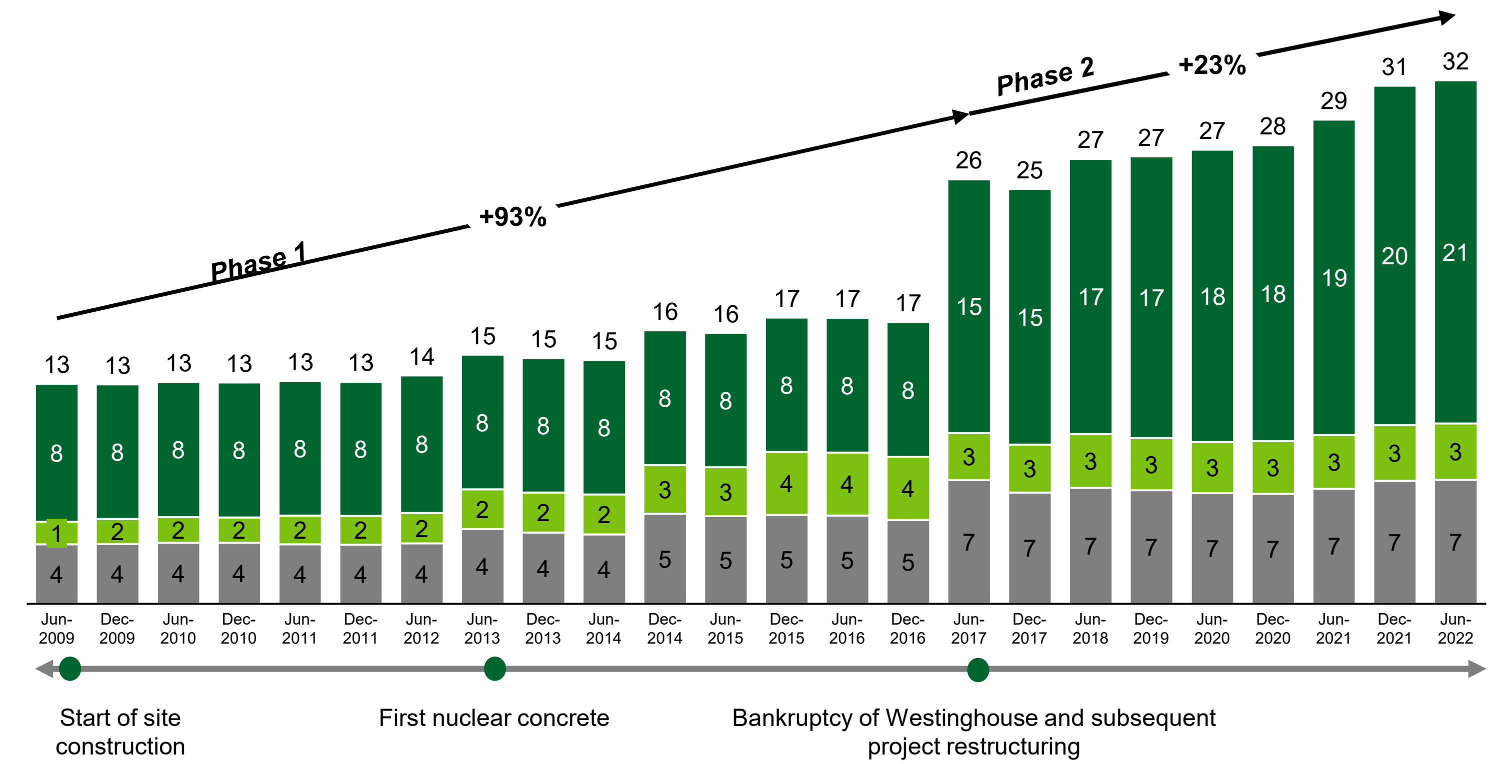
Figure 24: Illustrative major steps for building a nuclear power plant[xxxv]

Pre-project – focused on gaining approval from the NRC to begin construction of the plant. This includes demonstration of the safety of the design, the suitability of the site, and the need for the plant. The pre-construction preparation in this phase is critical for successful project implementation. A design that is mostly complete is a key factor in successful construction. The EPC readiness to construct, including design constructability reviews and resource loaded integrated schedules, is another key success factor. In past large nuclear plant projects, construction has begun with inadequate design completion and construction readiness, leading to schedule and budget overruns.

Project implementation – focused on constructing the plant, demonstrating design conformance to safety standards, and transitioning to operations. Construction of a nuclear power plant, like any other complex project, requires strong project management processes such as rigorous quality assurance and control practices and ongoing risk assessment. Another factor is the ability to source, train and maintain a labor force sufficient to construct per the schedule. During this period, more detailed design and procurement is typically completed particularly for the site-specific aspects of the nuclear power plant.

If reactor deployments go substantially (e.g., >20%) over cost and schedule, there is a risk of diminishing demand for follow-on projects, and the industry would not scale as needed to support decarbonization by 2050.

Projected total cost at completion of Vogtle Units 3 and 4[1], $B



Contribution to cost increase 2009-2022 – %

EPC – 68%
Original EPC agreement assigned **almost all construction risk to the contractor** through a **fixed price agreement** – poor initial risk assessment and budgeting led to the eventual bankruptcy of the initial contractor
New contractor takes over and re-benchmarks in 2017, after which, costs have still continued to rise

Owner's costs – 11%
Various costs have been re-shuffled into and out of owner's costs over the years, making it difficult to track individual contributors to cost change

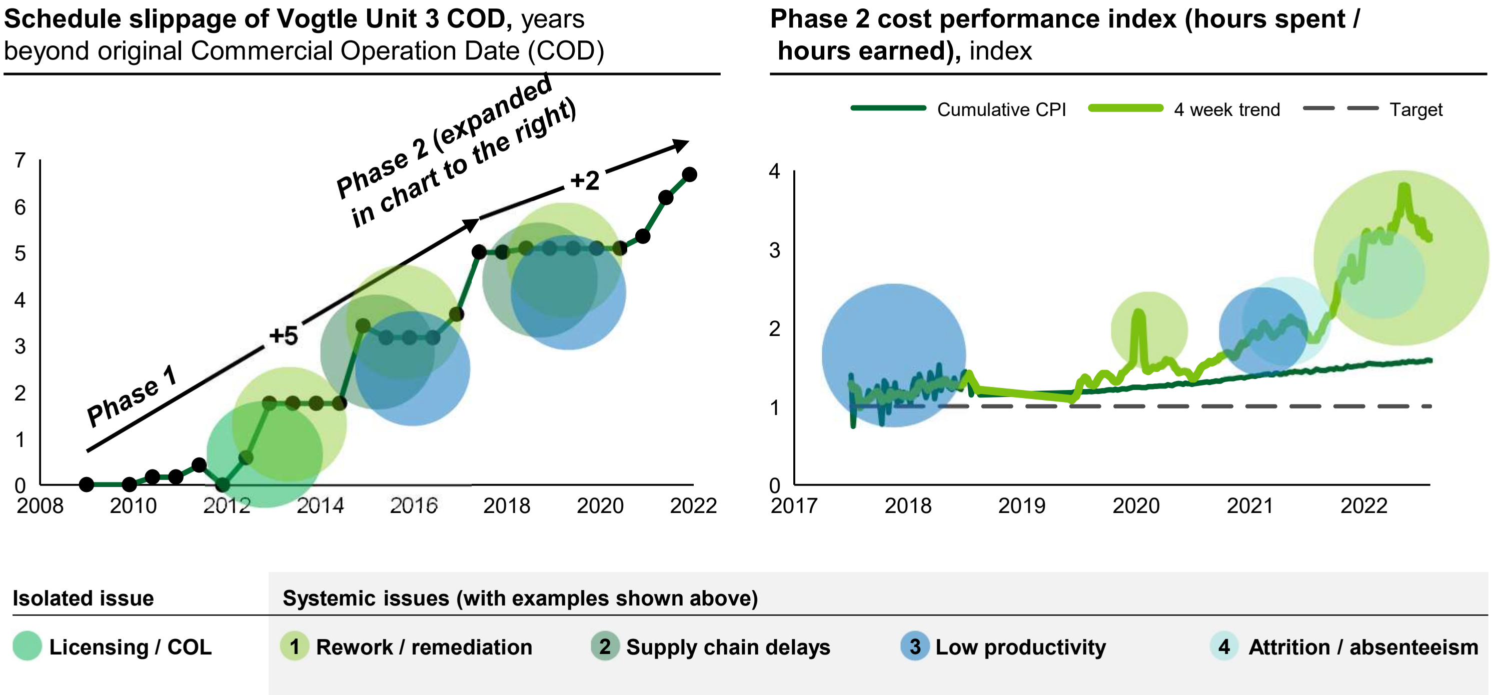
Financing costs – 21%
Financing costs have risen primarily due to construction schedule delays leading to increased interest accrual

1 These figures are an estimate of total project cost based on a scaled-up view of Georgia Power's 45.7% share of the project, this means of estimation is inexact due to the differing Financing and Owner's costs between stakeholders. Project costs that are excluded from the VCM reports include: (i) budgeted cost contingency that has not been allocated; (ii) additional cost contingency budgeted by certain other owners (iii) nuclear fuel costs (and related financing costs); and (iv) certain monitoring costs, some of which are owner-specific.
Source: Georgia Public Services Commission's Vogtle Construction Monitoring Reports (VCM)

Figure 25: Projected total costs of Vogtle Units 3 and 4 over time[10,xxxvi]

10 These figures are an estimate of total project cost based on a scaled-up view of Georgia Power's 45.7% share of the project, this means of estimation is inexact due to the differing Financing and Owner's costs between stakeholders. Project costs that are excluded from the VCM reports include: (i) budgeted cost contingency that has not been allocated; (ii) additional cost contingency budgeted by certain other owners (iii) nuclear fuel costs (and related financing costs); and (iv) certain monitoring costs, some of which are owner-specific

The rise in costs at Vogtle can be mainly attributed to EPC cost overrun, which are overruns in the cost of construction. This EPC cost overrun was driven by slower-than-expected project progress, resulting in a ~7 year delay (Figure 26). Four systemic issues have contributed to the performance against target schedules.



Source: Georgia Public Services Commission

Figure 26: Schedule slippage and performance against cost performance index at Vogtle[xxxvii]

1. Rework / remediation – original work does not function or does not meet quality standards and must be redone

Rework was a significant source of project delay for many years[xxxviii]. Known test failure rates of components have ranged from 40–80% over different time periods. Many of the tested components did not function properly and required corrective action to function as designed.

2. Supply chain delays – modules arrived late, incomplete, or both Poor module-delivery performance was a result of a few factors. Some of the designs sent to fabricators were incomplete and changed after fabricators started. In some cases, it was unrealistic to construct the modules as designed. In other instances, the required quality-assurance paperwork was lacking, so modules could not be shipped. Finally, site management eventually gave up on the module fabricator, and the modules were shipped incomplete for finishing on location.

3. Low productivity – labor has produced outputs more slowly than predicted, even before rework Tasks often took longer than estimated—even before rework—due to acute shortages in key trades. This shortage (1) necessitated the hiring of an inexperienced workforce, (2) resulted in poor management that delivered inadequate directions and improper scheduling, and (3) resulted in difficult-to-construct design (e.g., high levels of workspace congestion from a small plant footprint).

4. Attrition / absenteeism – labor has been unavailable when needed, and attrition hindered learning COVID-19 caused a much higher than normal rate of absenteeism—as many as 2,800 positive cases by December 2021—impacting all workstreams. This absenteeism was compounded by attrition. For example, there was a 50% attrition rate on electricians from Unit 3 to Unit 4. Because labor projections factored-in a positive learning rate from Unit 3 to Unit 4, these high levels of attrition caused these projections to be inaccurate.

Additionally, the license to begin construction on Vogtle was approved one year later than expected, although this delay was an isolated issue.

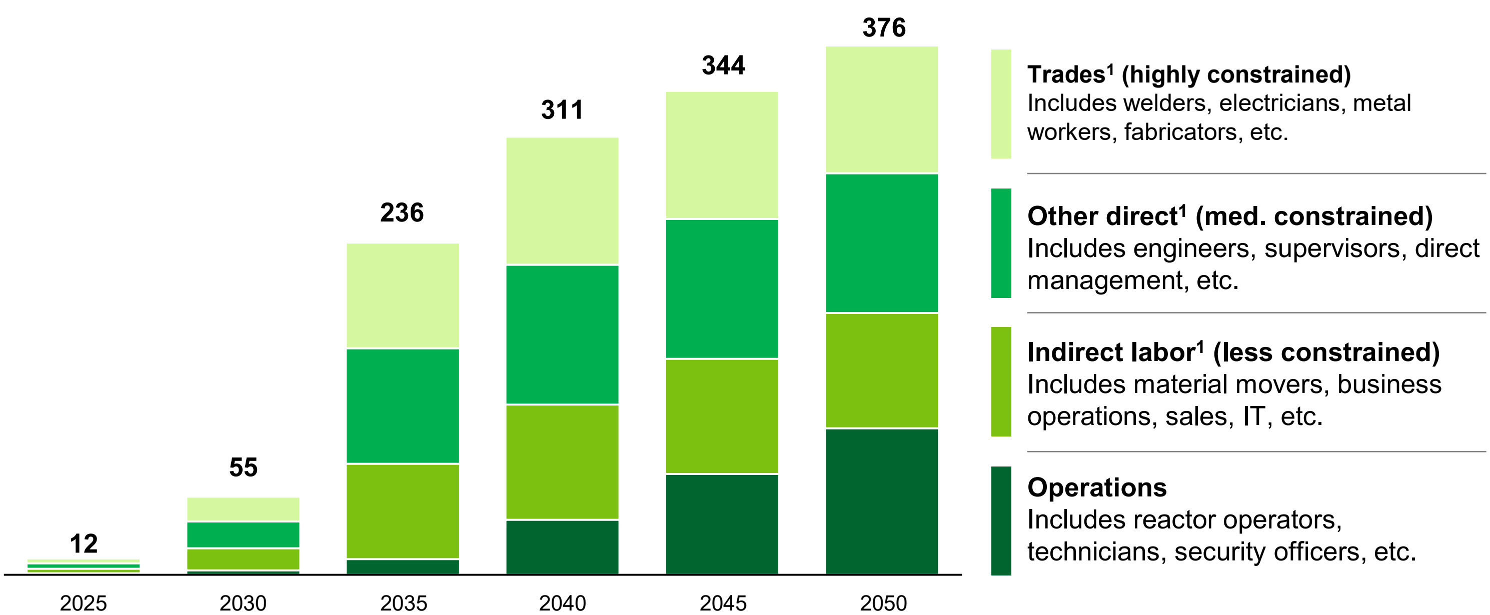
Section 3.c: Industrialization

Once the nuclear industry has gained momentum and new projects are being ordered, the industrial base must scale accordingly. Successful deployment of 200 GW by 2050 would require continuing to support new reactor designs, including additional applications (e.g., industrial heat, hydrogen generation, desalination, and global export), while also scaling-up the nuclear workforce, fuel supply chain, component supply chain, licensing capacity, testing capacity, and spent-fuel capacity.

Section 3.c.i: Workforce

Building 13 GW of new nuclear capacity per year would require ~375,000 workers by 2050 for construction, manufacturing, and operations; roughly ~100,000 would be required to operate the 200 GW of reactors in 2050 and ~275,000 would be required for construction and manufacturing. Many of these jobs are often union jobs with a significant ramp rate, so scaling up the workforce would require advance planning and collaboration with unions to ensure trained labor is available.

Workforce estimates for construction, manufacturing, and operations ramping to 13 GW per year, k jobs



1. Construction and manufacturing job estimates derived from capex costs
Source: EIA "Capital Cost and Performance Characteristic Estimates for Utility Scale Electric Power Generating Technologies"

Figure 27: Estimated construction, manufacturing and operations labor force required for deploying 200 GW by 2050[xxxix]

Section 3.c.ii: Fuel supply chain

Supporting 200 GW of new nuclear by 2050 would require the fuel supply chain capacity to increase by 200–300%.

The U.S. had a recent peak of 2,263 MT U_3O_8 mined in 2014. However, an additional 22,000 MT were procured by the U.S. globally in support of ~100 GW of existing nuclear power capacity. To support an additional 200 GW, the U.S. would need to expand mining/milling operations by an additional ~50,000 MT per year (i.e., grow by 22x the most recent peak). Mining/milling of uranium will need to be increased from the U.S., allies, and partners to ensure a secure supply for the expected growth in nuclear capacity.

As of January 2023, the Converdyn Metropolis Works facility is the only U.S. facility capable of converting triuranium octoxide (U_3O_8) to uranium hexafluoride (UF_6)—required for enrichment. This facility has been shuttered since 2017 due to market conditions but is the process of reopening in 2023. The plant has the capacity to produce 15,000 MT per year of uranium in the form of UF6 (Converdyn facility has reduced its capacity to 7,000 MT per year due to accommodate existing market demands). However, to meet the expected demand for 200 GW of new nuclear, it is expected that an additional ~65,000 MT per year of conversion capacity would be needed (i.e., an additional four Converdyn-sized operating facilities).

Existing U.S. uranium enrichment capability is ~4.9M SWU per year, while current U.S. demand is ~15M SWU per year. To meet the additional nuclear demand of 200 GW, the U.S. would need to increase the enrichment capability by ~30M SWU per year (i.e., 6x higher than current capacity) or ~40M SWU per year to be energy independent.

Additionally, nearly all Gen IV reactor designs will require HALEU fuel to operate.[11] Currently, there are no domestic enrichment capabilities for creating HALEU fuel; the only global HALEU enrichment capabilities are in Russia. For Gen IV reactors to succeed, a domestic supply of HALEU fuel would need to be developed. DOE is working to implement a strategy pursuant to section 2001 of the Energy Act of 2020 using funding appropriated by the Inflation Reduction Act, which would support the creation of such a domestic supply of HALEU. A recent INL report estimates that as much as 520 MTPA of HALEU fuel would be required by 2050, which equates to ~22M SWU of enrichment capacity[xl].

The existing U.S. nuclear fuel-fabrication capacity is ~4,200 MT per year across Westinghouse, Framatome, and Global Nuclear Fuel-Americas. This capacity serves to provide fuel to the existing U.S. fleet, while also providing fuel for international nuclear power plants. It is projected that an additional ~5,000 MT annual capacity of fuel fabrication would be required to support an additional 200 GW of new nuclear capacity on the grid.

While most Gen III+ reactors use the same fuel that existing reactors use, Gen IV reactors use advanced fuel designs that currently do not have a domestic supply chain. Some designs require TRISO fuel while others use metallic alloy fuel—compared to the oxide fuels used by Gen III+ reactors. To achieve commercial liftoff for Gen IV reactors, fuel fabrication facilities capable of supporting the fuel for both “first load” and subsequent reloads are required. Facilities for fabricating TRISO and metal fuels in the United States broke ground in 2022.

[11] HALEU is defined as "uranium having an assay greater than 5.0 weight percent and less than 20.0 weight percent of the uranium-235 isotope." Section 2001(d)(4) of the Energy Act of 2020

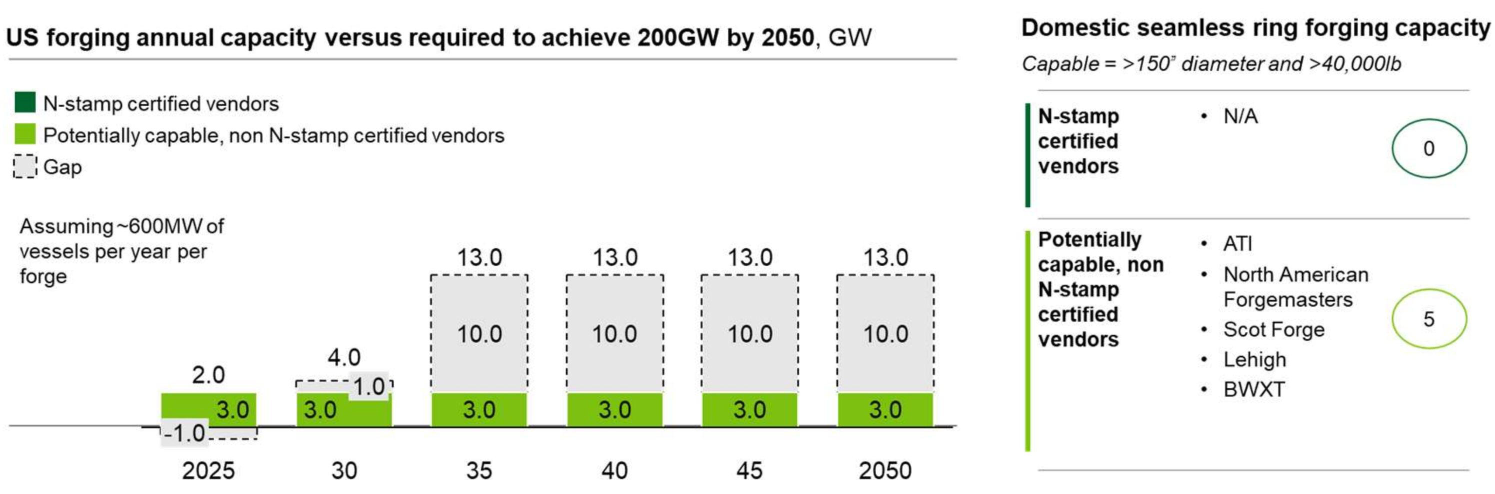
Section 3.c.iii: Component supply chain

The component supply chain consists broadly of material extraction, processing, component manufacturing and modular assembly or sub-assembly, depending on the degree of pre-construction fabrication of a given design, and must also scale to meet deployment rates.

Gen III+ reactors operate in a similar manner to the existing U.S. nuclear fleet, which are also light water reactors. While the supply chain may not be of sufficient capacity as of 2023 to support expansion of Gen III+ reactors, the designs are relatively well understood compared to Gen IV, and could be scaled relatively quickly.

However, Gen IV reactors operate in more exotic environments (e.g., high-temperature gas, molten salt, liquid sodium metal) that require a more capital-intensive buildout of the supply chain for the primary side of Gen IV reactors. The secondary side would likely operate in a manner similar to Gen III+ reactors and is less of a supply chain concern.

A common concern of the U.S. nuclear supply chain is the lack of availability of large forging capacity to make light water reactors. As of 2023, there is no domestic capacity for making nuclear grade forgings. However, certain vendors may have the ability to meet the quality requirements of commercial nuclear reactors. Even with that capacity, the U.S. would have a gap of ~10 GW per year of large forging capacity that would be required to achieve 200 GW of advanced nuclear by 2050 (Figure 28).



Source: McKinsey Power Model, Industry vendor interviews, Forging Industry Association; ASME

Figure 28: U.S. ring-forging capacity to achieve 200 GW by 2050 versus existing capacity, assuming all designs required ring forging

Section 3.c.iv: Licensing

Licensing resourcing and processes would need to scale up to support increased throughput of 13 GW per year. Predictable licensing timelines, e.g., within 2–3 years, have been highlighted by investors and other stakeholders as a key factor for enabling deployment at scale.[xli]

The NRC has stated that the generic licensing timelines for new reactors have traditionally been approximately 42 months for light water reactors under both part 50 and 52 licenses,[xlii] but the NRC is on track to complete the licensing process for Kairos's Hermes reactor in less than 24 months.[xliii] To consistently achieve licensing within 24 months, the NRC may require 7–8 staff members per core review team.

To achieve 13 GW per year of new nuclear deployment, the NRC might have to increase staff by ~500 dedicated license reviewers, with likely an additional 300–500 subject matter experts. Additionally, the NRC would likely need to grow by ~1,000 staff to accommodate construction oversight and operating reactor inspectors as well as specialty inspectors by 2050 for inspection of operating plants.

The NRC operates on a two-year budgeting cycle, therefore any operators planning on submitting a new license application must inform the NRC of their intention a minimum of two years prior to submittal to ensure the license review is performed in a timely manner. This will allow the NRC to hire the personnel necessary for the licensing review teams.

Section 3.c.v: Testing

Testing requirements for Gen III+ designs are relatively minimal, as most of the designs are consistent with existing nuclear reactor designs. However, to deploy Gen IV reactors, a fast-spectrum test reactor would be required for testing fuels and materials. The U.S. had planned on building a fast test reactor, the Versatile Test Reactor (VTR); however, funding was eliminated in 2022. There are only a handful of operating fast-neutron test reactors globally and most reside in Russia. To successfully deploy Gen IV reactors, the U.S. would need to invest in a fast-test reactor or align with other nations to use their test reactors to support the deployment of Gen IV reactors.

Section 3.c.vi: Spent nuclear fuel

Current storage of spent nuclear fuel (SNF)

Today, commercial SNF from light water reactors—currently managed/stored primarily by the nuclear utilities—is safely stored in highly regulated and monitored facilities. Commercial SNF has continued to accumulate at nuclear power plant sites in cooling pools and dry cask storage systems. As SNF pools reach their capacity limits, utilities have transferred spent nuclear fuel into dry cask storage at utility-owned dry storage facilities known as Independent Spent Fuel Storage Installations (ISFSI). All ISFSIs except for one are located on existing reactor sites where the SNF was generated. The Nuclear Regulatory Commission (NRC) licenses dry cask storage systems for 40 years and allows license renewals for 40 additional years.[xliv]

There are over 70 storage facilities at or near a nuclear power plant site in 35 states. In total, U.S. commercial reactors have generated about 90,000 metric tons of SNF since the 1950s.[xlv] The volume of the spent fuel assemblies is quite small considering the amount of energy they produce. If all of it were able to be stacked together—not including shielded packaging, it could fit on a single football field at a depth of less than 10 yards. In the short-term, continued storage in dry cask storage systems licensed by the NRC protects people and the environment from the radiological impacts of spent nuclear fuel.

Path to federal consolidated interim storage

Consolidated interim storage is an important component of a nuclear waste management system. DOE anticipates that a federal consolidated interim storage facility would need to operate until the fuel can be moved to final disposal. It will allow for the removal of SNF from reactor sites, provide useful research opportunities, and build trust and confidence with stakeholders and the public by demonstrating a consent-based siting approach. The duration of the interim period depends on the completion of a series of significant steps, such as the need to identify one or more sites, design site-specific facilities, license, and construct facilities, plus the time needed to move the SNF.

In FY21-23, Congress appropriated funds to the Department for federal interim storage activities, including preliminary work towards the development of a federal consolidated interim storage facility (CISF).[xlvi] Also, in 2021, DOE issued a Request for Information (RFI) on Using Consent-based Siting to Identify Sites for Interim Storage of Spent Nuclear Fuel and received 225 submissions in response.[xlvii] In 2022, DOE issued a funding opportunity announcement (FOA) to provide resources for communities interested in learning more about consent-based siting, management of spent nuclear fuel, and interim storage facility siting considerations.[xlviii]

DOE is committed to a consent-based approach to siting federal storage and disposal facilities and a waste management system that enables broad participation and centers equity and environmental justice. At an absolute minimum, the Department's consent-based siting process will include informed, inclusive participation of historically disadvantaged and underserved communities in the decision-making process. Community well-being is a key component of the consent-based siting process, which puts people and communities first. Through the consent-based siting process, potential host communities will have an opportunity to weigh the potential opportunities and risks of hosting a facility, including the social, economic, environmental, and cultural effects—both positive and negative—it may have on the community.

While the current focus for DOE is in on consolidated interim storage capability, the lessons learned from consent-based siting for a federal consolidated interim storage facility will be applicable for siting any permanent disposal facilities in the future—and potentially siting efforts for other technologies or other place-based initiatives. For more on the intersection of siting and energy and environmental justice, see the Overview of Societal Considerations and Impact document.

Expectations for permanent disposal

"Every country that has chosen a strategy for managing its SNF over the long term has opted for disposal in deep-mined, geologic repositories." – US Nuclear Waste Technical Review Board, 2015.

Permanent disposal in a mined deep geologic repository (DGR) is the foremost alternative for spent nuclear fuel and high-level radioactive waste disposition. Five decades of research, development, and demonstration in multiple countries supports the feasibility and safety of disposal of spent nuclear fuel and high-level radioactive waste in DGRs. Many countries other than the United States have decided to dispose of spent nuclear fuel and/or high-level radioactive waste in a mined DGR including: repository construction underway in Finland; license application submitted in France and Sweden; selected in Russia and Switzerland; and active site selection in Canada, China, Croatia, the Czech Republic, Germany, Hungary, India, Italy, Japan, the Netherlands, Romania, Slovakia, Slovenia, South Africa, South Korea, Spain, Taiwan, Ukraine, and the United Kingdom.

In 1987, Congress designated Yucca Mountain as the only site to be evaluated for a deep geologic repository; however, Congress ceased funding the Yucca Mountain Project in 2010. DOE has determined that Yucca Mountain is unworkable largely due to the lack of public support and necessary appropriations. See the "Path to federal consolidated interim storage" section for more on DOE's commitment to a consent-based approach for its waste management system.

Case Study: Disposal of Transuranic radioactive waste in the U.S.

The U.S. has already implemented a DGR for long-lived transuranic waste (note: Most transuranic waste in the United States is from nuclear weapons production facilities) at DOE's Waste Isolation Pilot Plant (WIPP) \in southeastern New Mexico. WIPP isolates long-lived radioactive waste in a bedded salt formation 655 m (2,150 ft) underground. Since 1999, WIPP has received more than 13,000 waste shipments from sites across the U.S.,[l] cleaning up 22 generator sites nationwide.

Impact of Gen IV advanced nuclear reactors on spent nuclear fuel

In the United States, research, development, and demonstration of Gen IV advanced reactors aims to enhance passive safety, provide versatility, reduce capital and operating costs, and reduce the amount of spent fuel requiring disposal. However, while Gen IV reactors would produce a smaller volume of spent fuel per unit of power generated, deployment of advanced reactors would not significantly alter the inventory of radioactive isotopes associated with power generation, and thus would not change the need for permanent disposal of spent nuclear fuel or high-level radioactive waste.

Section 3.d: Capital formation

Deploying ~200 GW of nuclear capacity in the U.S. could require ~$700B in capital formation by 2050, with $35-40B required by 2030 and $300-400B required by 2040. These investment figures are built out from estimated overnight costs for reactors (using FOAK to NOAK learning rates as described in Section 2.b), and are representative of deployment costs including siting, upfront engineering, materials, construction, labor, cost of capital, etc. Given they are built out from individual reactor cost estimates, they may potentially undercount some of the investments required to scale the industrial base, e.g., new manufacturing facilities or workforce training.

Some advanced nuclear companies have successfully announced and executed initial public offerings (IPOs) via special purpose acquisition companies (SPACs) and completed private investment in public equity (PIPE) financing rounds. These investments have primarily been focused on reactor designers, rather than the industrial base.

Capital providers across the risk-return spectrum show different levels interest in nuclear. On one end, a small group of equity investors and advisors beyond venture capital (VC) see a clear and necessary role for nuclear in the energy transition, and they are developing their investment theses for nuclear (e.g., some PE and infrastructure funds, investment banks). On the other end, most other capital providers do not have nuclear "on their radar" and are not considering it as part of their investment / lending strategy. This group includes many equity investors (e.g., other PE and infrastructure funds, institutional investors) and debt providers (e.g., banks, debt funds). This group considers nuclear to be outside of their risk appetite due to perceived technology risk and regulatory risk, investment length, concerns about project execution, and lack of a robust pipeline of projects with secured customer orders. In addition, some investors also mention concerns about public image and reputation, and the lack of a consistent classification of nuclear investments in green / ESG investment frameworks.

To consider a more active investment stance in nuclear, these capital providers are waiting to see more projects nearing deployment (e.g., final regulatory approval and site selection work) and further involvement from major players (e.g., large utilities). Further education of the investment community and the public on the important role of nuclear in the energy transition is key.

All capital providers agree that the government would need to play a significant role for nuclear to take off in the next ten years, including capital deployment, risk mitigation/guarantees and acceleration of regulatory/permitting processes.

Section 3.e: Equity and environmental justice (EEJ)

Advanced nuclear deployment can provide notable benefits including grid reliability and resilience, clean energy access and affordability, pollution reduction, high-paying jobs, and tax revenue to communities,[li] including rural, low-income, or communities of color who face high levels of energy burden and energy poverty, limited or no access to clean energy, and high exposure to pollution from fossil fuel power plants.[lii, liii, liv] Polling shows that communities surrounding reactor sites view nuclear more favorably than the general public,[lv] yet the benefits of these sites have not been equitably distributed, with the economic impact of reactors often benefitting whiter and wealthier communities. Nuclear fuel cycle facilities, such as uranium mining and milling, and the U.S. weapons program have disproportionately harmed low-income communities, communities of color, and tribes.[lvi]

Engaging in early, frequent, transparent, and two-way dialogue with host communities across the entire fuel cycle creates the greatest likelihood of project success. A lack of community buy-in can spur community- or organization-led lawsuits and protests, which may delay, or even cancel, nuclear projects.[lvii] Community engagement can and should begin before submission of an application to the NRC for licensing. Then, once the NRC licensing process begins, community engagement should continue and will also be implemented through the National Environmental Policy Act.

In addition to instituting community-engagement, projects can mitigate EEJ risks (risks both to the project and caused by the project) by being aware of potential impacts and taking steps to maximize benefits and minimize harms. There are many ways for projects to maximize benefits and minimize harms in line with EEJ goals and principles.[lviii] The D&D Introduction covers actions related to 1) the distribution of impacts (i.e., who experiences benefits vs burdens) and 2) procedure (i.e., giving power to impacted individuals/groups to make decisions about things that affect their lives).

Additional EEJ considerations for nuclear are integrated throughout this report, including plant operation, land impacts, and grid stability. Assessing these considerations through the lens of how different communities or groups will be impacted, how impacts will interact with (potentially alleviating or exacerbating) existing burdens, and how communities can inform decision-making can inform more just and equitable deployment. For EEJ considerations for spent nuclear fuel, please see Chapter 3.c.vi.

Chapter 4: Challenges to Commercialization and Potential Solutions

Key takeaways

- The nuclear industry is at a commercial “liftoff” stalemate between potential customers and the value chain needed to deploy projects
- To progress beyond this stalemate, deliberate action to kickstart and sustain the nuclear industry is necessary (i.e., demand generation), which could involve public sector financial support
- During project delivery, lessons learned from Vogtle should be incorporated to inform project management, and project management knowledge from all future projects could be preserved in a public-private knowledge sharing collaboration effort
- During industrialization, the public and private sectors could track progress towards the necessary capacity of workforce, fuel supply, component supply, licensing, testing, and spent fuel management, and could offer financial support where constrained

Reaching 200 GW of new nuclear capacity in the U.S. by 2050—though effective generation of a committed orderbook, project delivery, and industrialization—will require targeted action by both public and private sectors. This section provides a selected set of possible actions required to effectively scale the advanced nuclear industry and reach 2050 decarbonization targets.

Section 4.a: Committed orderbook

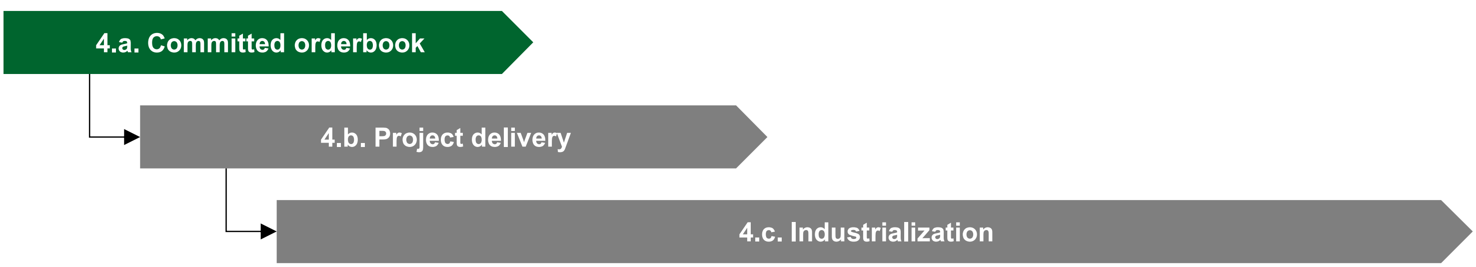


Figure 29: The three phases of new nuclear-capacity scale-up

In generating a committed orderbook for 5–10 deployments of a single reactor design, the primary challenge has been the nuclear industry's commercial stalemate between potential customers and the value chain needed to deploy those projects.

Regulated utilities are likely to be many of the first movers for deploying advanced nuclear. Because of the risks of cost and schedule overruns, it is unlikely that a first mover will emerge to deploy advanced nuclear without rate recovery. Therefore, regulated utilities or public power will more likely be first movers as opposed to merchant or non-traditional companies. Based on interviews, other customers like technology or industrial companies may play an important role as off-taker for output from advanced nuclear. However, these interviews also suggest that they have little appetite for building or operating nuclear themselves, likely relying on partnerships with utilities or PPA models as they currently do with renewable projects. However, multiple utilities have stated that they would like to "wait and see" how the first deployed advanced reactors meet cost and schedule expectations before committing.

The stalemate poses a significant risk. If demand does not materialize for a critical mass of reactors, supply chain standup will be less efficient and it will not be possible to move down the learning curve with repeat deployments. Further, achieving 200 GW by 2050 at 13 GW per year would require more than ~40 SMRs or ~13 large Gen III+ reactors coming online annually. With a projected two-year licensing period and 3–5 years of construction, "waiting to see" the results of the first deployments would likely lead to missing decarbonization targets and missing out on opportunities for establishing a strong U.S. nuclear industrial base.

Challenge: The industry is at a commercial liftoff stalemate - there is not currently a committed orderbook for the first 5–10 nuclear reactors

Potential solutions:

The private sector could pool demand for one or more reactor designs, which could provide benefits including de-risking the initial builds by sharing the costs and potential overruns across the pool, sharing learn-by-doing lessons by deploying the same workforce from the initial build to future constructions, and providing a substantial signal to the industry to allow for scaling the supply chain. Interviews with industry stakeholders suggest this demand pool could take many different forms, including but not limited to:

1. **Consortium committing to 5-10 (or more) reactors:** A group of companies, e.g., utilities, could enter a cost sharing agreement for the construction of multiple reactors, likely of the same design. This pooled demand would allow for sharing risk across multiple owners and could smooth the cost curve from the first reactor to the last. The consortium structure would involve some inherent complexity in coordinating across multiple companies, but regulated utilities are recognized as being generally collaborative, mitigating this risk.

2. **Use of developer to build reactors to sell or lease to end-users:** A developer could buy and construct reactors in bulk and then lease the asset or sell the power through a PPA to end-users. This model would reduce the risk for the end users as the risk would fall on the developer. This would also allow for building out the supply chain and learn by doing. This model is common in the power industry outside of nuclear. However, this model would need to be carefully considered for end-users as the financial constructs of this approach may not be appealing to regulated utilities.

3. **Export of 5-10 reactors to foreign off-takers:** Committed orders for exports would help generate the critical mass of reactors enabling the domestic supply chain and manufacturing to scale, but the learnings and workforce from early construction would likely be limited.

To break the current stalemate and generate demand for 5–10 nuclear reactors of the same design by 2025, different forms of government financial support could help de-risk early projects and accelerate private sector commitment. The following four mechanisms are intended to show the potential forms of support that could accelerate deployment and were informed by interviews with utilities, investors, and other stakeholders.

1. **Cost overrun insurance:** A third party (either government or non-government) could agree to cover certain costs of reactor construction above a certain cost threshold as a project insurer. For example, a project might establish a cost threshold that once exceeded, would result in partial coverage by a government or other entity that shares the risk (e.g., up to 50% of total cost overrun). This form of financial support would reduce the risk of unbounded cost overruns to the project owner and could accelerate orders from U.S. utilities and other customers. However, a direct statute would be necessary from Congress to allow the U.S. Government to fill this role.

2. **Financial assistance, e.g., tiered grants:** Tiered grants, starting at the highest dollar amount for the first reactor and decreasing with each subsequent deployment, could offer partial risk assurance and motivate customers to accelerate commitments to capture the maximum financial support. Tiered grants could start at amounts expected to result in a very competitive LCOE for nuclear power and scale back. Ensuring that first-movers receive the best deal could induce customers to commit earlier. Establishing right-sized tiered financial assistance would require predictive ranges of construction costs, which have been difficult to estimate with certainty.

3. **Government ownership:** Government could purchase nuclear plants directly. For example, the Tennessee Valley Authority (TVA)—a federally-owned electric utility—recently entered an agreement with GE Hitachi Nuclear Energy to support planning and preliminary licensing for the deployment of the BWRX-300 SMR design. Additionally, SMRs and microreactors could be well-suited for providing resilient and reliable off-grid power directly to military installations and other national security infrastructure.

4. **Government-enabled off-take certainty:** Government entities could strengthen demand-certainty for asset owners through a combination of off-take agreements for nuclear power (e.g., direct power purchase agreements for up to 10 years [12]). In areas with a utility service monopoly for the government site, a government entity could purchase power indirectly through the utility service monopoly if the service monopoly agreed to enter into a power purchase agreement with the project owner for the government.[13] This support could scale back with each deployment, e.g., such that each reactor ordered represents the best deal, the second the next-best, and so on.[14]

4.b: Project delivery

Figure 30: The three phases of new nuclear-capacity scale-up

12 The USG is limited to a 10 year term for most utility contracts. See 40 U.S.C. § 501(b).
13 See 40 U.S.C. § 591.
14 In the United Kingdom, to support scaling of the offshore wind and other low-carbon industries such as nuclear, a contract-for-difference model provides government “guarantees” for an offtake price such that the difference between the guaranteed price and what the electricity can achieve in the market is covered by government support.

Performance at recent nuclear deployments that have gone over-schedule and over-budget (see Section 3.b on Vogtle) have resulted in a wariness of potential customers to invest in new nuclear capacity. This reluctance has resulted in stagnation of the nuclear industry and a loss of the nuclear industrial base required to successfully execute projects.

However, the issues that have arisen at these projects are preventable. Many of the major issues at recent nuclear construction projects are general megaproject problems rather than nuclear-specific difficulties. By investing early in the proper planning and processes, project management can avoid the common pitfalls of megaprojects and nuclear construction. This section uses the example of the Vogtle project in Georgia to illustrate actions necessary to avoid potential cost overruns.

Challenge: The U.S. has not recently executed an individual nuclear project reasonably on-time and on-budget (+/- 20%)

Potential solutions: Use lessons learned from Vogtle to inform best practices for a new individual nuclear plant project.

The systemic issues at Vogtle can be traced back to seven primary root causes. Six of these seven root causes are within project leadership's control and could be avoided effectively in future projects (Figure 31).

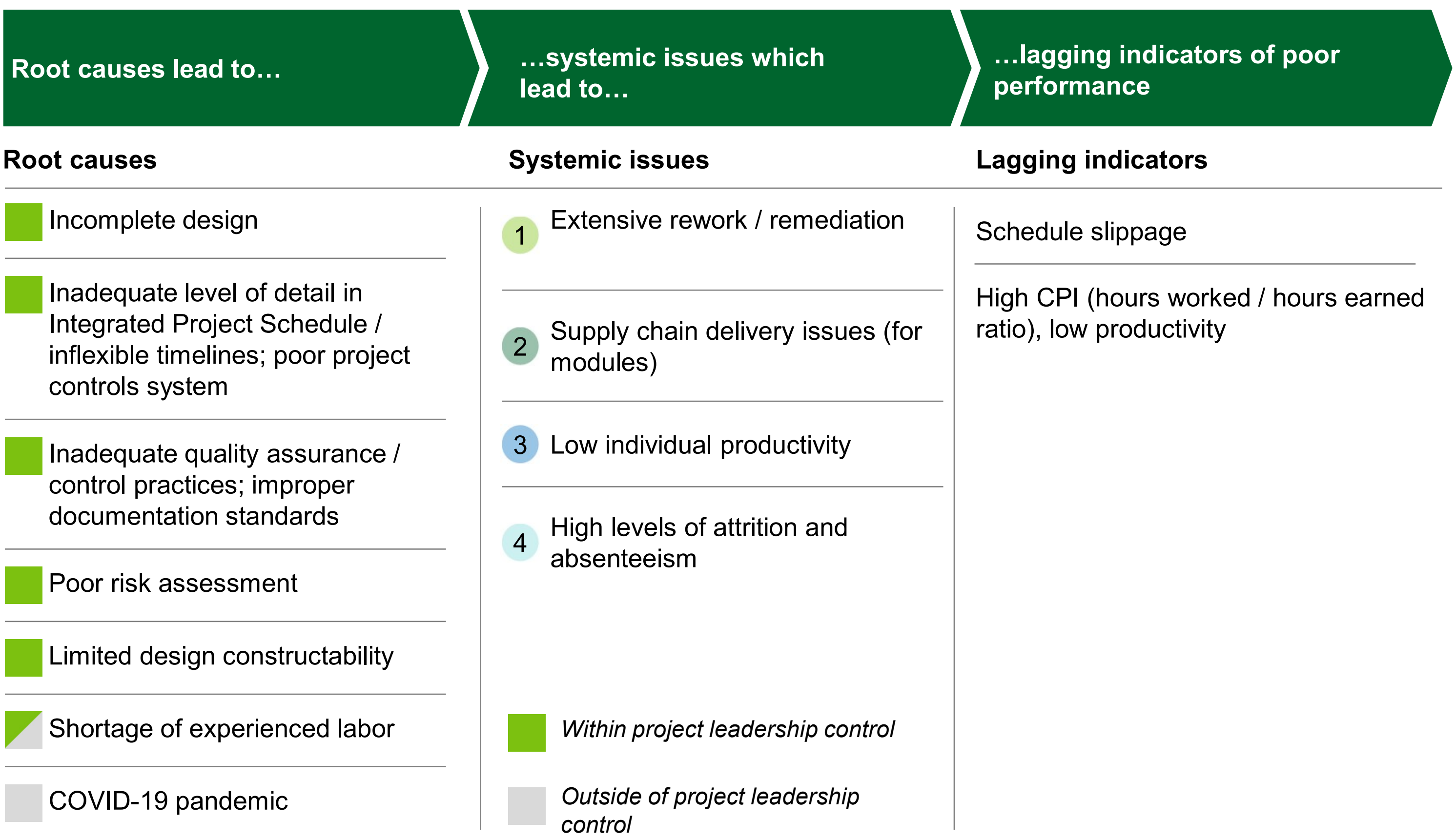


Figure 31: Root causes and systemic issues associated with Vogtle cost and schedule overruns

1. Complete the design before starting construction

Complete >70% of the design (everything that can be completed prior to site selection) before starting construction, or at least before module fabricators start fabrication, and develop detailed "Certified for Construction" work packages before starting construction.

Advanced nuclear developers who are not currently under government cost-share programs have indicated they are reluctant to spend additional funds to finalize designs without having a committed orderbook. This leads to an impasse where buyers expect construction to commence promptly once contracts are signed, however construction should not begin until the design is nearly finalized.

Grants to reactor developers and/or their customers who not part of government cost-share programs to support the completion of all aspects of the design that can be completed without having a site selected could be critical to ensuring construction challenges are avoided.

2. Conduct a detailed "constructability review" of the design to ensure the project is executed in the most efficient manner

Ensure the selected design has involved construction professionals in the design process. Conduct design-to-construct and design-to-operate analysis (e.g., ensure subsystems are possible to construct, ensure workspace congestion minimized).

3. Create a resource-loaded, achievable, and detailed Integrated Project Schedule and project-controls processes to support execution

Draft a Level 3 Integrated Project Schedule (i.e., owner L3, Contractor L4) before the start of construction. Ensure that the schedule is flexible to missed dates and ensure that it is reasonable and well-understood. Account for workspace congestion in project scheduling. When possible, reuse successful project schedules and work packages from other projects. Resist schedule compression as a result of missed deadlines. Implement rigorous project controls system with transparency into progress indicators; familiarity and transparency is more important than "latest and greatest".

To support the initial project delivery, the government could provide a grant to advanced-reactor companies to develop an Integrated Level 3 project schedule, including—but not limited to—site construction activities, modular fabrication activities, bill of materials, scheduling long-lead items (e.g., large forgings), and labor needs and skillsets required at each step in the buildout process.

Additionally, any lessons learned on the FOAK build should be clearly understood, documented, and revised for future builds.

The use of lean construction techniques (e.g., kitting) should also be used to minimize time wasted in the field and maximize value-added time.

4. Ensure quality assurance (QA) / quality control (QC) and documentation standards are clear and consistent

Codify QA / QC and documentation standards and ensure that labor and management understand and accept these standards. Ensure labor receives adequate training on QA / QC and documentation standards. Promote top-down culture of quality throughout the organization and a culture of reporting transparently to the top of the project management organization and to the owner. Ensure an avenue for direct labor feedback (e.g., on why quality standards are not being met) and adjust accordingly. Fully integrate previously used documentation control systems, design “drawing” systems, wiring control systems, etc.

Constructors should work closely with regulators to ensure all QA materials are understood and meeting the expectations of the regulators. This alignment will allow the constructors to get ahead of any problems and correct any issues the regulator may have before any identified issues lead to substantial rework.

5. Conduct rigorous project-risk-assessment across the lifecycle of the project; identify and mitigate high-priority risks with clear ownership; regularly revisit the risk register to modify, add, or retire risks

Use lessons learned on previous builds to inform the true scale of potential risks and to ensure realism in accounting for these risks. Reassess risks often and take action to mitigate them. Ensure documentation standards are sufficient to surface risks earlier rather than later. Use daily performance tracking to provide transparency, identify critical path challenges, and provide additional support as needed.

6. Invest early and heavily in technical and process training for workforce

Budget for intensive training programs that will be required to train non-nuclear workforce to nuclear standards. Implement a standardized, non-nuclear-to-nuclear construction training program across all functions. Ensure the employment offering is competitive for local labor markets.

The Department of Energy could evaluate existing construction labor gaps (e.g., welding) and invest in community colleges / trade schools to ensure that the required capabilities for construction are developed.

Industry interviews suggest NRC requirements for working on-site during the construction of a nuclear power plant may restrict on-the-job trainings. While having certain qualifications for many tasks is a necessity for safe construction (e.g., certified welders), other roles that do not impact nuclear safety should be less stringent (e.g., citizenship requirements for non-safety-related construction).

Challenge: The U.S. has no institutionalized project-management knowledge for nuclear plant construction to inform future nuclear construction projects

Potential solutions: Once a single project is executed successfully, it will be important to leverage the knowledge gained from the project to improve the performance of all follow-on projects.

A possible collaboration between the public and private sectors could be the creation of an entity for project management knowledge to be shared across projects, including Integrated Project Schedules, work packages, lessons learned, and risks.

Section 4.c: Industrialization

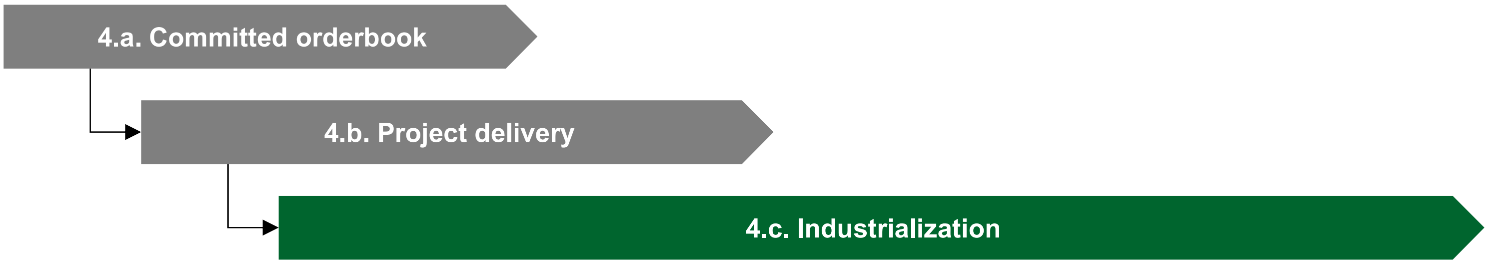


Figure 32: The three phases of new nuclear-capacity scale-up

As of 2023, The nuclear industrial base is not equipped to deliver 13 GW per year of new nuclear capacity, a rate that could deliver 200 GW by 2050. Across labor, fuel supply chain, component supply chain, licensing, testing, and spent fuel, deliberate action would be necessary to reach scale-up. Given the timeframe for industrialization, many of these actions will have a longer ramp time.

Section 4.c.i: Workforce

Challenge: The U.S. would need an additional ~375,000 people with technical and non-technical backgrounds to support the deployment and operation of 200 GW of new nuclear by 2050; today it has ~100,000

Potential solutions: By 2030, a labor force of ~50,000 would be required for construction and manufacturing. Approximately ~10,000 of these workers would need to be skilled craft workers (e.g., welders, electricians); the workforce with this skill set is highly constrained today. Supply of other direct labor (e.g., engineers, project managers, project supervisors) is also highly constrained. Constraints come from both the lack of a scaled domestic industry to provide consistent training for execution of megaprojects and from an overall skilled-labor shortage in the nuclear field. By 2050, a labor force of ~100,000 would be required for new nuclear plant operations in addition to ~275,000 required for construction and manufacturing.

Possible actions by the public sector include:

- Identify, quantify, and monitor the most highly constrained trades / labor types, provide financial support (e.g., grants, low-cost loans) to recruit and train new labor in these areas, or provide regional education programs to facilitate the development of necessary skills, possibly in collaboration with industry
- Collaborate with industry unions to ensure nuclear workforce is trained with sufficient lead time for reactor construction and operation

Possible actions by industry include:

- Develop a committed orderbook with long-term commitments to nuclear power to encourage workers to become nuclear certified
- Identify previously trained talent from Vogtle and VC Summer and recruit for future projects
- Identify and recruit from other potential talent pools such as local industry unions (e.g., IBEW, UA), local technical schools, local high schools, adjacent industries, outreach to military veterans, and coordinated efforts to re-recruit those who have left the industry

Section 4.c.ii: Fuel supply chain

Challenge: The U.S. will need access to an additional ~50,000 MT per year of U_3O_8 mining / milling capacity to support the deployment of 200 GW of new nuclear capacity by 2050; the U.S. currently has ~2,000 MT per year U_3O_8 mining / milling capacity

Potential solutions: The U.S. needs to secure a source of uranium to support the projected demand of advanced nuclear reactors. This supply would potentially need to be split between developing a domestic supply and working with other OECD countries to ensure a sufficient uranium supply (e.g., Australia, Canada).

Possible actions by the public sector include:

- Classify uranium as a critical material
- Ensure any non-domestic U_3O_8 supply comes from allies and partners

Possible actions by industry include:

- Trend the expected demand and identify when the projected uranium spot-price is financially viable to open existing reserves
- Identify opportunities to start prospecting for new uranium reserves based on the most recent technologies

Challenge: The U.S. would need an additional ~65,000 MT per year of UF_6 conversion capacity to support the deployment of 200 GW of new nuclear capacity by 2050; it currently has 7,000 MT per year of UF_6 conversion capacity

Potential solutions: In the near-term, the U.S. could support power plant operators in acquiring conversion capabilities through OECD countries to ensure sufficient availability of UF_6. In the long-term, as demand is projected to grow, there may not be a need for any government intervention, as the long-term investment in uranium conversion may be financially viable for existing or new market entrants.

Possible actions by the public sector include:

- Provide low-cost loans to existing and new entrants into the market in support of growing the U.S. conversion capabilities
- Provide support navigating the licensing process for new entrants to build and operate new conversion facilities

Possible actions by industry include:

- For existing conversion facilities, identify the cost required to scale existing operations and the required new demand to cover short-term cost investments
- For new entrants into the market, follow nuclear deployment projections and determine the point when investing in a new conversion plant makes financial sense

Challenge: The US does not have sufficient LEU enrichment capabilities to support 200 GW of new nuclear; enrichment capacity would need to grow by ~30M SWU per year to meet additional demand or 40M SWU per year to be energy independent

Potential solutions: The public sector could provide incentives to invest in building domestic enrichment capacity; in the long-term, as demand is projected to grow, there may not be a need for any government intervention, as the short-term investment may clear the hurdle rate for return on invested capital.

Possible actions by the public sector include:

- Provide off-take agreements, financial assistance, and/or low-cost loans to existing and new entrants into the market in support of growing U.S. enrichment capabilities

Possible actions by industry include:

- For existing enrichment facilities, identify the cost required to scale existing operations (and the corresponding required new demand to cover the investments)
- For new entrants into the market, follow nuclear deployment projections and determine the point when investing in a new enrichment plant makes financial sense
- Continue R&D on new enrichment technologies in support of future global demand

Challenge: Long-term HALEU demand could require ~22M SWU per year of enrichment capacity, but the U.S. currently has no HALEU enrichment capacity

Potential solutions: The DOE is pursuing multiple pathways to produce HALEU through its HALEU Availability Program authorized by section 2001 of the Energy Act of 2020. In the long-term, DOE expects sufficient demand for HALEU fuel would drive commercial expansion without the need for government intervention.

Possible actions by the public sector include:

- Implement the HALEU Availability Program, which should include collaboration between industry and government to identify the critical short-term HALEU need and provide a sufficient incentive to meet the existing demands, including creation of a reserve, or stockpile (e.g., HALEU Bank) to meet increases of fluctuations in demand to build the HALEU stockpile[15]
- Provide low-cost loans for enrichers of HALEU future deployment of HALEU supply aligned with projected HALEU demand

Possible actions by industry include:

- Track projected HALEU demand and identify when it is financially viable to enter the market

15 The Inflation Reduction Act appropriated $700M to DOE to implement the HALEU Availability Program under section 2001 of the Energy Act of 2020. DOE may require additional appropriations to fully implement the Program.

Challenge: Fuel fabrication capacity would need to increase from ~4,200 MT per year to ~9,200 MT per year to support 200 GW of new nuclear capacity

Potential solutions: Either existing fuel-fabrication facilities will need to scale production or new fuel-fabrication facilities will need to be built. Government and industry should follow deployment timelines and determine when it makes financial sense to either expand capacity or construct new fuel-fabrication facilities. Some Gen IV reactor OEMs have plans to build their own fuel-fabrication facility, which should be sized appropriately for expected fuel manufacturing demand.

Possible actions by the public sector include:

- Track the capacity of fuel-fabrication facilities and ensure that there is a sufficient supply for reactors coming online
- Provide low-cost loans (e.g., through the DOE Loan Programs Office) to support expansion of existing fuel-fabrication facilities or to bring new fuel facilities online

Possible actions by industry include:

- Fuel manufacturers could sign agreements with advanced reactor OEMs to be the fuel supplier and expand existing capabilities to support fuel demand
- Other companies that have fuel-manufacturing capabilities could consider supporting fuel manufacturing for advanced reactor OEMs to support fuel fabrication
- Gen IV reactor OEMs could sign agreements with either existing fuel manufacturers or new entrants to provide fuel-fabrication services as needed for the reactor design
- Gen IV reactor OEMs who plan on manufacturing their own fuel could (1) build small-scale operations for initial deployment or source fuel from another vendor and (2) design fuel-fabrication facilities to have sufficient capacity for expected throughput required for long-term fuel needs

Section 4.c.iii. Component supply chain

Challenge: There is not enough N-stamp certified supply-chain capacity to support 13 GW per year of added nuclear capacity. There is no U.S. large-forging capacity. For small forging, if all vendors were able to obtain N-stamps there is capacity to support 3 GW per year, which will need to expand to support 13 GW per year

Potential solutions: To date there are 170 N-stamp holders across six different N stamp types.[lix] The current N-stamp holders have installed capacity to support the existing fleet of ~100 GW of nuclear reactors, new reactors, and additional nuclear industry support (e.g., fuel fabrication facilities, test reactors). In order to scale the industry to 200 GW by 2050, the number of N-stamp holders would likely need to increase, or the existing N-stamp holders would need to scale capacity for the new construction that is required. The process for obtaining an N-stamp can take over a year and cost hundreds of thousands of dollars. Organic expansion may occur with guaranteed off-take agreements and industry growth, and additional actions could accelerate this expansion.

For the largest forgings required for large LWRs, such as the AP1000, there is not currently domestic supply and domestic production would require either onshoring of domestic production or new entrants into the space. In the near-term, the U.S. will likely source large forgings from international partners. However, in the long-term, the U.S. could build this capacity domestically to ensure energy security.

Possible actions by the public sector include:

- Identify critical gaps in the nuclear supply chain based on the reactor designs selected and then work with existing N-stamp holders to promote the expansion of their capabilities to support the needs of new reactor designs
- Identify the forging needs required for the projected deployment of advanced nuclear reactors
- Provide grants and low-cost loans to build sufficient capacity to support the deployment of advanced nuclear reactors in the U.S.
- Monitor the response of supply-chain-to-industry demand signals and determine if additional financial incentives are necessary
- Possible actions by industry include:
- Track demand for advanced nuclear and develop forging capabilities that can meet the U.S. demand
- Advanced-reactor OEMs could identify and sign agreements with manufacturers of critical components to ensure construction is not delayed due to lack of critical components

Challenge: Construction of SMRs will require dedicated modular assembly capabilities that either do not exist or are constrained, and the requirements will differ by design

Potential solutions: Unique capacity will be required for each design; fewer designs will be necessary to reduce total industry costs.

Possible actions by the public sector include:

- Provide low-cost loans for the construction of module-manufacturing facilities
- Provide guidance to new module-manufacturing facilities on developing an NQA-1 quality-assurance program
- Evaluate what critical skills are required for modular buildout and assembly and ensure those skills are developed as part of the DOE labor-training program

Possible actions by industry include:

- Identify the critical modules that will be required by advanced-reactor EPCs and develop capabilities to construct the modules

Challenge: Some of the materials used to construct nuclear reactors have been identified as critical minerals on the U.S. Geological Survey Critical Minerals list[lx]; of particular concern are Hafnium, Niobium, Yttrium, Chromium, and Nickel[lxi]

Potential solutions:

Possible actions by the public sector include:

- Where domestic sourcing is possible, provide financial incentives to existing U.S. mines for building the U.S. stockpile of these minerals
- Where domestic sourcing is possible, provide financial support for proven mines to establish mining operations in time to support projected demand
- Where domestic sourcing is possible, support the licensing process of new mines required to meet the long-term demand
- Ensure any non-domestic supply of these minerals comes from allies and partners

Possible actions by industry include:

- Trend the expected demand and identify when the projected mineral spot-price is financially viable to open existing reserves
- Identify opportunities to start prospecting for new mineral reserves based on the most recent technologies

Process step	SC segments to meet the demand of the final product	Significant domestic suppliers	Cost competitive among U.S. suppliers	Cost competitive between U.S. suppliers vs. global suppliers	Is foreign supply source significant secure?	Likely best course of action
Mining & milling	Indium, Niobium, Yttrium, Hafnium	No	N/A	N/A	May be	**Leverage intl. markets**
	Chromium, Nickel	No	?	?	Yes	**Leverage intl. markets**
	Cadmium, Cobalt, Copper, Lead,, Silver, Tin, Titanium,Tungs-ten, Vanadium, Zirconium	Yes	Yes	Yes	Yes	**Expand existing U.S. capability and leverage intl. markets**
Processing	Steel	Yes	Yes	Yes	N/A	**Expand existing U.S. capability**
	Concrete	Yes	Yes	Yes	N/A	**Expand existing U.S. capability**
	Other	Yes	Yes	Yes	N/A	**N/A**
Component	Large component forging and mfg	No	?	?	Yes	**Expand existing U.S. capability and leverage intl. markets**
	Other component forging and mfg	Yes	Yes	Yes	Yes	**No action**
Assm.	Module assembly	No	N/A	N/A	May be	**Build U.S. Capability**

1. Based on plants under construction in year to achieve 200GW by 2050

Figure 33: Nuclear power component supply chain current state

Section 4.c.iv: Licensing

Challenge: The NRC would need to scale its license-application capacity from ~0.5 GW per year to ~13 GW per year to meet projected demand

Potential solutions: The NRC's capacity is determined both by actions taken by the NRC to improve efficiency and increase resources and by activities from applicants to improve and expedite application interactions.

Possible actions by the public sector include:

- Consider implementing licensing standardization, simplification, digitization, and optimization; all can increase throughput and reduce regulatory resource burdens[16]
- Ensure 10 CFR 53 results in further standardization of risk-informed licensing criteria, safety-related determinations, and license execution allowances and expedient remediation pathways
- Clearly define changes that impact safety—including safety-related versus non-safety-related components, systems, and boundaries; any design changes that do not impact safety should not require NRC review

Possible actions by industry include:

- Commit to pre-licensing activities such as high-quality Probabilistic Risk Assessment (PRA) engagement to risk-inform the applicant's work and the use of Early Site Permits and Standard Design Certifications; the use of these activities can be further incented through novel financing like deferred or outcome-based costs
- EPCs, designers, and contractors could upskill and train on regulatory requirements and remediation paths; these skills are essential for an effective workforce to be capable of executing construction-to-license requirements

Section 4.c.v: Testing

Challenge: The U.S. does not have fast-spectrum reactor testing capability to support Gen IV reactors.

Potential solutions: For the successful long-term deployment of Gen IV reactor designs, facilities that provide both high-temperature and fast-neutron spectrum testing will be necessary. The U.S. had extensive fast-spectrum testing capabilities between 1951 and 1994, but there has been no domestic capability for fast-spectrum testing since 1994. A fast-spectrum test-reactor would provide the expanded capacity and accelerated testing capabilities needed to support innovation and the qualification of fuels, materials, instrumentation, and surveillance for growing nuclear power deployment options; this testing capability would benefit all advanced reactors and fuel-cycle technology advancements; it will be essential for the Gen IV reactors to come.

Possible actions by the public sector include:

- Fund a new, fast-spectrum test reactor to support the coming Gen IV reactors

16 Finalization of NRC's Generic EIS for Advanced Reactors will help expedite the review process for advanced reactors by determining those impacts which are substantively the same for all advanced reactor designs and which require plant-specific analysis. See https://www.nrc.gov/reactors/new-reactors/advanced/rulemaking-and-guidance/advanced-reactor-generic-environmental-impact-statement-geis.html

Section 4.c.vi: Spent nuclear fuel

Challenge: The U.S. should continue efforts to identify sites and develop facilities for consolidated interim storage and permanent disposal of spent nuclear fuel

Potential solutions: New legislation would be required to build a federal consolidated interim storage facility or allow development of geologic repositories for permanent disposal at sites other than Yucca Mountain, Nevada. Until new legislation is passed, DOE could undertake preliminary steps towards development of one or more consolidated interim-storage facilities including, but not limited to, engagement in a consent-based siting process. Further development and operation of a federal consolidated interim storage facility are subject to specific constraints that would need to be addressed.

Possible actions by the federal government include:

- Once authorized, proceed with the siting and development of one or more Federal consolidated interim-storage facilities through a new, consent-based process for siting[lxii]
- Once authorized, focus on consent-based siting for one or more geologic repositories as well as federal consolidated interim storage facilities.[17]
- Once authorized, demonstrate a continued Federal commitment to develop one or more deep-geologic repositories by preparing and issuing for public comment a draft plan for the consent-based siting and phased development and operation of a repository.[lxiii]

17 For more information on the importance of consent-based siting for short-term storage, consolidated interim storage, and permanent disposal, see Spent Nuclear Fuel section of Chapter 3.

Chapter 5: Metrics and Milestones

Four types of key performance indicators (KPIs) will be tracked to understand the progress in advanced nuclear deployment and scale. Priority KPIs can be grouped to guide successful market scale-up from demonstrations and FOAK projects through commercialization at scale:

- Leading indicators are indicative of the relative readiness of the industry and markets for at-scale adoption (e.g., early signs that advanced nuclear is "on-track" to play a significant role in a net-zero grid)
- Lagging indicators are representative of successful scaling and adoption of advanced nuclear and provide useful check-ins and metrics for the health of the industry
- Outcomes show the broader impact of new advanced nuclear deployment (e.g., job creation, emissions reduction)

These indicators will be tracked and reported periodically throughout the DOE. There are several priority KPIs that will be indicative of successfully tracking toward a net-zero pathway. Other metrics may also be important for advanced nuclear deployment, but these metrics lay out the "high water mark" for the readiness of technology deployment.

Leading indicators show the ability of advanced nuclear technologies and players to create the pathway needed by 2030 to meet 2050 net-zero goals

- **Demand generation**
  - 5–10 sites with a committed pool-of-demand by 2025 of either one certified design or one mature design undergoing the certification process

- **Project delivery**
  - 5–10 completed site permits by 2028
  - 45,000 additional trade workers trained by 2030 (i.e., workers in addition to those already serving in a nuclear servicing capacity)

Lagging indicators will be most important for tracking scale-up progress. Additionally, performing retrospectives will help inform future technology commercialization efforts

- **Project delivery**
  - Commission the initial demand pool of 5–10 sites of one design by 2035
  - Achieve 10%+ learning rates between FOAK and final demand-pool reactor to achieve overnight capital costs under $4,000 per kW
  - Achieve consistent, less-than-three-year-combined operating licensing timeline
  - Build an industrial base capable of commissioning 6 GW per year new capacity by 2035

- **Industrialization**
  - At least 13 GW annual COL approval by 2035[18]
  - At least 13 GW of annual ITAAC approval by 2039[19]

18 Activity occurs 4 years prior to commissioning
19 The last activity of commissioning

Appendices

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