U.S. DEPARTMENT OF ENERGY

Pathways to Commercial Liftoff: Advanced Nuclear

SEPTEMBER | 2024

Comments

The Department of Energy welcomes input and feedback on the contents of this Pathway to Commercial Liftoff. Please direct all inquiries and input to liftoff@hq.doe.gov. Input and feedback should not include business sensitive information, trade secrets, proprietary, or otherwise confidential information. Please note that input and feedback provided is subject to the Freedom of Information Act.

Authors for the Original Nuclear Liftoff Report and Update

Julie Kozeracki, Loan Programs Office (lead)

Chris Vlahoplus, Loan Programs Office

Loan Programs Office: Ken Erwin, Alan Propp, Sonali Razdan

Office of Clean Energy Demonstrations: Rasheed Auguste, Tim Stuhldreher, Christina Walrond

Office of Nuclear Energy: Melissa Bates, Erica Bickford, Andrew Foss, Derek Gaston, Cheryl Herman, Rory Stanley, Billy Valderrama

Office of Technology Transitions: Katheryn Scott

Office of Policy: Tomotaroh Granzier-Nakajima, Paul Donohoo-Vallett

Argonne National Laboratory: Tom Fanning

Idaho National Laboratory: Brent Dixon, Abdalla Abou Jaoude, Chris Lohse

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Office of Technology Transitions: Vanessa Chan, Stephen Hendrickson, Hannah Murdoch, Lucia Tian

Office of Clean Energy Demonstrations: Tim Beville, Jill Capotosto, Theresa Christian, Kelly Cummins, Andrew Dawson, Melissa Klembara, Mark Natale

Office of Policy: Steve Capanna, Carla Frisch, Elke Hodson, Piper O'Keefe

Office of Nuclear Energy: Alice Caponiti, Janelle Eddins, Mike Goff, Sal Golub, Andy Griffith, Alison Krager Hahn, Katy Huff, John Krohn, Kim Petry, Jason Tokey

Office of Energy Efficiency and Renewable Energy: Patrick Gilman, Jeff Marootian, Paul Spitsen

Office of the General Counsel: Martha Crosland, Anne Finken, Stewart Forbes, MC Hammond, Mofetoluwa Obadina, Avi Zevin

Office of the Secretary: Kate Gordon

Office of Minority Economic Impact: Shalanda Baker, Kelly Crawford

Argonne National Laboratory: Taek Kim, Aymeric Rousseau

Idaho National Laboratory: Chandrakanth Bolisetti, Ashley Finan, Christine King, Erin Searcy

Special thanks: Chad Cramer, James Krellenstein, Jane Reed, Koroush Shirvan

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Executive summary

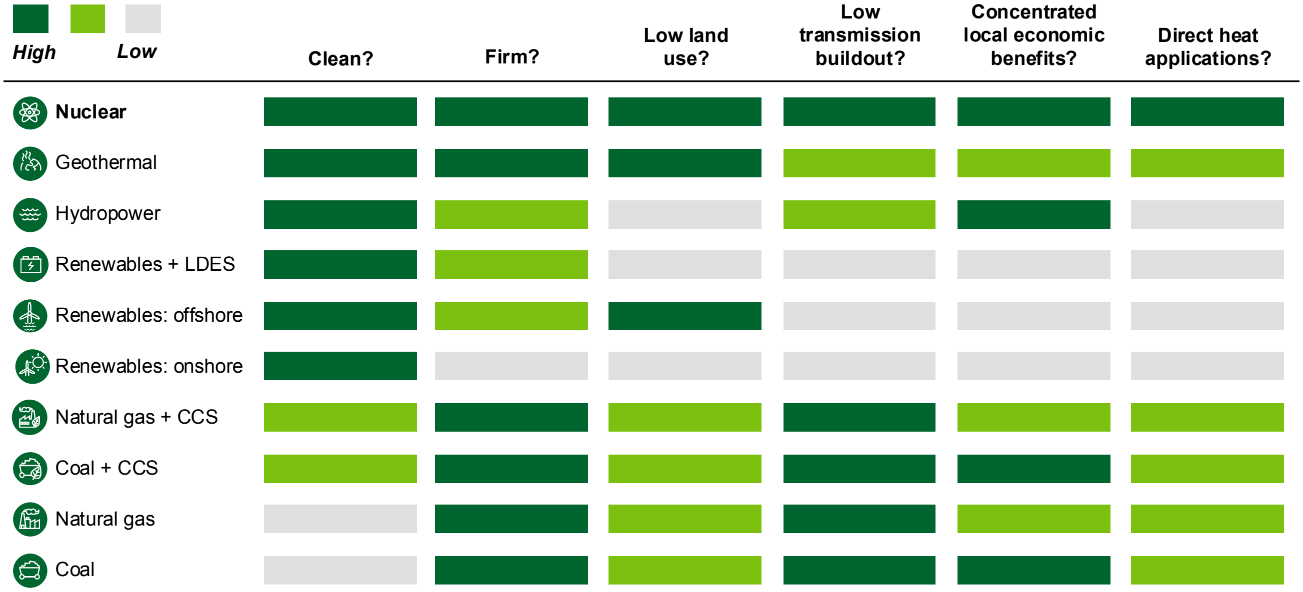
The Pathways to Commercial Liftoff reports aim to establish a common fact base with the private sector around the path to liftoff for critical clean energy technologies. Their goal is to catalyze more rapid and coordinated action across the value chain for deployment. The Nuclear Liftoff Report was published in March 2023 as a "living document" to be updated as the market evolved. This updated report, published September 2024, adds new content and refreshes original content.

US nuclear capacity has the potential to triple from ~100 GW in 2024 to ~300 GW by 2050. The original report clarified nuclear's value proposition and path to large scale deployment. Since publication, a widespread surge in electricity demand after decades of stasis has increased the need for and interest in nuclear. Much of this load growth is being driven by artificial intelligence and data centers with a particular need for carbon-free 24/7 generation concentrated in a limited footprint. This provides a set of customers who are willing and able to support investment in new nuclear generation assets. Combined with the Inflation Reduction Act (IRA) incentives, this demand has created a step change in the valuation of the existing fleet and new reactors. In 2022, utilities were shutting down nuclear reactors; in 2024, they are extending reactor operations to 80 years, planning to uprate capacity, and restarting formerly closed reactors.

Nuclear has an essential role in the energy transition as a clean firm complement to renewables. Power system decarbonization modeling, regardless of level of renewables deployment, shows the US will need at least ~700–900 GW of additional clean firm capacity to reach net-zero; nuclear is one of the few proven options that could deliver this at scale. Nuclear does not "displace" or "compete with" renewables; decarbonization will require both new nuclear and renewable capacity. Including nuclear and other clean firm resources reduces the cost of decarbonization by reducing the need for additional variable generation capacity, energy storage, and transmission.

Nuclear provides a differentiated value proposition for a decarbonized grid. Nuclear 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 high-paying jobs and 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, including high temperatures for industrial heat.

Figure 1: Nuclear provides a differentiated value proposition



■ ▨ □
High *Low*

	Clean?	Firm?	Low land use?	Low transmission buildout?	Concentrated local economic benefits?	Direct heat applications?
Nuclear	■	■	■	■	■	■
Geothermal	■	■	■	▨	▨	▨
Hydropower	■	▨	□	▨	■	□
Renewables + LDES	■	▨	□	□	□	□
Renewables: offshore	■	▨	■	□	□	□
Renewables: onshore	■	□	□	□	□	□
Natural gas + CCS	▨	■	▨	■	▨	▨
Coal + CCS	▨	■	▨	■	■	▨
Natural gas	□	■	▨	■	▨	▨
Coal	□	■	▨	■	■	▨

The existing fleet of 94 nuclear reactors at 54 sites provide ~20% of US electricity generation and almost half of domestic carbon-free electricity. Investing in subsequent license renewals is essential for maintaining the existing fleet: of the 94 operating US reactors, 84 have licenses that will expire prior to 2050; 24 have licenses that will expire prior to 2035. Power uprates totaling ~2-8 GW could add near-term capacity to existing reactors. Existing nuclear sites offer significant benefits for siting new nuclear, and preliminary analysis shows there may be room for ~60-95 GW of new nuclear at existing sites. Multi-unit plants benefit from economies of scale: generating costs at multi-unit plants are 30% cheaper per MWh than single unit plants.

Advanced nuclear includes a range of proven and innovative technologies across two generations (Gen III+ and Gen IV) and includes three size categories (large, small, and micro). Gen III+ reactors are evolutions of the US operating fleet: they use water as a coolant, use low enriched uranium as fuel, and have passive safety systems. Gen IV reactors will use non-water coolants and fuel that are not currently used by the US fleet and will offer multiple advantages, including expanded use cases such as high temperature heat for industrial applications. Tripling nuclear capacity by 2050 likely will require both Gen III+ and Gen IV designs. Reactor down-selection and standardization are critical for cost reduction, though meeting key market needs (e.g., bulk electricity generation including for data centers, industrial processes requiring high temperature heat and/or steam, and remote applications) will likely require different designs.

- **Large light water reactors (generally ~1000 MW) are essential for bulk electricity production.** The US nuclear operating fleet consists of large light water reactors that designers and operators chose to make bigger over time to take advantage of economies of scale in operations, driving a lower cost per MW than smaller reactors.
- **Small modular reactors (SMRs) are generally considered ~50 to ~350 MW.** Even if SMRs may be more expensive than large reactors as measured by $/MW and $/MWh, they offer advantages for certain applications, e.g., replacing smaller retiring coal plants or industrial processes requiring high temperature heat as well as potential siting, construction, and financial advantages.
- **Microreactors (generally <50 MW) could serve a variety of use cases where reliability, transportability, and compactness are highly valued** and alternatives are expensive, e.g., military bases, remote applications including mining, rural communities, industrial operations, and disaster relief.

The US government is supporting the demonstration and deployment of new nuclear. The IRA provided substantial tax credits and increased the authorities of the Loan Programs Office (LPO) for the deployment of commercial technologies, while demonstration and research programs are funded and underway within the Office of Clean Energy Demonstrations (OCED) and the Office of Nuclear Energy (NE) to de-risk more innovative technologies. For existing reactors, the IRA provided a production tax credit (PTC); for new reactors, a PTC or a 30% investment tax credit (ITC) that can become 50% with adders. The IRA also created new LPO authorities for existing and new reactors. In 2024, Congress provided $2.72B to incentivize a domestic fuel supply chain, provided $900M to support Gen III+ SMRs, and passed the ADVANCE Act to increase licensing efficiency.

At Nth-of-a-kind (NOAK) costs, new nuclear is expected to play a critical role in a deeply decarbonized system. While first-of-a-kind (FOAK) reactors may be expensive, repeat deployments within a design are expected to drive substantial cost reductions. Eliminating rework, experience, and cross-site standardization are expected to drive the majority of FOAK to NOAK cost reductions. The nuclear industry, working together with customers and offtakers, can accelerate the learning curve by down-selecting and standardizing reactor designs, minimizing time between projects, and siting multiple units at the same location.

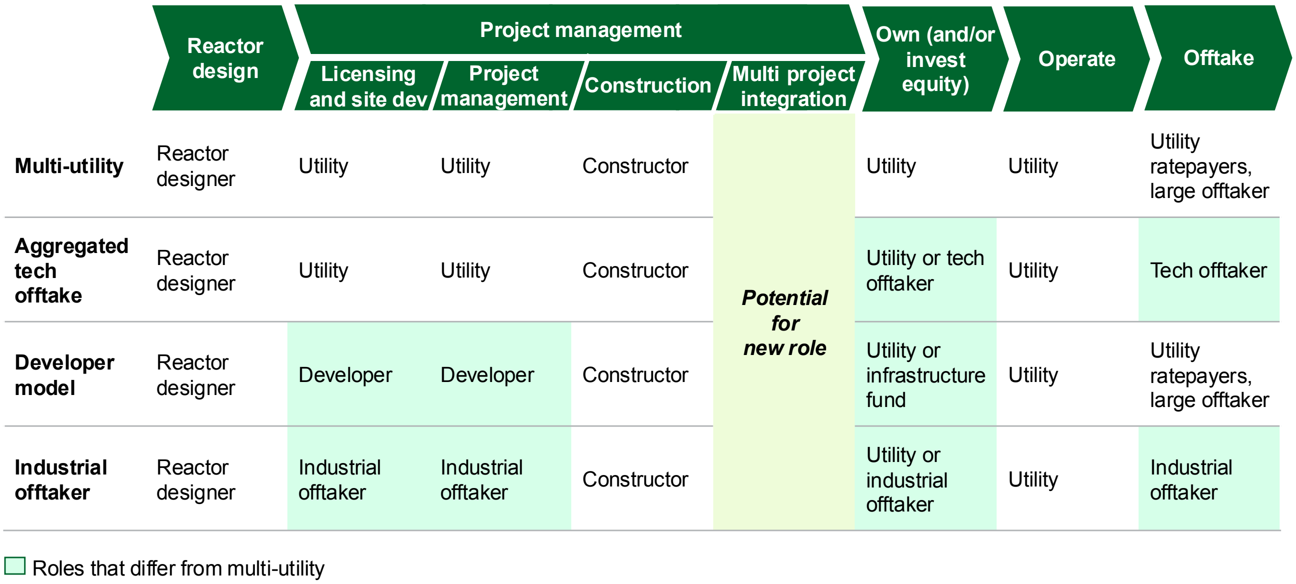
Levelized cost of electricity (LCOE) does not capture the full benefits of nuclear as a clean firm resource. These include the value of an 80-year operating asset, the value of firm generation to provide power during key periods of grid need or when other variable resources are not generating, and the value of clean electricity relative to carbon emitting resources. LCOE also does not fully account for the value of reliable, carbon-free heat for industrial steam, which is critical to many industrial processes and has few decarbonized alternatives.

Waiting until the mid-2030s to deploy new nuclear at scale could lead to missing decarbonization targets and/or significant nuclear supply chain overbuild. If deployment starts by 2030, ramping annual deployment to 13 GW by 2041 would provide 200 GW by 2050; a five-year delay could require 20+ GW per year to achieve the same 200 GW and could result in as much as a 50% increase in the capital required. The path to liftoff requires three overlapping stages: committed orderbook, project delivery, and industrialization.

A committed orderbook of 5–10 deployments of at least one reactor design is the first essential step for catalyzing commercial liftoff. These 5-10 reactors should be of the same design as construction costs are largely expected to decrease based on repeat building and learning by doing.

Consortium approaches aggregate demand and push through the "first mover disadvantage" to realize and share cost reductions. The nuclear industry must solve the issue of spreading early costs over subsequent reactors such that there is no longer a benefit to waiting for the Nth project. Many key roles must be filled for a successful nuclear project: reactor design, project development, owning, operating, and offtake.

Figure 2: Any nuclear project requires many roles to be filled; consortium approaches can help aggregate demand and create partnerships



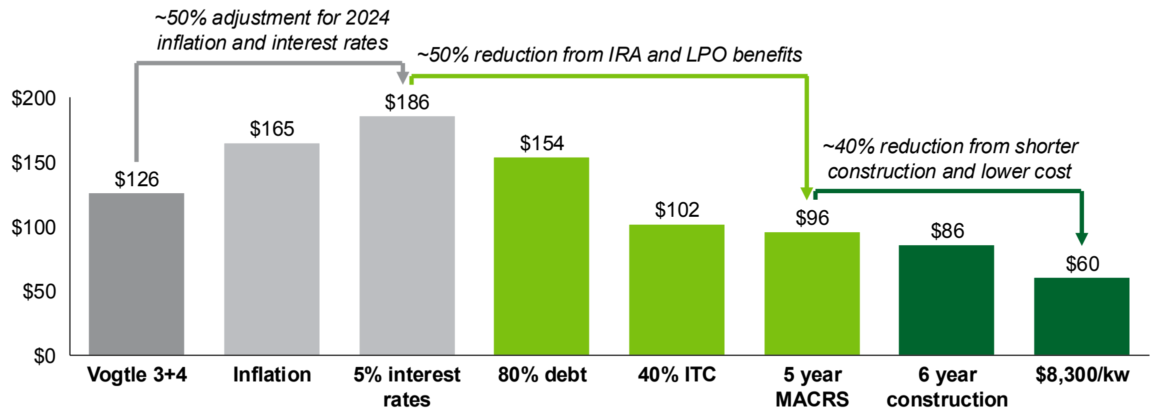
	Reactor design	Project management				Own (and/or invest equity)	Operate	Offtake
		Licensing and site dev	Project management	Construction	Multi project integration			
Multi-utility	Reactor designer	Utility	Utility	Constructor	***Potential for new role***	Utility	Utility	Utility ratepayers, large offtaker
Aggregated tech offtake	Reactor designer	Utility	Utility	Constructor		Utility or tech offtaker	Utility	Tech offtaker
Developer model	Reactor designer	Developer	Developer	Constructor		Utility or infrastructure fund	Utility	Utility ratepayers, large offtaker
Industrial offtaker	Reactor designer	Industrial offtaker	Industrial offtaker	Constructor		Utility or industrial offtaker	Utility	Industrial offtaker

🟩 Roles that differ from multi-utility

Delivering the first projects reasonably on-time and on-budget will be essential for achieving liftoff; Vogtle provides essential lessons for project delivery. The completion of Units 3 and 4 made Vogtle the largest clean energy generation site in the US (as well as the largest energy generation site of any kind in the US). The cost of Vogtle Units 3 and 4 is not the correct anchor point for estimating additional AP1000s given costs that should not be incurred again. Vogtle began construction with an incomplete design, an immature supply chain, and an untrained work force; the AP1000 design is now complete, there is now supply chain infrastructure, and Vogtle trained over ~30,000 workers. The next AP1000s would also realize substantial cost reductions with benefits from the IRA, including the investment tax credit of 30-50% and LPO loans for up to 80% of eligible project costs.

Figure 3: Even assuming Vogtle costs inflated to 2024, next AP1000 could be under $100/MWh with IRA benefits, and closer to ~$60/MWh with cost reductions

LCOE using NREL model, 2024 $/MWh



	Vogtle 3+4	Inflation	5% interest rates	80% debt	40% ITC	5 year MACRS	6 year construction	$8,300/kw
Overnight capital cost	$11,000	$15,000	$15,000	$15,000	$15,000	$15,000	$15,000	$8,300
Construction time	11 years	11 years	11 years	11 years	11 years	11 years	6 years	6 years
Interest rate on debt	3.5%	3.5%	5%	5%	5%	5%	5%	5%
Debt fraction	60%	60%	60%	80%	80%	80%	80%	80%
Tax credit	PTC (old)	PTC (old)	PTC (old)	PTC (old)	40% ITC	40% ITC	40% ITC	40% ITC
Depreciation	15 years	15 years	15 years	15 years	15 years	5 years	5 years	5 years

Full scale industrialization and tripling of nuclear capacity by 2050 would require commensurately scaling the value chain:

- **Workforce:** The US would need to grow its nuclear workforce by ~375,000 (from ~100,000 today) to provide the skillsets for construction, operations, and supply chain.
- **Fuel supply chain:** Per year, the US would need access to ~55,000-75,000 MT per year of U_3O_8, produce ~70,000-95,000 MT per year of UF_6 through conversion, have an additional ~45-55M SWU of enrichment capacity (including HALEU enrichment capacity), and fabricate an additional ~6,000-8,000 MT per year of fuel.
- **Component supply chain:** The US would need to substantially grow the component supply chain to support 300 GW of nuclear; the largest gap is in large component manufacturing, e.g., reactor pressure vessels.
- **Licensing:** The NRC would need to scale its license application capacity to 13 GW per year, which would likely require significant additional resources.
- **Spent nuclear fuel**: DOE is committed to a consent-based approach to siting federal consolidated interim storage and disposal facilities. The US should continue current efforts to identify sites for federal consolidated interim storage and apply lessons from those efforts to future siting efforts for the permanent disposal of spent nuclear fuel.

The nuclear industry is building momentum to break the commercial stalemate as utilities and other potential customers see the successful operation of Vogtle Units 3 and 4, anticipate sustained electrical load growth, and internalize IRA benefits. However, the industry must overcome remaining barriers to achieve liftoff.

Market power prices do not consistently compensate nuclear for the value it provides. Innovative power purchasing is a key tool for large offtakers, including tech and industrial companies, to catalyze new generation. Clean firm standards could help drive nuclear deployment. A standard value for clean firm power could help decision makers account for nuclear's decarbonization and reliability benefits.

Many potential customers cite cost or cost overrun risk as the primary barrier to committing to new nuclear projects. Cost overrun is not a monolith: costs are divisible for sharing among stakeholders who are able to manage project risks and who stand to benefit from project completion. Consortium arrangements and partnerships can reduce the financial exposure of any individual participant. Note that the ITC applies 30-50% to capital cost regardless of initial budget, so in effect provides "overrun insurance," which many potential customers have cited as increasing their willingness to commit to new nuclear.

Figure 4: Nuclear projects have a variety of tools to share and reduce costs and risks

	Sharing costs across projects and participants	**Insuring resiliency through cost scenarios**	**Ensuring project management best practices**
Function	Lowers barrier to entry and facilitates critical mass of orders	Defines cost distributions for project resiliency	Promotes on time and on budget delivery
Cost impact	Shares expected costs	Shares unexpected costs	Reduces unexpected costs
Examples	• Consortium committing to 5-10 (or more) reactors • Financial assistance, e.g., grants • Government build and ownership	• Completion or debt guarantees • Contingent equity • Contingent debt • Flexible PPA prices	• Mature cost estimates • Construction best practices incorporating lessons from Vogtle • FOAK to NOAK cost levers

- Investment tax credit or overrun insurance (*both sharing and insuring*)
- Government-enabled offtake certainty (*both sharing and insuring*)

The US must develop nuclear and megaproject delivery infrastructure. The integrated project delivery model aligns incentives between owners and contractors to deliver projects on-time and on-budget. Funding constructability research could target the drivers of cost overruns and improve project delivery.

New nuclear has a critical role in decarbonization, strengthening energy security, reliability, and affordability while providing 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 new nuclear achieves commercial liftoff and rises to meet the challenge in time.

Glossary

Advanced nuclear	Gen III+ and Gen IV nuclear reactors
AI	Artificial intelligence
ARDP	Advanced Reactor Demonstration Program
DOE	United States Department of Energy
EPC	Engineering, procurement, and construction (or contractor performing)
FOAK	First-of-a-kind
Gen III+	Generation III+, light water reactors with passive safety
Gen IV	Generation IV, reactors that use coolants other than water
GW	Gigawatts, which in this report refers to gigawatts electric
GWh	Gigawatt-hour
HALEU	High assay low enriched uranium, enriched >5% and <20%
INL	Idaho National Laboratory
IPD	Integrated project delivery
IRA	Inflation Reduction Act
kW	Kilowatt
LEU	Low enriched uranium, enriched <5%
LCOE	Levelized cost of electricity
LPO	Loan Programs Office
LWR	Light water reactor
MW	Megawatts, which in this report refers to megawatts electric
MWh	Megawatt-hour
NOAK	Nth-of-a-kind, when most cost reductions have been realized
NRC	United States Nuclear Regulatory Commission
OCC	Overnight capital cost (construction costs without interest)
SMR	Small modular reactor
SNF	Spent nuclear fuel
SWU	Separative work unit, used to quantify enrichment services
US	United States
Vogtle	Alvin W. Vogtle Electric Generating Plant

Chapter 1: Introduction and objectives

Purpose of Liftoff reports

Liftoff reports describe the market opportunity, current challenges, and potential solutions for the commercialization of a portfolio of technologies to serve society's energy needs. Liftoff reports are an ongoing DOE-led effort to engage directly with energy communities and the private sector across the entire clean energy landscape. Their goal is to catalyze rapid and coordinated action across the full technology ecosystem.

Reports will be updated periodically as living documents and are based on best available information at the time of publication. For more information, see liftoff.energy.gov.

Scope of this report

This update report focuses on the pathways required for advanced nuclear to accelerate commercial deployment. For purposes of this report, advanced nuclear technologies include Gen III+ and Gen IV reactors across three categories: large reactors, small modular reactors, 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. 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 analysis 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 is a working document and will be refreshed on a periodic basis to incorporate the latest developments in advanced nuclear technologies and business models.

Chapter 2: Nuclear technologies and value proposition

Advanced nuclear includes multiple technology types across two generations: Gen III+ and Gen IV and includes three size categories: large, small, and micro.

Nuclear has a differentiated value proposition for a decarbonized grid. Many decision makers do not have comprehensive tools or frameworks for quantifying the benefits of nuclear leading to an undervaluation of benefits and overvaluation of costs. Nuclear energy generates clean carbon-free electricity; provides firm power that complements renewables in a decarbonized grid; provides this electricity with low land-use; has lower transmission requirements than distributed or site-constrained generation and can often leverage existing infrastructure from retiring fossil generation assets; has significant regional economic benefits; and has a wide variety of use cases beyond electrical generation. Nuclear provides this while maintaining an outstanding safety record.

Section 2.a: Nuclear's role in the energy transition

Nuclear has an essential role in the energy transition as a clean firm complement to renewables. Nuclear provides clean firm capacity; modeling shows including nuclear and other clean firm resources with variable renewables reduces the cost of decarbonization.[1] Nuclear can help address the power needs coming from load growth, where much of the demand is disproportionately for 24/7 electricity, e.g., data centers.

Nuclear does not "displace" or "compete with" renewables; decarbonization requires both nuclear and renewables. Nuclear provides clean firm generation that enables the increased deployment of variable renewables like wind and solar. When nuclear capacity has been retired, it has not been fully replaced with wind and solar; it has largely been replaced with natural gas, e.g., Indian Point in New York.[2] A more apples-to-apples comparison of nuclear is with other clean firm sources, e.g., geothermal, hydropower, solar or wind paired with long duration energy storage (to firm generation), or fossil generation paired with carbon capture (to clean emissions).

Tripling existing nuclear capacity domestically, in line with the declaration the US signed with more than 20 other nations at COP28, will enable a path to decarbonization.

Section 2.a.i: Power sector load growth

Since the original publication of this report in 2023, US power demand projections have continued to increase. After decades of stasis, US utilities must adapt to a surge in electricity demand driven by data centers (particularly to support high performance computing and artificial intelligence applications), manufacturing and industrial growth, and electrification, particularly transportation along with building and industrial electrification.[i] Load growth is both widespread and concentrated at or near new load centers with a particular need for carbon-free baseload generation at industrial to utility scale with a limited footprint. Many electricity customers (e.g., tech companies, industrial manufacturers) have made commitments to procuring clean electricity and highly value reliability. See section 2.a.ii for additional information on nuclear's value proposition for these use cases.

As reflected in 2023 Federal Energy Regulatory Commission filings, grid planners nearly doubled the five year load growth forecast, with the nationwide forecast of electricity demand increasing from 2.6% to 4.7% growth.[3] In December 2023, the North American Electric Reliability Corporation more than doubled its 9-year electricity demand forecast from the prior year, from ~220 to ~560 GWh of growth.[4,5]

While the scale and timing of demand growth will vary regionally, near-term growth is happening faster than expected. Given the pace of change in data center development and end-use electrification, load growth projections will continue to evolve and are difficult to estimate.

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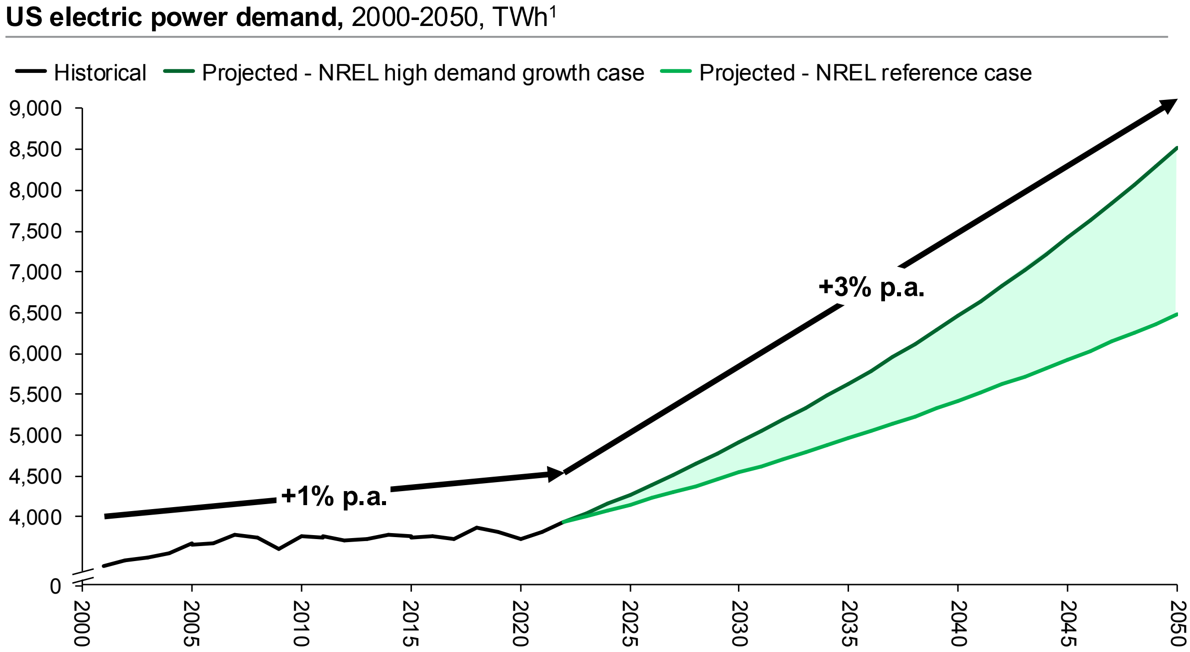
[i] Learn more about DOE research and resources available to support responding to electricity demand growth at energy.gov/electricitydemand.

Figure 5: Electricity demand could more than double by 2050[6,7]



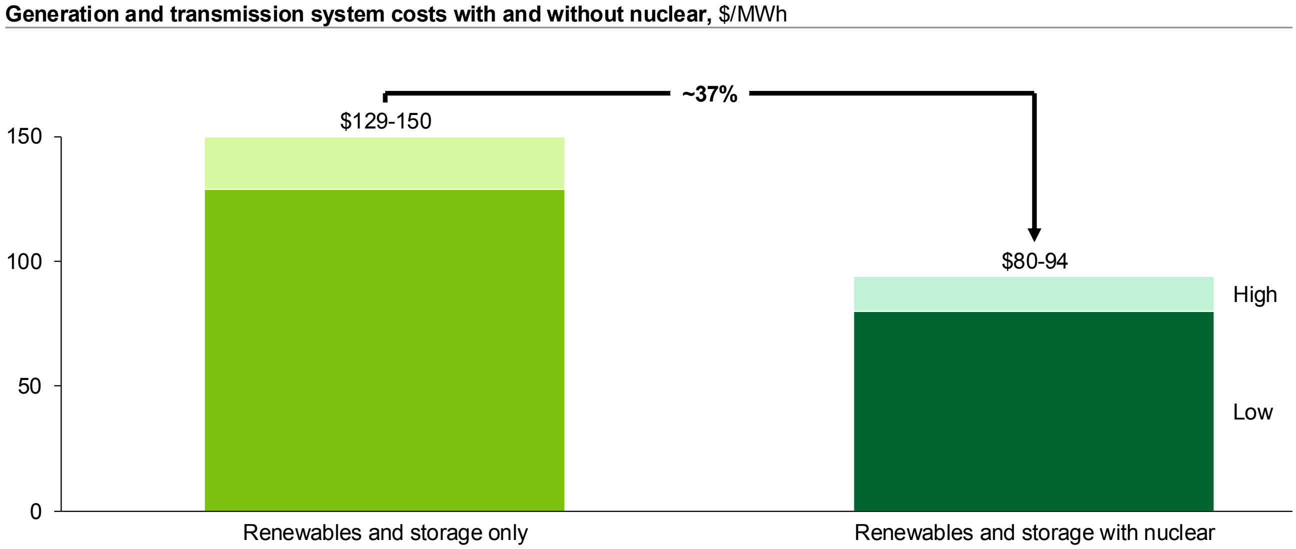
1. Historical demand shown in chart represents retail sales of electricity across all sectors

Section 2.a.ii: Clean firm capacity

Achieving net-zero in the US by 2050 would require at least ~700–900 GW of additional clean firm capacity.[8] System-level decarbonization modeling, regardless of renewables deployment, suggests that the US needs significantly more clean firm capacity to reach net-zero. Throughout this report, “clean firm” is defined as power or power-producing capacity intended to be available at all times during the period covered by a guaranteed commitment to deliver, even under adverse conditions, while maintaining low net and lifecycle GHG emissions.[9,10] Clean firm power sources include nuclear, hydropower, geothermal, fossil generation with carbon capture, and variable renewables paired with long duration energy storage.

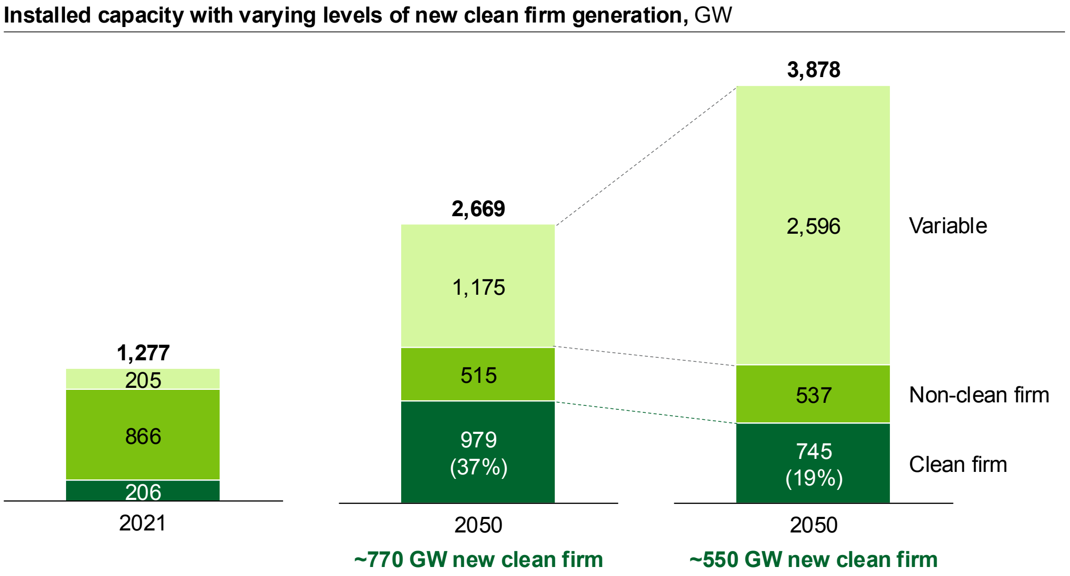
Including nuclear and other clean firm resources reduces the cost of decarbonization.[11] A cost-optimal portfolio includes a diverse mix of clean firm generation, variable renewables, and flexible balancing resources, including energy storage of varying durations. Batteries and demand response (virtual power plants) are essential technologies, but do not obviate the value of clean firm resources.

Figure 6: Modeled decarbonization scenarios for California show including nuclear with variable renewables and storage reduces system costs[12]



Clean firm generation reduces the need for building additional variable generation capacity, energy storage, and transmission. Despite the low capital and operating costs of variable renewables, system decarbonization with only variable renewables and storage results in higher system costs because of the volume of generation capacity required for adequacy and reliability (and subsequent decrease in marginal value and utilization rates).[13] Additionally, firm technologies can produce electricity during the most expensive hours when wind and solar are unavailable. Even when priced at a premium per unit of energy, the inclusion of clean firm resources reduces overall system costs.

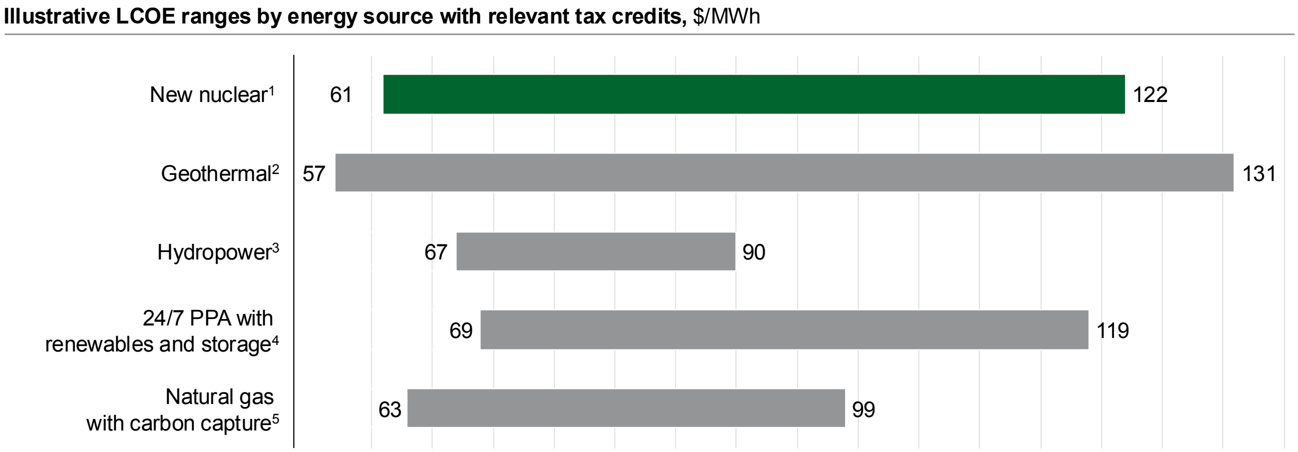
Figure 7: System-level modeling shows increasing clean firm capacity reduces the need for additional variable generation[14]



Customers with clean energy targets and high reliability requirements have started to increasingly value clean firm resources, e.g., Google's projections[15] for meeting decarbonization targets for their global data centers found that including clean firm technologies (including advanced nuclear) would reduce costs by ~40% versus only wind and solar with lithium-ion storage. These cost savings are largely from reducing over-procurement of variable renewables and storage.

Nuclear complements variable renewable generation and is cost competitive with other sources of clean firm power, e.g., geothermal, hydropower, solar or wind with long duration energy storage, and fossil generation with carbon capture, as each of these technologies is demonstrated at scale and moves down the cost curve. There are only a few options for clean firm power, and nuclear power is one of the only options proven at scale. Nuclear power has been commercially operating since the 1950s, while carbon capture and long duration energy storage are still being commercialized.

Figure 8: Illustrative LCOE ranges of clean firm sources incorporating relevant tax credits[16]



Note these LCOE ranges are generally "early of a kind," meaning between FOAK and NOAK; 1. New nuclear LCOE estimated from 6 year construction and overnight capital cost of $7,000/kW to $20,000/kW including 30% 48E ITC (without either 10% adder) with 80% debt at 5% interest rates; 2. Geothermal LCOE calculated using NREL ATB 2024 inputs and model with 30% ITC (without adders) and 5% interest rates. Values reported for Deep EGS / Binary geothermal, using 2024 ATB Moderate case (high end) and 2035 ATB Advanced case (low end). LCOE for conventional (Hydrothermal / Binary) fall within this range at $78 (2024 ATB Moderate) to $57 (2035 ATB Advanced); 3. New Hydropower LCOE reported for Nonpowered Dams (NPD) only, excluding upgrades to existing fleet and new stream-reach development (NSD). LCOE modeled using NREL ATB 2024 inputs and model with 30% ITC (without adders) and 5% interest rates. Values reported as average of "medium cost" models for 2024 ATB Moderate case (high end) and 2035 Advanced case (low end); 4. 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; this is not renewables and storage alone, but relies on a grid with fossil or other generation when renewables and storage are not available; 5. Natural gas with carbon capture and storage numbers from the McKinsey Power Model used for the Carbon Management Liftoff Report and include the 45Q tax credit

Section 2.a.iii: Tripling nuclear capacity

Modeling results indicate need for 200+ GW of new nuclear, tripling existing capacity. Multiple system-level decarbonization modeling exercises have concluded that, especially with estimates for renewables buildout that account for limitations from transmission expansion and land use, significant new nuclear power is required by 2050.

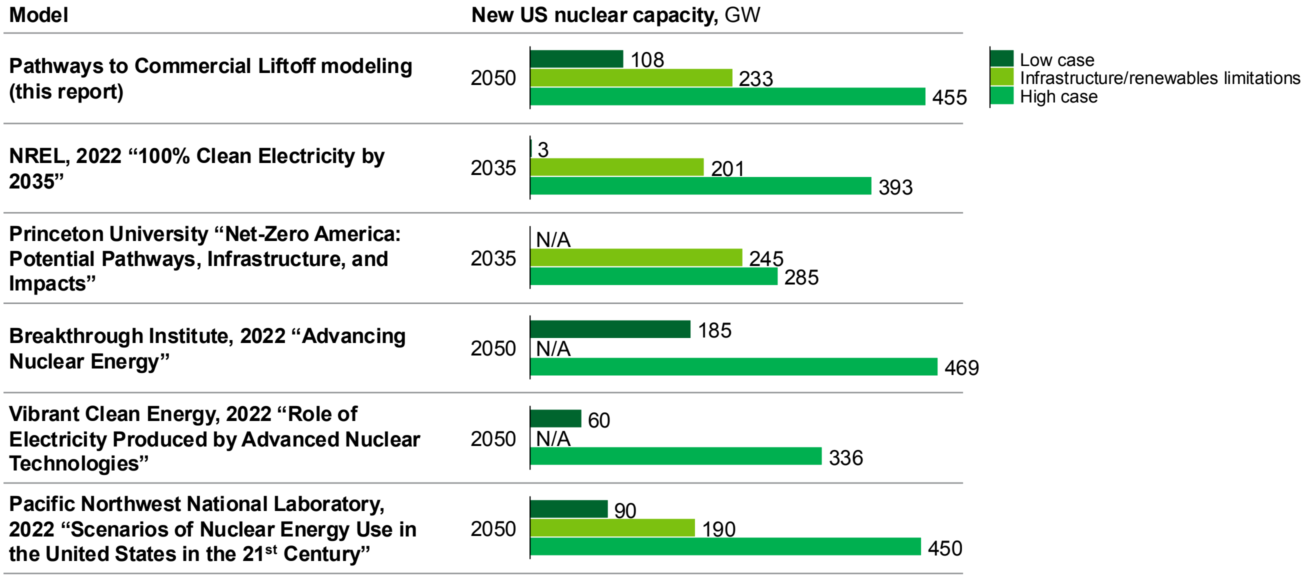
Throughout this report, 200 GW of new nuclear is used as a benchmark for substantiating what it would take to deploy at scale, a mid-point from modeling exercises that appears ambitious yet achievable. This level of deployment is consistent with The Long-Term Strategy of the United States: Pathways to Net-Zero Greenhouse Gas Emissions by 2050, which includes scenarios with substantial increases in US nuclear capacity and electricity generation.[17]

The US joined more than 20 countries in launching the Declaration to Triple Nuclear Energy[18] at COP28, the 2023 United Nations Climate Change Conference. Recognizing that analyses from the OECD

Nuclear Energy Agency and World Nuclear Association show that global installed nuclear energy capacity must triple by 2050 to reach global net-zero emissions by the same year, the participants in this pledge:

- Commit to work together to advance a global aspirational goal of tripling nuclear energy capacity from 2020 by 2050
- Commit to supporting the development and construction of nuclear reactors
- Recognize the importance of extending the lifetimes of nuclear power plants
- Recognize the importance of promoting resilient supply chains
- Commit to mobilize investments in nuclear power, including through innovative financing mechanisms
- Invite shareholders of the World Bank, international financial institutions, and regional development banks to encourage the inclusion of nuclear energy in their organizations' energy lending policies as needed

Figure 9: A variety of net-zero modeling efforts indicate the need for 200+ GW of new nuclear capacity in the US by 2050

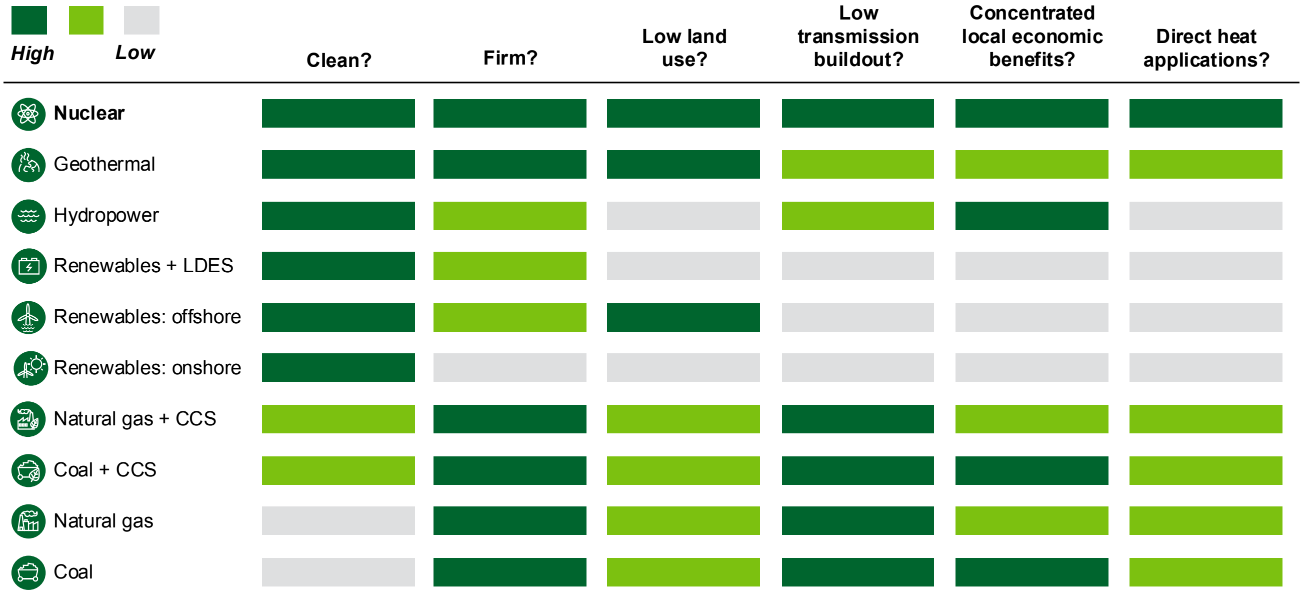


1."Low" and "high" refer to the level of nuclear build out; methodology for "low" and "high" nuclear build-out cases differ report to report

Section 2.a.iv: Nuclear's value proposition

Six features contribute to nuclear power's differentiated value proposition for a decarbonized grid. Nuclear energy generates clean carbon-free electricity; provides firm power that complements renewables in a decarbonized grid; provides this electricity with low land-use; has lower transmission requirements than distributed or site-constrained generation and can often leverage existing infrastructure from retiring fossil generation assets; has significant regional economic benefits; and has a wide variety of use cases beyond electrical generation. Nuclear provides this while maintaining an outstanding safety record.

Figure 10: Select elements of nuclear's differentiated value proposition[19,20,21,22,23,24,25,26,27,28]



■ ▨ □

High *Low*

	Clean?	Firm?	Low land use?	Low transmission buildout?	Concentrated local economic benefits?	Direct heat applications?
Nuclear	■	■	■	■	■	■
Geothermal	■	■	■	▨	▨	▨
Hydropower	■	▨	□	▨	■	□
Renewables + LDES	■	▨	□	□	□	□
Renewables: offshore	■	▨	■	□	□	□
Renewables: onshore	■	□	□	□	□	□
Natural gas + CCS	▨	■	▨	■	▨	▨
Coal + CCS	▨	■	▨	■	■	▨
Natural gas	□	■	▨	■	▨	▨
Coal	□	■	▨	■	■	▨

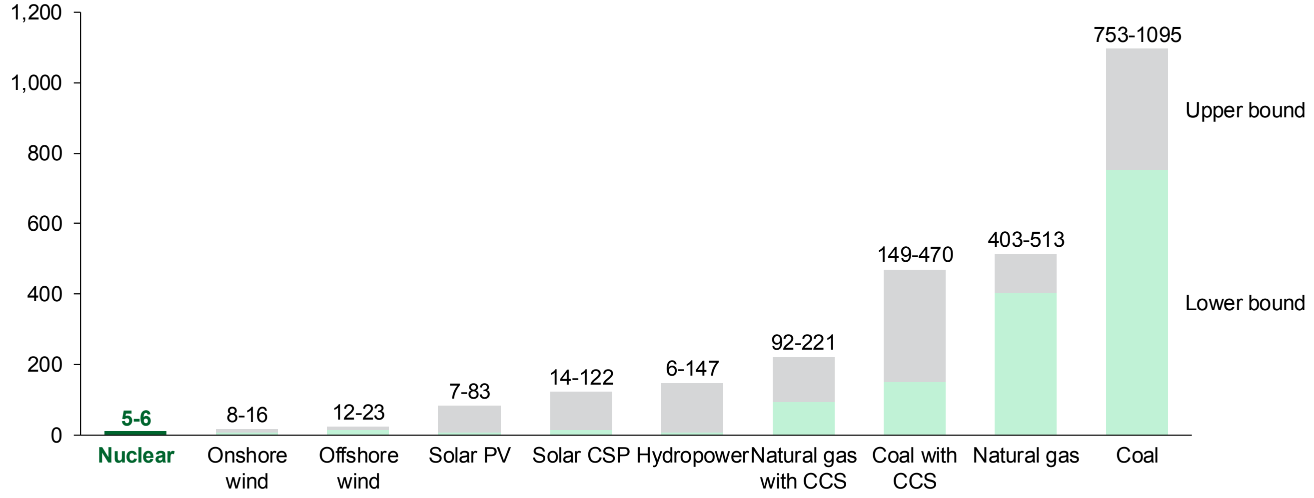
1. Clean: as measured by net or lifecycle greenhouse gas emissions, g CO2 eq. (NREL) 2. Firm: power or power-producing capacity, intended to be available at all times during the period covered by a guaranteed commitment to deliver, even under adverse conditions (EIA glossary) 3. Low land use: as measured by land use intensity of electricity and acres/MW 4. Grade reflects the impact in modeling studies which show 50% reduction in new transmission buildout in scenarios with higher share of firm power vs intermittent renewable sources, when normalized for energy demand (Princeton NZA study) 5. Economic benefits concentrated in the local community as measured by jobs, wages, tax basis, and economic multipliers 6. Ability for a generating asset to decarbonize beyond electricity generation, e.g., high temperatures and high reliability for industrial heat

1. Nuclear energy generates clean, carbon-free electricity.

Nuclear power has one of the lowest lifecycle emissions of any major generating energy source,[29] providing electricity to the grid with the lowest CO_2 emissions per MWh of any currently available technology.

Figure 11: Nuclear generates clean electricity with very low lifecycle emissions[30]

Lifecycle greenhouse gas emission ranges for different energy sources, g CO_2 eq. per kWh



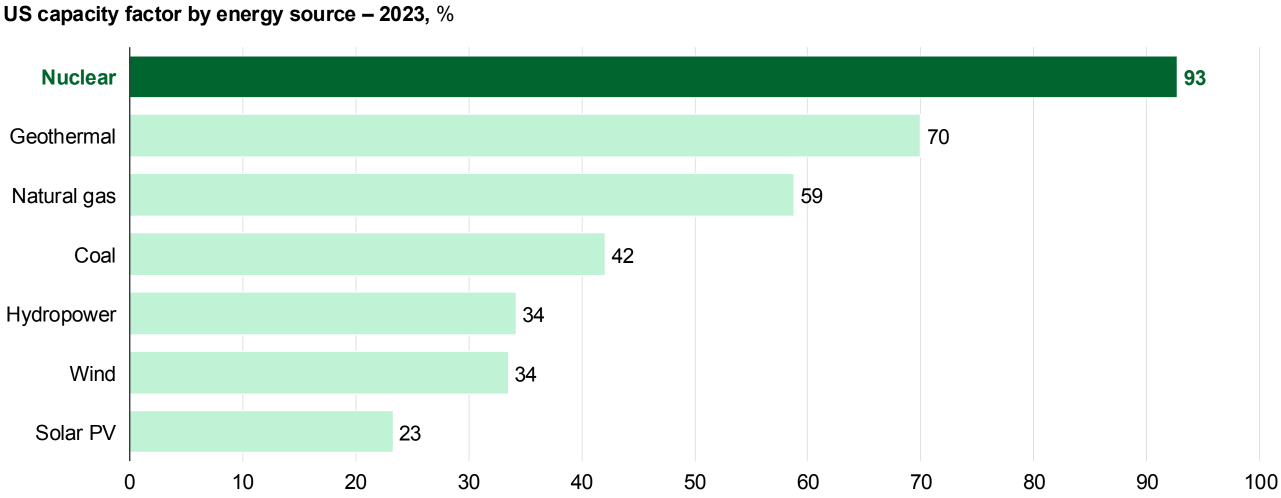
This carbon-free characteristic means that utilities can replace more carbon-intensive generation (e.g., coal) with nuclear to achieve federal, state-, local-, or company-level emissions targets. This is especially important for players that are used to operating a system with a large amount of baseload power: 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 that currently host high-emitting energy sources.[31]

Nuclear has lower materials intensity than other electricity sources. Nuclear requires just 0.6 to 1.4 tons of infrastructure raw materials per GWh of electricity produced, lower than for solar, onshore wind, and offshore wind.[32] Since nuclear provides clean firm power, incorporating battery storage further increases material demands for solar and wind relative to nuclear. Nuclear consumes 11-38% the mass of critical materials per GWh than solar, wind, and battery technologies. Per GWh generated, nuclear has the lowest mining intensity out of clean electricity generation sources and has almost no other materials requirements other than uranium for fuel.[33]

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 grid will be very difficult and expensive without 20-40% clean firm power.[34,35] Firm power refers to power or power-producing capacity intended to be available at all times during the period covered by a guaranteed commitment to deliver, even under adverse conditions. With an increasing portion of the grid supported by renewables, the value of dispatchability provided by firm power increases. A variety of technologies including nuclear can help maintain grid stability via synchronous inertia, reactive power, and other benefits. See 2.a.ii for more on clean firm capacity.

Figure 12: Nuclear has the highest capacity factor of any energy source[ii,36]

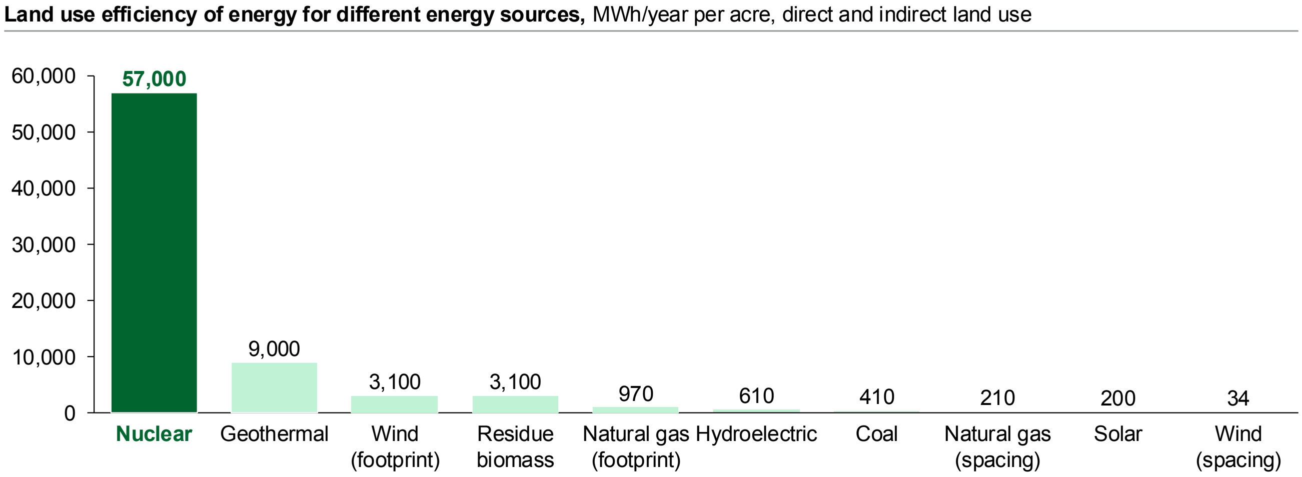


Nuclear provides a firm power source and system benefits that can help ensure reliability and stability across the grid.[37] Nuclear power can help prevent blackouts in a future grid, which will be increasingly reliant on variable power sources. Firm power helps utilities provide a reasonable reserve margin through all hours and all seasons 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 US; increasing grid reliability and resilience for underserved, overburdened communities can support improved health outcomes, public safety, economic security, and overall quality of life.

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.[iii]

Figure 13: Nuclear produces the most electricity per acre of any energy source[38]



[ii] 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.

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

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 US (i.e., roughly the size of New Mexico and Arizona combined).[39]

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.

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

Nuclear power can have lower transmission requirements than many other generation sources because it faces fewer technical limits for siting closer to demand[iv] and 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. While significant investment in expanding or upgrading transmission infrastructure (e.g., upgrading substations, increasing voltage of existing transmission lines) is often still needed to support additional large generation resources (e.g., nuclear, offshore wind), the locational flexibility of nuclear can help reduce the total miles of new transmission lines. For example, regions with low sustained wind would require transmission to bring in power from outside of the region. Siting nuclear power does not generally depend on technical geographic constraints to the same degree as other types of clean firm technologies[v] (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. Reducing the total number of new transmission miles needed can help significantly reduce total investment costs, project development timelines, and community and environmental impacts.

Nuclear's high power density means that transmission lines connected to nuclear power plants can carry more total energy per mile. This can help maximize the asset utilization of transmission infrastructure investments built for nuclear power relative to transmission built for lower capacity factor sources of power that are built to carry short-duration peak events. 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[40] (a conclusion supported by system-level modeling).[41] This may support greater parity in access to clean firm power for underserved, overburdened communities.

The ability to leverage the same transmission, water, and land-based infrastructure as retiring fossil generation could yield substantial savings versus greenfield construction.[42] Additionally, the opportunity to enhance the capacity of existing transmission infrastructure and rights-of-way to maximize utilization of existing grid infrastructure can also help support nuclear deployments while mitigating new grid infrastructure requirements.[vi]

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, as measured in GDP increase per dollar invested.[43] 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.[44] Nuclear electric power generation's workforce is more gender diverse than the overall energy workforce, with a larger share of female workers (36% compared to 26%).[45]

[iv] 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.

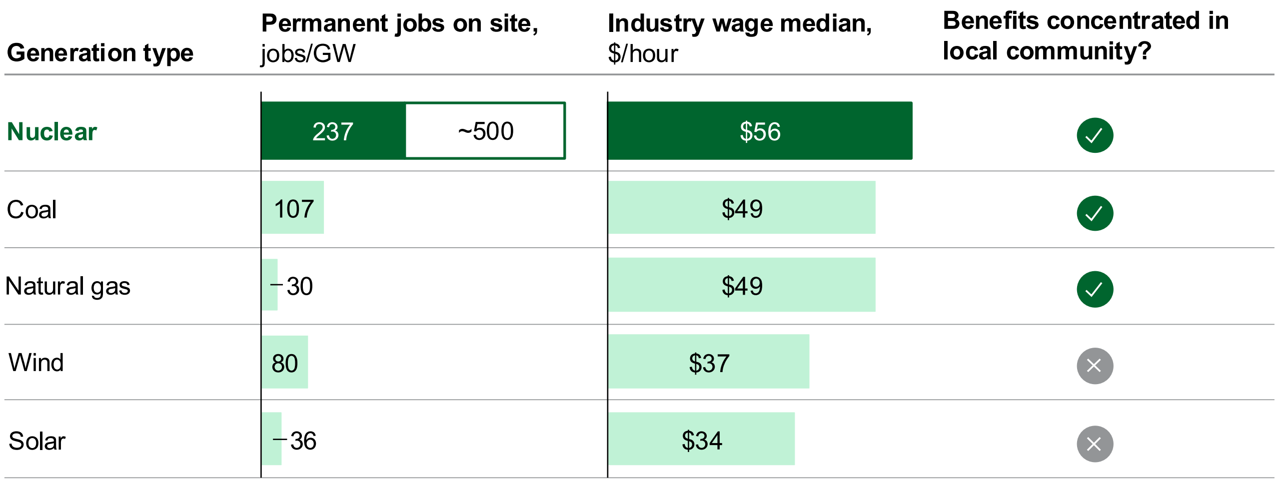
[v] However, factors like seismology, geology, hydrology, and population density factor in heavily to nuclear siting decisions. *See*, e.g., 10 CFR § 100.10, Factors to be considered when evaluating sites.

[vi] Opportunities to enhance the capacity of existing transmission infrastructure (e.g., reconductoring with advanced conductors, deploying grid-enhancing technologies) is further discussed in the *Innovative Grid Deployment* Liftoff report.

States and regions have been studying the impact of nuclear on their communities:

- In the Southeast US (Georgia, North Carolina, South Carolina, Tennessee, and Virginia), the nuclear industry creates over 150,000 direct, indirect, and induced jobs, which have average wage of ~$90,000, 65% higher than the regional average wage; for every 10 direct nuclear jobs, 18 additional jobs are created (double the regional average of 9 additional jobs)[46]
- Nuclear's economic development benefits extend beyond direct and indirect jobs: the magnitude and density of clean firm power attracts investments and industries that create jobs, e.g., electric vehicle and battery manufacturers accessing Georgia's grid bolstered by Vogtle[47]
- In Colorado, the closure of a coal plant will remove high-paying jobs and tax revenues, and of all technologies studied, nuclear provided the most jobs (the only technology with >50 jobs), the highest salary range (~$60,000-200,000), and highest yearly tax payments (~$95M) to support the community[48]

Figure 14: Nuclear provides high paying jobs and the most jobs on site per GW[49,50]



Note 237 jobs is an estimate for SMRs; ~500 represents the current operating fleet of large reactors; coal and natural gas are both the value of "Fossil Fuel Electric Power Generation;" when they were measured separately in the 2020 USEER Wage Report, they were within ~5% of each other; hydropower onsite jobs per GW not available, but industry median wage was $51/hour

Nuclear is also one of few power generation sources that can preserve the volume of high-paying jobs from retiring coal plants. An effective energy transition is one that preserves the viability and livelihood of the communities impacted by the shift to clean energy sources. A study analyzed almost 400 coal power plant sites and found that ~80% of those sites have the characteristics needed to host a nuclear reactor. This allows utilities to invest in new generation while repurposing the existing footprint and preserving and expanding high-paying jobs in local communities.[51] Coal-to-nuclear transitions present critical opportunities to ensure an equitable transition to a decarbonized grid while increasing domestic manufacturing capabilities.

Nuclear power is also highly compatible with unionized labor; jobs in the nuclear sector tend to require more training and include both roles requiring college degrees and roles needing a wide variety of trade labor skills.[52] At 19%, nuclear was the most unionized (represented by a labor union or covered under a collective bargaining agreement or a project labor agreement) energy technology, higher than the overall energy average of 11% (and the national private sector average of 7%).[53] Additionally, the manufacturing, construction, operation, and maintenance of power plants are a key enabler of both scaling up and reshoring the domestic industrial base.

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

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

Figure 15: Nuclear has a wide variety of use cases beyond wholesale electricity production[54,55,56,57,58,59,60,61,62,63]

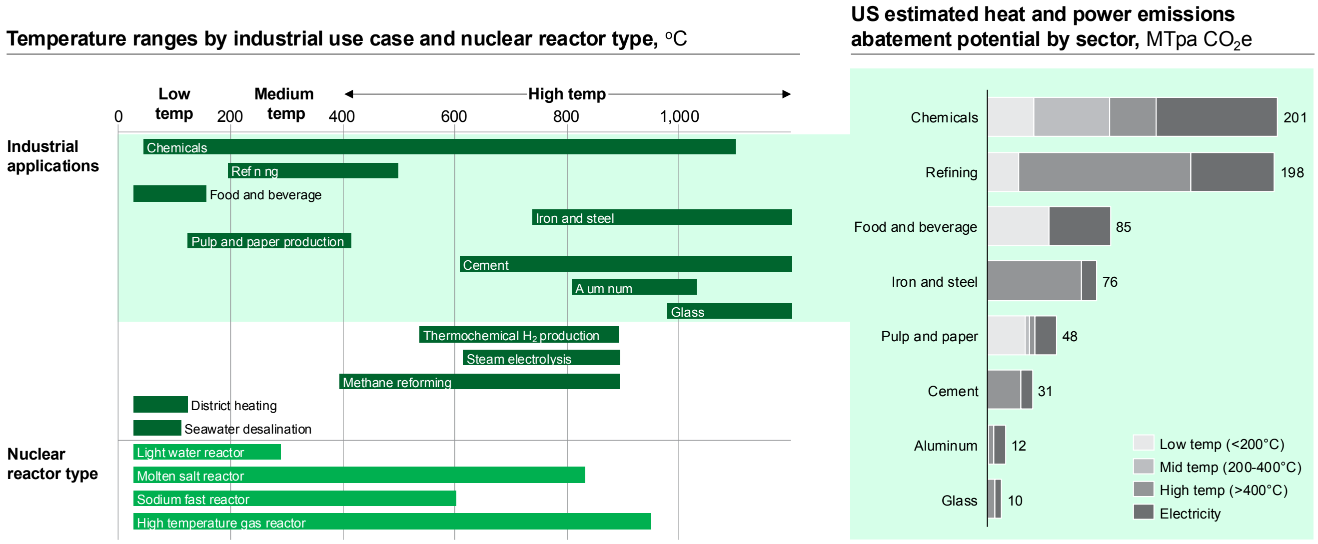
Use case	**US total power demand by 2050,** GW	**Current willingness to pay**	**Nuclear value proposition**
Wholesale electricity	~2200	Lower	**Provide clean firm power** to complement variable generation and provide grid stability
Hydrogen production	~280-330	Lower	**Provide clean firm power** for electrolytic hydrogen with optional nuclear waste heat to improve efficiency
Data centers	~80-140	Moderate	**Provide clean firm power** to support 24/7 demand and help firms achieve decarbonization targets
Industrial process heat and steam	~75-100	Moderate	**Power density, reliability, and high temperatures** essential for industrial decarbonization
Water desalination	~50-80	Lower	**Replace fossil fuel-based** technologies with high availability and low marginal cost
Craft propulsion	~20-25	Moderate	**Replace fossil fuels** in shipping industry to support decarbonization targets
District heating	~9	Moderate	**Replace fossil fuel combined heat and power** and boilers for regional heating applications
Off-grid power	~8	Higher	**Replace expensive diesel generation** in remote areas, military bases, and disaster relief operations

While direct electricity production is likely to remain the primary use case for new nuclear reactors, many additional use cases require 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 and increased aggregate system efficiency.

Tech companies, e.g., Amazon, Apple, Google, Meta, and Microsoft, require firm power with high uptime to support artificial intelligence and data center operations. Several of these companies have made commitments to achieve 100% clean energy for their global operations, necessitating clean, firm power with nuclear well-positioned to support those commitments.

Nuclear's power density, reliability, and ability to produce high temperatures are valuable for industrial decarbonization. Industrial activities accounted for 1,873 MMT CO2e in 2022, 30% of US greenhouse gas emissions; 78% of those are direct emissions (e.g., heat and steam production, process emissions from chemical reactions) and the remaining 22% is from electricity consumption.[64] Some industrial processes require 24/7 electricity, necessitating behind-the-fence generation for reliable power. Many of the most energy-intensive industries also rely on uninterrupted, high-pressure steam, for which nuclear is among the few alternatives to fossil fuels.

Figure 16: Nuclear provides high temperature heat that can decarbonize industrial applications[65,66,67]



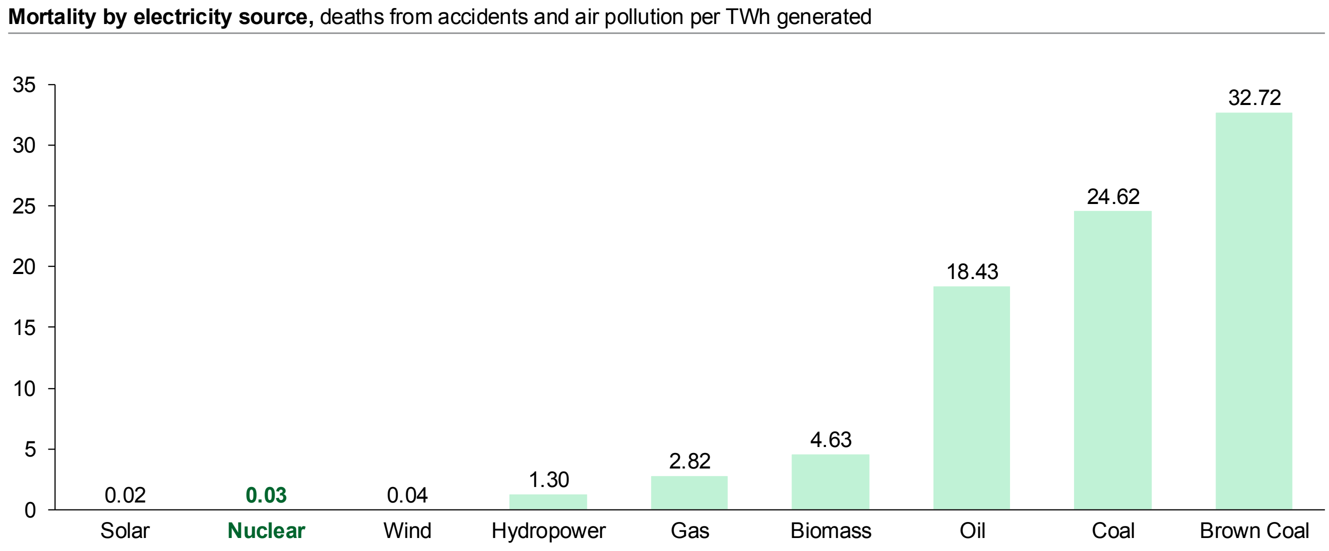
Decarbonizing industrial heat has challenging requirements, given many industrial heat users require high-temperature heat with ~99% uptime, which cannot be easily met with variable renewable energy sources. Efficiently transporting heat is difficult, requiring assets to be co-located close to facilities with a small footprint, given space constraints in industrial facilities. Nuclear can also use waste heat to increase overall efficiency and deliver consistent and cost-competitive decarbonized heat to industrial consumers.

Advanced nuclear reactors are well positioned to replace today's combined heat and power systems.[vii] With minimal additional space, they can produce on-site, grid-independent, highly consistent electricity and thermal energy with temperature ranges 200-850°C. Some advanced nuclear technologies could decarbonize heavy industries such as chemical plants and refineries by directly replacing fossil fuels for process heat.[68]

[vii] In 2023, Dow began working with X-energy to develop high temperature gas reactors to provide electricity, steam, and heat at an industrial site in Texas.

US commercial nuclear has a powerful safety record. By incidence of occupational injuries, working in nuclear is ~5x safer than working in electric power generation broadly and ~10x safer than the average for all industries.[69] Globally, nuclear power has one of the lowest mortality rates per TWh of electricity, in line with solar and wind.[70]

Figure 17: Nuclear is one of the safest sources of energy, in line with solar and wind[71]



Three Mile Island Unit 2 had the most serious incident in US commercial nuclear operating history, and yet its small radioactive releases had no detectable health effects on plant workers or the public.[72] Lessons learned have been incorporated into nuclear safety culture and the NRC has developed clear guidelines to ensure and enforce safety culture in the nuclear power industry.

Additionally, the US Naval Nuclear Propulsion Program maintains an outstanding record of over 171 million miles safely steamed on nuclear power. The program currently operates 96 reactors and has accumulated 7,500 reactor-years of safe operation.[73] The occupational exposure received by the average nuclear-trained sailor living onboard one of the Navy's nuclear-powered ships in 2022 was less than 1/30 of the radiation received by the average US citizen from natural background sources that year.[74]

Section 2.b: Nuclear technologies

Advanced nuclear includes multiple technology types across two generations: Gen III+ and Gen IV. Gen III+ reactors use water as a coolant and LEU as fuel (similar to the reactors currently operating in the US) and have passive safety features that are enabled by enhanced systems that can automatically shut down the reactor without operator action. Because of these shared characteristics with the operating nuclear fleet, commercial deployment of Gen III+ reactors is likely to be nearer-term than other, more innovative reactor types. Gen IV reactors offer additional use cases and safety features. They will use novel coolants and many will use HALEU as fuel, which is not in use by the US nuclear fleet today .

Advanced nuclear includes three size categories: large, small, and micro. In this report, large nuclear plants are defined as having ~1,000 MW capacity, SMRs as having ~50-350 MW capacity, and microreactors as having less than ~50 MW. For reference, 1 MW can power about 800-1,000 homes.

Figure 18: Advanced nuclear includes Gen III+ and Gen IV reactors of all sizes; note this is not exhaustive[75,76,77,78]

	Gen III+	Gen IV		
Coolant	Light water	Gas	Liquid metal	Molten salt
Examples	• Pressurized water reactor • Boiling water reactor	• High temperature gas reactor • Gas fast reactor	• Sodium fast reactor • Lead fast reactor	• Fluoride high temperature reactor • Molten chloride fast reactor
Typical fuel	LEU, LEU+	HALEU	HALEU	HALEU
Outlet temperature	~300°C	~750°C	~550°C	~750°C
Power output	Large, small	Small, micro	Small, micro	Small
Example reactor designers	• GE Hitachi • Holtec • NuScale • Westinghouse	• BWXT • General Atomics • Radiant • X-energy	• ARC • TerraPower • Oklo	• Kairos • Terrestrial

Tripling nuclear capacity by 2050 likely will require both Gen III+ and Gen IV designs. Decades of experience operating large LWRs and the completion of large Gen III+ reactors at Vogtle position large LWRs to help meet the challenge of nearer term bulk electricity generation. Gen IV reactors offer higher temperatures for industrial uses and the designs have been built as far back as the 1950s, but limited operational experience will require heavy investment in commercialization, in the way LWRs have received investment and experience from the Navy and commercial sector for the last 70 years. Reactor down-selection and standardization are critical for cost reduction, though meeting key market needs (e.g., bulk electricity generation including for data centers, industrial processes requiring high temperature heat and/or steam, and remote applications) will likely require different designs.

Section 2.b.i: Existing US nuclear fleet

94 nuclear reactors operating at 54 sites provide ~20% of US electricity generation and almost half of domestic carbon-free electricity. All 94 operating reactors are light water reactors: 63 pressurized water reactors and 31 boiling water reactors. The average reactor capacity is 1031 MW; the smallest reactor is 519 MW and the largest is 1401 MW.[79]

Multi-unit plants benefit from economies of scale: generating costs at multi-unit plants are 30% cheaper per MWh than single unit plants.[80] 19 sites have only one reactor, 31 have two reactors, three have three reactors, and only Vogtle has four reactors.

91% of residents living closest to US nuclear power plants view them favorably (households with people who work at the plant were excluded).[81] For years, plant neighbors have expressed more favorable opinions of nuclear energy than the general US public.

Existing nuclear sites offer significant benefits for siting new nuclear.[viii] Many sites were designed for two or more reactors when only one was built, e.g., the Shearon Harris Nuclear Plant in North Carolina was designed for four reactors, but currently only has one. Based on two preliminary reviews by three of the National Laboratories, among operating, formerly operating, and planned nuclear sites, most likely have room for new SMRs or large reactors.[82,83] Analysis using the Oak Ridge Siting Analysis for Power Generation

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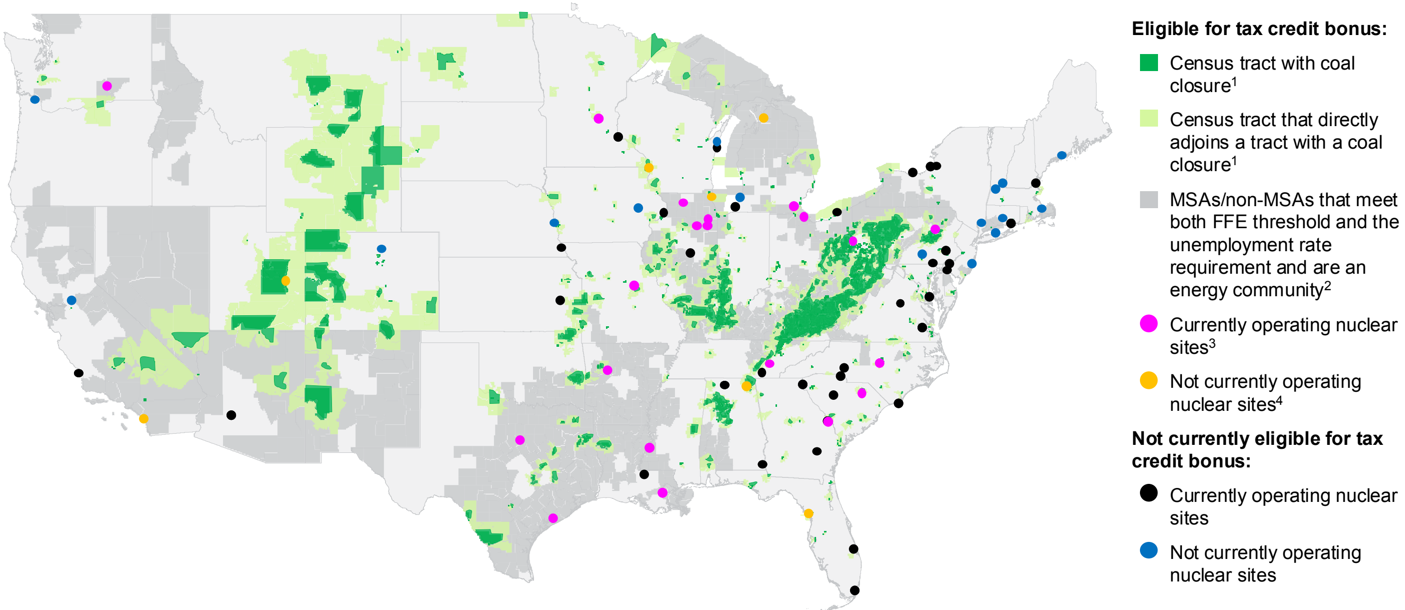
[viii] There are some new nuclear plans at existing sites, e.g., Holtec intends to build SMRs at Palisades (in addition to the reactor restart) and Dominion issued an RFP for new nuclear at North Anna.

Expansion tool found potential for ~60-95 GW of new nuclear at existing nuclear sites. Adding new nuclear at existing nuclear sites creates benefits from economies of scale (e.g., sharing security, training, buildings), leveraging existing site characterization (e.g., water access and seismic profile), and strong community support. Many sites already have been issued early site permits (ESPs)[84] and combined licenses (COLs)[85] from the NRC.

New nuclear built at operating nuclear sites and formerly operating nuclear sites that meet the IRA's eligibility criteria can receive the IRA's energy communities tax credit bonus, which provides an additional 10% investment tax credit (above the base 30% credit). All brownfield coal plants retiring and repowering with new nuclear are also likely to be eligible; coal sites ~120-170 GW of new nuclear at coal sites.[86]

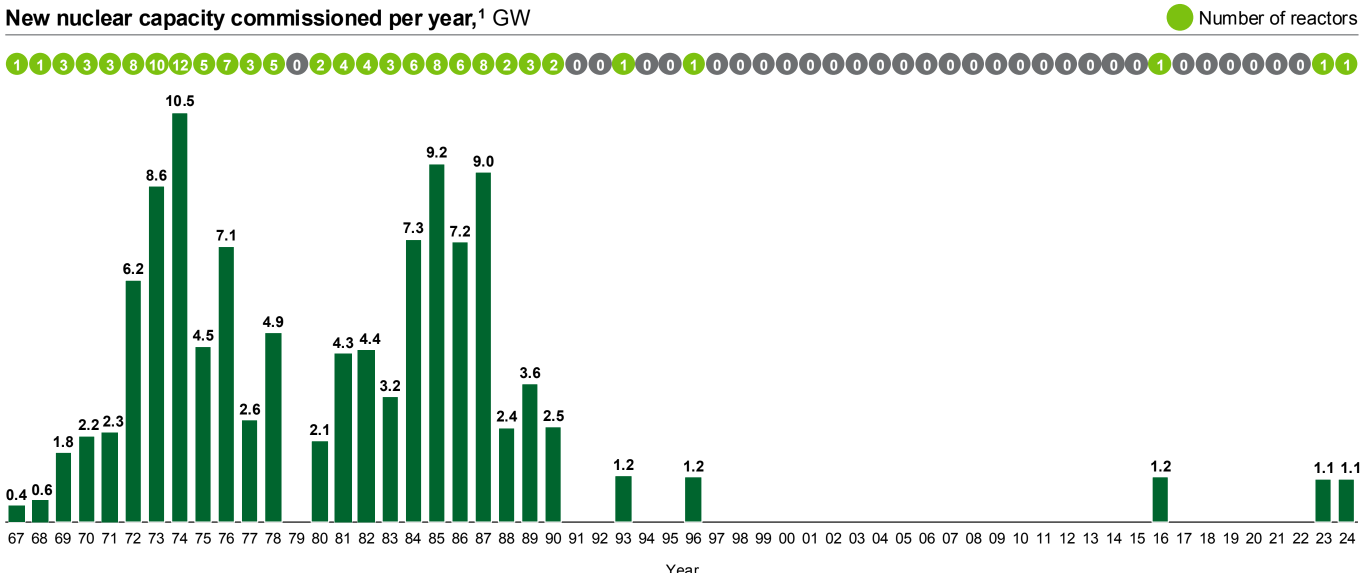
Figure 19: 20 operating nuclear sites and 5 formerly operating sites are in communities eligible for energy community tax credit bonuses[87]



1. Census tract with a coal closure or directly adjoining a census tract with a coal closure 2. MSAs/non-MSAs that meet both the Fossil Fuel Employment threshold and the unemployment rate requirement 3. Arkansas Nuclear One, Beaver Valley, Braidwood, Byron, Callaway, Columbia, Comanche Peak, Davis-Besse, Dresden, Fermi, Grand Gulf, H.B. Robinson, LaSalle, Monticello, Shearon Harris, South Texas, Susquehanna, Vogtle, Waterford, Watts Bar 4. Bellefonte (unfinished), Big Rock Point (retired), Blue Castle (proposed), Crystal River (retired), La Crosse (retired), San Onofre (retired), Zion (retired)

Over 90% of the 2024 US nuclear fleet was constructed in the 1970s and 1980s. From 1973 to 1987, the US averaged more than 6 GW of new nuclear reactors commissioned per year. At peak, in 1974, 12 reactors connected to the grid, adding 10.5 GW of capacity.

Figure 20: Commercial nuclear capacity and number of reactors commissioned by year[88]



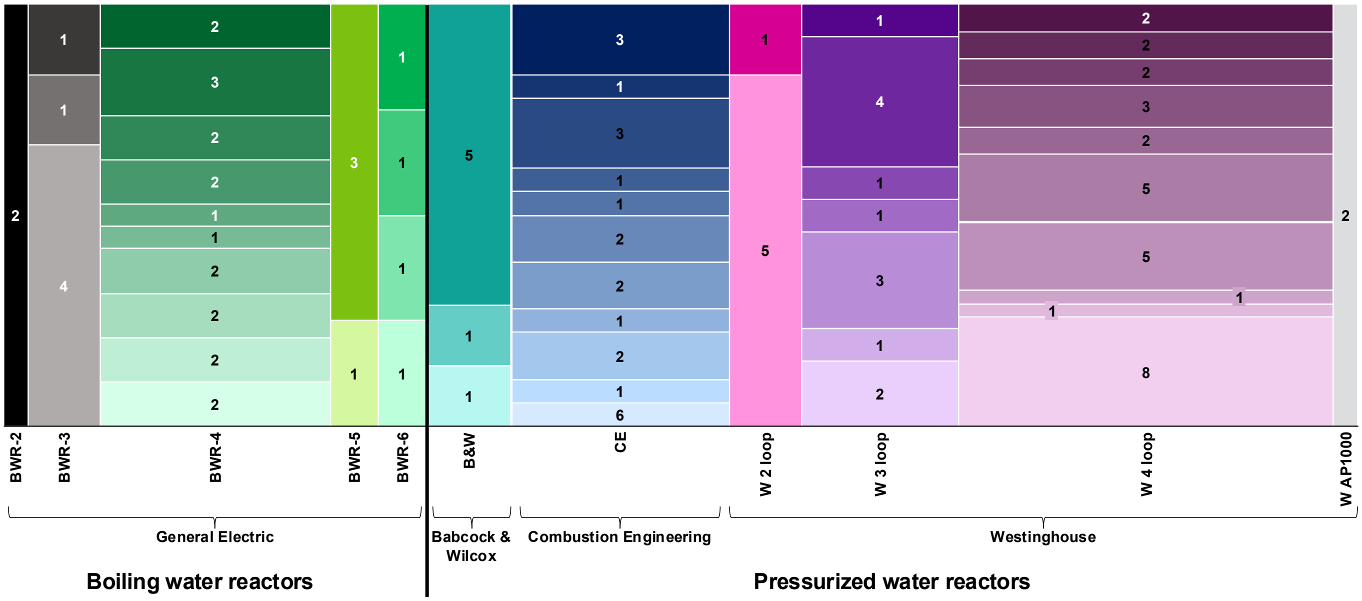
1. Excludes test and prototype reactors Note: Watts Bar 1 & 2 construction originally began in 1973 and halted in 1985; construction resumed on Unit 1 in 1992 and Unit 2 in 2007

The US has constructed over 50 different commercial reactor designs, which may have diluted the potential learning benefits of repeat building. Although the fleet is all LWRs (and “only” boiling water reactors and pressurized water reactors), reactor designers and customers pursued multiple designs in parallel and created bespoke customizations within designs. For example, the BWR-4 series of reactors had designs that ranged from ~600 MW to over 1300 MW. The lack of standardization extends beyond variations in the nuclear steam supply system (NSSS) vendor, model, and power. The balance of plant, crucial safety systems, structural architecture, and civil engineering design, which account for a large portion of construction costs, were handled by multiple architecture and engineering companies. This resulted in substantial variations in overall plant design and cost, even among plants using the same NSSS design and reactor power, reducing the impact of sequential learning. Standardization of reactor designs is key for decreasing lead times and costs; innovation can, perhaps counterintuitively, lead to higher capital costs and longer lead times.[89]

Figure 21: The US has constructed over 50 different commercial reactor designs[90]

US commercial nuclear reactors by design

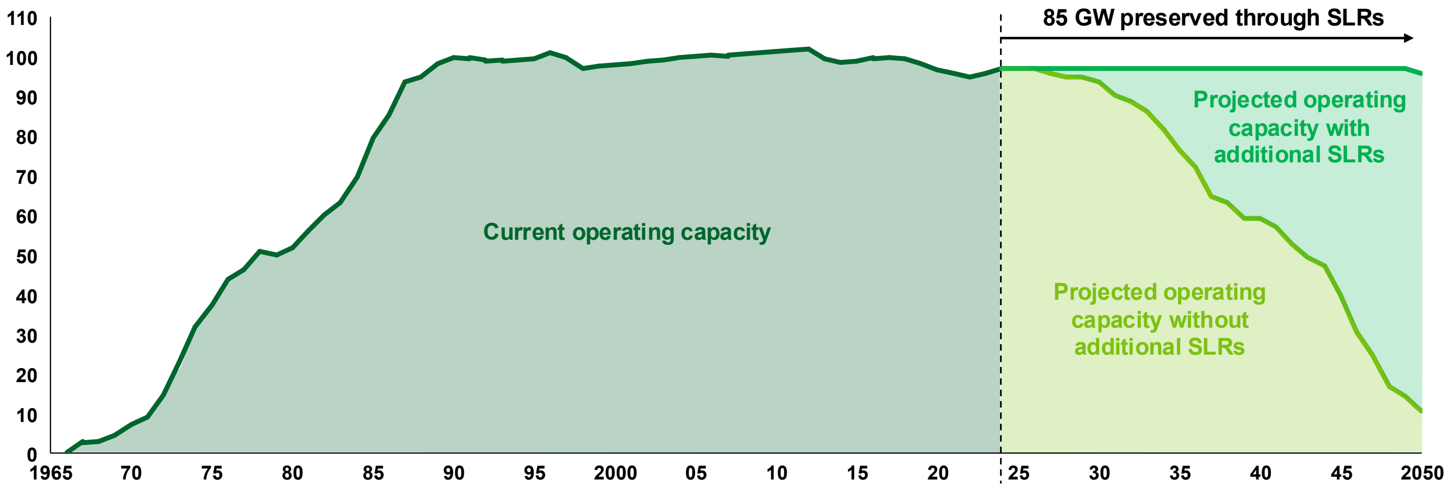
Columns show design families, colors show >50 MW differences, box area sized by number of reactors



Investing in subsequent license renewals is essential for maintaining the existing fleet: of the 94 operating US reactors, 84 have licenses that will expire prior to 2050; 24 have licenses that will expire prior to 2035. US commercial nuclear reactors are issued 40-year operating licenses at commissioning. An initial license renewal (ILR) grants an additional 20 years of operation for 60 total years of operation. A subsequent license renewal (SLR) can extend operations for an additional 20 years beyond the ILR for 80 total years of operation.

Figure 22: Historic and projected US nuclear operating capacity based on the potential for subsequent license renewals[91]

Nuclear historic and projected operating capacity by current license status,[1,2] GW



1. Excludes test and prototype reactors; does not include potential restarts 2. Current licensing status includes all confirmed initial and subsequent license renewals only

Power uprates could add near-term capacity to existing reactors; estimates for uprates in the fleet range from ~2 to ~8 GW. The NRC has approved 172 power uprates associated with 100 reactors between 1977 and 2021 which have added ~8GW of capacity to the US fleet. The three types of uprates include:

- **Extended power uprates** have increased capacity by up to ~20% and require significant modifications to major balance-of-plant equipment.
- **Stretch power uprates** go up to ~7% and usually involve changes to instrumentation setpoints but do not involve major plant modifications.
- **Measurement uncertainty recapture power uprates** have increased capacity by up to ~2% with enhanced techniques for calculating reactor power.

Load growth and the IRA created a step-change improvement in the potential of existing fleet. For existing reactors, the IRA provided a PTC; for new reactors and, in some cases uprates on existing reactors, the IRA provided a PTC and a 30% ITC that can become 50% with adders.[97] The IRA also created new LPO authorities for existing and new reactors. As recently as 2022, utilities were retiring nuclear reactors; in 2024, they are working to extend reactor life to 80 years, planning to uprate capacity, and restarting reactors that have ceased operations (but have not yet been fully decommissioned).[ix] While the outlook for the existing fleet has improved, maintaining and uprating these assets to reach their full potential will require significant planning and investment along with commitment from customers and electricity markets to value clean firm capacity. For more, see 2.c.i.

[ix] As of September 2024, Holtec is working on restarting Palisades; Constellation is planning to restart Three Mile Island Unit 1 (now Crane Clean Energy Center) supported by a Microsoft power purchase agreement.

Section 2.b.ii: Large light water reactors

Large reactors provide powerful economies of scale. The current US nuclear operating fleet consists of large light water reactors (LWRs), with most exceeding 1000 MW. Large multi-unit nuclear plants have the lowest production costs: generating costs at multi-unit plants are 30% cheaper per MWh than single unit plants. This low cost per MWh makes large reactors a good solution for bulk electricity generation.

Designers and operators chose to make nuclear reactors bigger over time to take advantage of economies of scale in operations. Shippingport, the first commercial nuclear reactor, connected to the grid in 1957 and was 60 MW. All 20 operating reactors under 870 MW began construction before 1970. The effects of economies of scale mean that, in many modeling efforts, large reactors have lower costs per MW than smaller reactors because many fixed cost categories are spread across, for example, 1100 MW of capacity instead of 300 MW.

Most new large reactors are Gen III+ reactors, LWRs based on decades of operating experience with advanced passive safety features and more modern instrumentation and controls. Vogtle Units 3 and 4 are AP1000 reactors, a Gen III+ design with power output of 1117 MW and a compact nuclear island with less concrete and steel per MW compared to other LWRs, as well as fewer valves and pumps.[92]

Load growth and the completion of Vogtle have increased the value of large reactors to customers. New load growth makes GW-scale reactors an attractive option for replacing retiring fossil generation while adding incremental capacity. The completion of Units 3 and 4 made Vogtle the largest energy generation site in the US. Many of Vogtle's biggest challenges (e.g., incomplete design, immature supply chain, untrained workforce) were solved for the AP1000 during construction; see 3.b.i for more.

Despite the advantages, large reactors have proven difficult to construct in a manner that reaches NOAK cost given megaproject issues and a proliferation of different designs. Additionally, it takes more capacity to come down the learning curve, e.g., for a given amount of capacity, 7 GW, 300 MW SMRs could reach ~23OAK cost versus ~7OAK for a 1000 MW reactor.

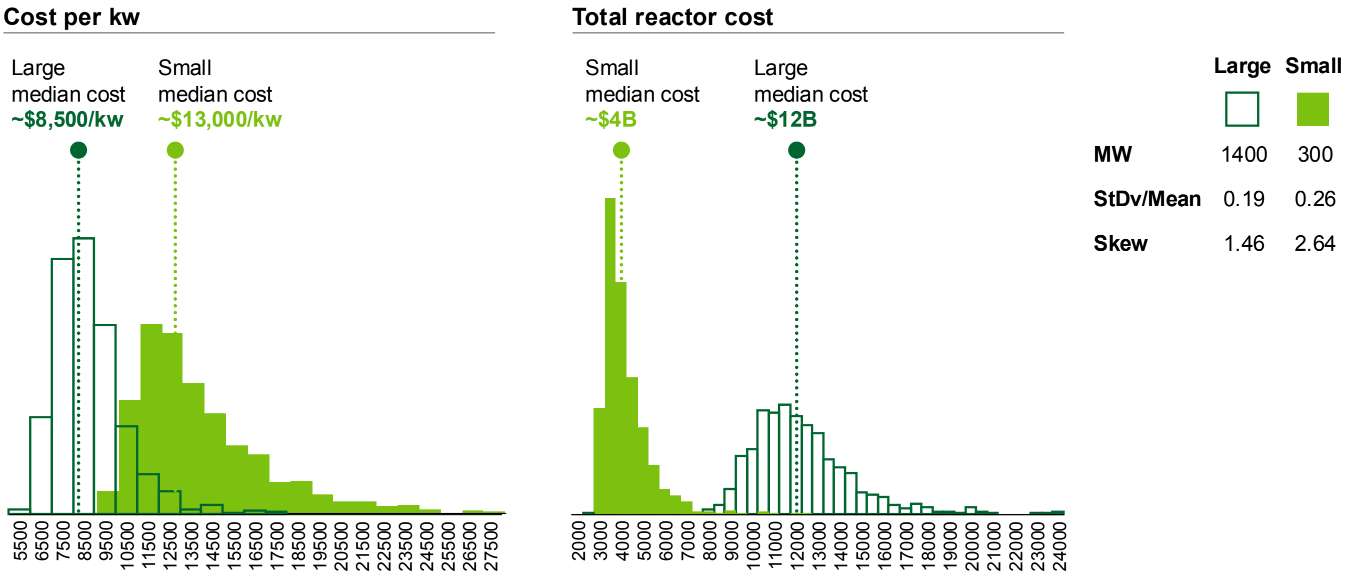
Section 2.b.iii: Small modular reactors

For SMRs, "small" is generally considered under ~350 MW, while "modular" generally refers to standardized factory production. Because civil works construction drives nuclear capital cost, the value proposition for SMRs centers around maximizing design standardization and factory production. To realize this potential, SMRs must move a substantial portion, e.g., more than ~50%, of overall spend into the factory setting; without this, an SMR risks being a civil works construction project without the benefit of economies of scale. SMR construction will require dedicated modular assembly capabilities and the requirements will differ by design. Unique capacity will be required for each design; design down-selection will be critical for standardization and reducing total industry costs.

Even if SMRs may be more expensive than large reactors as measured by $/MW and $/MWh, SMRs may be the right fit for certain applications, e.g., replacing smaller retiring coal plants or industrial processes requiring high temperature heat.

SMRs offer the potential for lowering the absolute dollar risk bands for construction. As an example, a $4B SMR with a 50% cost overrun would result in completed FOAK cost of $6B; a $10B large reactor with the same 50% cost overrun will result in a completed FOAK cost of $15B. Accordingly, with less money, an SMR could complete FOAK construction and implement cost-saving learnings on the second-of-a-kind reactor. These lower costs could also lower barriers to entry for potential customers who cannot easily make a $6B+ commitment.

Figure 23: Large reactors are cheaper $/kw with narrower cost distributions, while SMRs may offer smaller overall project costs[93]



	Large	Small
	☐	🟩
MW	1400	300
StDv/Mean	0.19	0.26
Skew	1.46	2.64

Note: these are modeled costs for large and small boiling water reactors; specific designs will have their own cost profiles that will vary

SMRs could be more cost-effective in constrained labor environments, e.g., US, Western Europe. Recent successes in large reactor construction at a low capital cost can be found in South Korea, China, and UAE[92]. At the same time, large reactor projects in the US and Europe have been struggling with cost overruns. One major driver of these different experiences is labor constraints, which may include quantity of labor available, quantity of labor certified, quantity of labor with prior experience in nuclear, and rates of pay for labor. Labor constraints may impact large reactor costs more than SMR costs 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 markets where availability of nuclear construction employees is highly constrained.

Section 2.b.iv: Microreactors

Microreactors could serve a variety of use cases where their compact size, transportability, and reliability are highly valued, e.g., military bases, remote applications including mining, rural communities, industrial operations, and disaster relief, many of which currently rely on expensive diesel generators with costs approaching up to ~$600/MWh. Microreactors are generally considered smaller than 50 MW; smaller reactor designs are 1-10 MW capacity range.

- **Factory production and modularity:** most microreactor components are intended to be factory produced to increase standardization, learning rate, and cost predictability
- **Transportability:** could be shipped to remote areas and moved from one location to another by truck, vessel, or plane
- **Streamlined siting and installation:** factory produced modules are intended to be shipped to location, reducing the need for on-site construction
- **Grid independence:** co-location with offtakers
- **Longer refueling cycle:** most designs have ~3-10 years between refueling (which leads to the colloquial term “nuclear batteries”)

Microreactors need to have radically different cost and construction profiles to help counteract diseconomies of scale. Given historical difficulties with nuclear construction, the minimization of on-site preparation and construction costs is appealing to many customers. To realize this value, the vast majority of microreactor overnight capital costs, e.g., ~70-80%, may need to be in the factory setting. The ability to mass-produce microreactors in a manufacturing facility will play a large role in determining their commercial viability. Some nuclear costs are not proportional to size, so spreading costs across 10 MW versus 1000 MW means microreactors are likely to be more expensive $/MW and $/MWh than large reactors (even though the overall “check size” may be smaller).

- Depending on the design, fuel is likely to account for a greater proportion of costs; unlike large LWRs, microreactor fuel could be ~30% or more of the levelized lifetime cost due to lower fuel burnup[94] (and civil works construction being a smaller proportion of costs)
- Depending on configuration and regulation, microreactors may or may not have fewer operators per MW

However, given use cases with specific requirements, microreactors are still likely to have uptake even if the $/MWh are more expensive than larger reactors. Cost uncertainty is high due to nascency, lack of data, and loss of economies of scale. As such, it may be more feasible for customers to purchase production slots for future reactors (versus traditional power purchase agreements).

To justify investment in manufacturing facilities, microreactor designers may require a committed orderbook of ~30-50 reactors (versus the ~5-10 needed for SMRs or large reactors). Note an orderbook of 50 reactors would only amount to 500 MW total for 10 MW reactors, which could be achievable for a single industrial customer.

Given microreactor designers are considering factory fabrication to deploy multiple units of a standardized design, the NRC is proactively engaging with stakeholders and developing licensing strategies to support the effective and timely licensing of microreactors of a standardized design.

Section 2.b.v: Gen IV reactors

Gen IV reactors use materials and coolants that hold potential for improved safety and operations, but have not been widely commercially operated. Designs emphasize passive safety which place the plants into a safe condition relying on the natural laws of physics instead of operator action or active safety systems. They are also more capable of providing use-cases beyond grid-scale electricity than are LWRs (see section 2.a).

Non-LWRs are not "new" in that many of the designs were operated decades ago, e.g., the sodium fast reactor at Enrico Fermi in Michigan from 1966-1975 and the high temperature gas reactor at Fort Saint Vrain in Colorado from 1979-1989. However, all US commercial nuclear reactors operating today are LWRs.

Gen IV reactors, with their different technologies, materials, supply chains, and FOAK executions, are likely to incur high initial construction costs as some initial nonrecurring costs are incurred, e.g., establishing testing infrastructure. The high potential FOAK OCCs can be partially offset by government demonstration funding, e.g., the ARDP, and ITCs. Similar to LWR SMRs, Gen IV reactors will have challenges overcoming the $/MW of lower power output versus large LWRs. However, expanded benefits, such as their ability to produce high-temperature heat for industrial processes, may offer opportunities for power produced by Gen IV reactors to command a premium not captured in traditional LCOE models.

Given limited operating history, Gen IV reactors may undergo meaningful design enhancements following the construction and operation of the first demonstration plants. These design changes, while ultimately beneficial, may temporarily hinder the realization of learning effects until the design basis has stabilized. This "burn in" phase, while ultimately delivering on the promise of these designs, has the potential to delay full commercialization. It is unknown how quickly Gen IV reactors will get through their own "burn in" phase and reach design and operational optimization.

For reference, LWRs have been in commercial use for decades and benefit from those years of experience in design, operating, and maintenance learnings. The first commercial LWR began operation in 1957, and it was not until 2002 when the average capacity factor for the US nuclear fleet first reached 90%.[95]

Section 2.c: Down the cost curve

The US government is supporting the demonstration and deployment of new nuclear technologies. The IRA provided substantial tax credits and increased loan authority for the deployment of commercial technologies, while demonstration programs are funded and underway to de-risk innovative nuclear technologies.

While FOAK reactors may be expensive, repeat deployments within a design are expected to drive substantial cost reductions. Reducing capital costs requires taking action both for FOAK best practices and levers to get from FOAK to NOAK costs.

LCOE does not capture the full benefits of nuclear as a clean firm resource. Nuclear compares favorably to other generation sources when accounting for full costs of provision.

Section 2.c.i: Government support and resources

The Office of Clean Energy Demonstrations (OCED) manages the Advanced Reactor Demonstration Program with $2.8B of DOE funding:

- X-energy – Xe-100 high temperature gas reactor
- TerraPower – Natrium sodium fast reactor

The Office of Nuclear Energy (NE) manages the ARDP Risk Reduction awards with $651M of DOE funding:

- BWXT – BANR Advanced Nuclear Reactor
- Holtec – SMR-300 pressurized water reactor
- Kairos – Hermes fluoride salt-cooled high-temperature reactor
- Southern Company / TerraPower – Molten Chloride Reactor Experiment
- Westinghouse – eVinci Microreactor

NE manages the ARDP Advanced Reactor Concepts 2020 (ARC-20) with $55M of DOE funding:

- General Atomics – FMR
- Advanced Reactor Concepts Clean Energy – ARC-100
- MIT – MIGHTR

In 2024, Congress provided $900M to support grid-scale deployment projects for Gen III+ SMRs.[96] Up to $800M was appropriated to OCED for near term utility commercial deployments and $100M was appropriated to NE to support design, licensing, supply chain development, and site preparation.[x]

In 2024, Congress provided $2.72B to incentivize a domestic commercial HALEU and LEU supply chain. Combined with funding provided by the Inflation Reduction Act ($700M), the Department is working to establish a $3.42B fuel program. Among other things, the Department will incentivize new centrifuge capacity by entering into contracts with enrichers to provide the Department with material (HALEU and LEU), which the Department will make available to utilities. The revenue from sales of this material will be credited to the American Energy Independence Fund as offsetting collections, which the Department may use to buy more material from new capacity, subject to congressional appropriations. The Department has issued three Request for Proposals in 2023 and 2024 to increase deconversion and enrichment services to meet the needs of the current and future nuclear fleet.

In January 2024, DOE's Civil Nuclear Credit (CNC) Program finalized terms for up to $1.1 billion in credit payments for the Diablo Canyon Power Plant. Units 1 and 2 of Pacific Gas and Electric Company's Diablo Canyon Power Plant provide 9% of the total California power generation and were previously scheduled to cease commercial operations in 2024 and 2025, but credits from the CNC Program support a path forward for Diablo Canyon to continue operating.

The Loan Programs Office (LPO) has billions of dollars in loan authority available through Title 17 through Section 1703, Innovative Energy and Innovative Supply Chain, and Section 1706, the Energy Infrastructure Reinvestment Program. To qualify for 1703, energy projects must either involve innovative technologies or be paired with investments from State Energy Financing Institutions. To qualify for 1706, energy projects must retool, repower, repurpose, or replace energy infrastructure; 1706 also allows for projects that enable existing energy infrastructure to be upgraded to reduce their greenhouse gas emissions. Eligible project types include constructing new reactors, uprates and upgrades to existing reactors, and restarts of closed reactors. Across the supply chain, eligible project types include conversion, enrichment, fabrication, and nuclear component manufacturing. In 2014 and 2019, LPO provided $12B in loans for Vogtle Units 3 and 4, saving ratepayers hundreds of millions of dollars in interest costs. In 2024, LPO provided a loan of up to $1.52B to restart Palisades, an 800 MW pressurized water reactor that ceased operations in 2022. Large scale and long term debt financing is essential for nuclear deployment at scale given the magnitude

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[x] In November 2023, after the initial publication of this report, the Carbon Free Power Project with NuScale was discontinued, underscoring the need for committed, flexible offtake.

of construction. Interest costs can be a substantial portion of total project costs (see figure 27) and LPO financing is the most affordable option.

Idaho National Laboratory (INL) has a variety of resources developed to support the development of advanced nuclear technologies. NE launched the National Reactor Innovation Center (NRIC) to help innovative technologies move through the later stages of commercialization. By providing developers with access to national laboratory infrastructure, NRIC enables them to resolve technical challenges, validate advanced reactor concepts, and facilitate the testing and demonstration of advanced reactor technologies. Additionally, through support of the Nuclear Science User Facilities (NSUF) program, NE is using the expertise and facilities of the national laboratories and universities to help reactor developers improve technology readiness.

NE is supporting the construction of new testbed capabilities through NRIC at INL. The Demonstration and Operation of Microreactor Experiments (DOME) and Laboratory for Operation and Testing in the United States (LOTUS) test beds will host experiments and operational nuclear microreactor concepts. NE is building the Microreactor Applications Research Validation and Evaluation (MARVEL) project at INL to test how a microreactor can be operated in an integrated energy system on an operating microgrid. This will give developers the ability to test load following capabilities, process heat utilization, water purification, and hydrogen production.

The Department of Defense is 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. Eielson Air Force Base has released a request for proposals for a microreactor pilot project. The Army is also asking for proposals for microreactors to be sited at military bases, which could contribute volume to a commercial microreactor orderbook.

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.

The Inflation Reduction Act provides a powerful boost to nuclear power economics. The IRA introduced two technology-neutral clean electricity tax credits (48E and 45Y) and the zero-emission nuclear power production credit (45U).[97] Importantly for multi-year nuclear construction projects, the qualified investment for the 48E clean electricity ITC includes progress expenditures on property that takes at least 2 years to construct and has a useful life of at least 7 years. [98,99]

Figure 24: The IRA provides substantial tax credits for new and existing nuclear

IRA provision	Description	Adders	Notes
48E Clean Electricity ITC	Provides 30% investment tax credit for the capital cost for a nuclear plant	+10% for siting in energy communities +10% for domestic content	**Facility eligible for both adders would get 50% effective ITC**
45Y Clean Electricity PTC	Provides an inflation adjusted $27.5/MWh in production tax credits for the first 10 years of power produced by a nuclear plant	+10% for siting in energy communities +10% for domestic content	**Must choose ITC or PTC (not both)**
45U Zero-Emission Nuclear Power PTC	Provides an inflation adjusted $15/MWh in production tax credits for every MWh of power produced by a nuclear plant in the existing nuclear fleet[1]		**Only applies to plants placed in service before August 16, 2022**

All are subject to prevailing wage and apprenticeship requirements, otherwise they are 5x lower than listed

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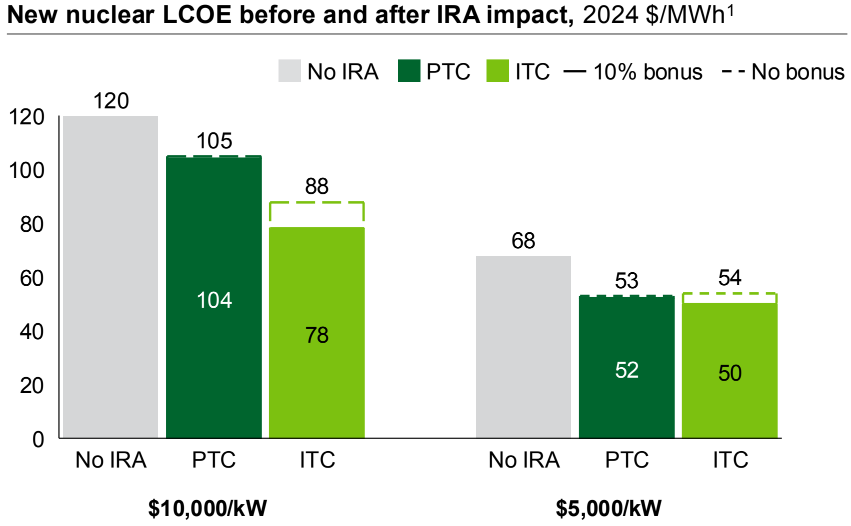
[1] Full credit is dependent on a plant's gross receipts; credit starts decreasing once gross receipts reach $25/MWh threshold and scales down until revenue equals $43.75, where the credit will equal $0

Construction cost and qualification for bonuses may drive value of the ITC versus the PTC by project, noting that every project owner will have a unique set of considerations. Because of nuclear's capital-cost-driven LCOE, the ITC has a greater impact for projects with higher construction cost:

- The 30% ITC (no bonus) may be more lucrative when OCC is greater than ~$5,000/kW; the PTC may be more lucrative when OCC is less than ~$5,000/kW
- The 40% ITC (one 10% bonus) may be more lucrative when OCC is greater than ~$4,000/kW
- The PTC may be more lucrative for reactor restarts, given the projects are likely to be less expensive per kW than new construction

The 10% energy community and 10% domestic content bonuses are also more valuable for the ITC than the PTC, as they represent 33% increases over the value of the 30% ITC, as opposed to the 10% boost to the PTC. Note the ITC applies 30-50% to capital cost regardless of initial budget, so in effect provides "overrun insurance," which many potential customers have cited as necessary for committing to new nuclear.

Figure 25: The ITC has greater impact for projects with higher construction cost versus the PTC[100,101]


New nuclear LCOE before and after IRA impact, 2024 $/MWh[1]

1 LCOE calculated using NREL ATB LCOE model; assumes 5% interest rate on LPO debt, 5 year MACRS, 7 year construction

Section 2.c.ii. Getting from FOAK to NOAK costs

At NOAK costs, new nuclear is expected to play a critical role in a deeply decarbonized system. While FOAK reactors may be expensive, repeat deployments within a design are expected to drive substantial cost reductions. Most nuclear learning curve savings are realized during the first few units: cost reductions of ~45-60% are estimated between the first and third plant deployed of a given reactor concept.[102,103]

Reducing construction costs requires taking action both for FOAK best practices and levers to get from FOAK to NOAK costs. FOAK best practices require investing heavily in upfront project planning and scheduling; for more on best practice FOAK levers and lessons from Vogtle, see 3.b.i.

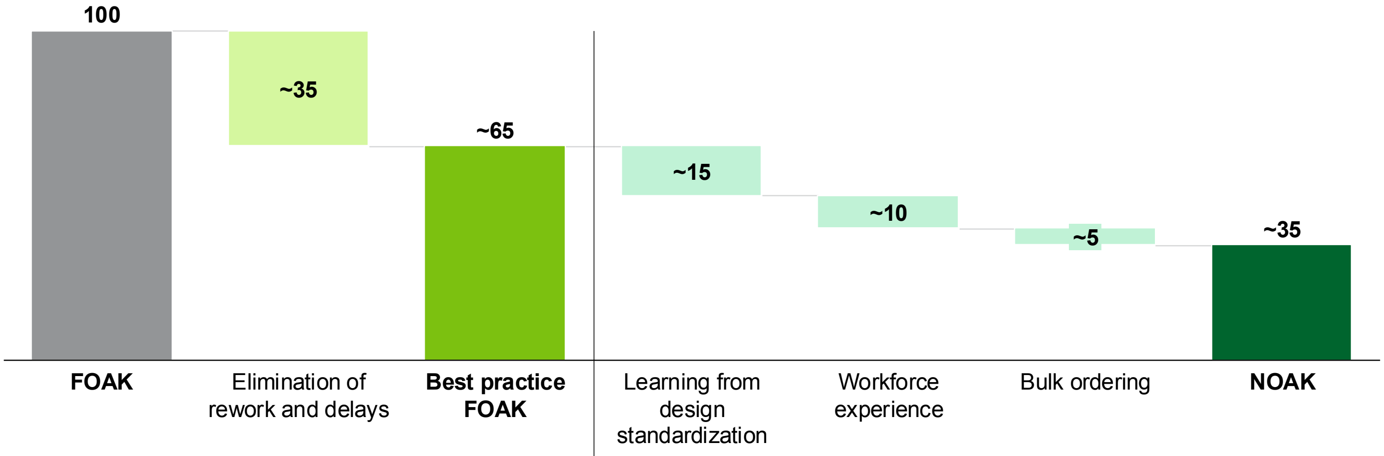
Following the initial publication of this Liftoff report, INL, ANL, and MIT created a framework for quantifying pathways from FOAK to NOAK costs.[104] The framework isolates learning effects into levers that can be adjusted to evaluate their impact on cost reduction, including:

- **Design completion**: when construction begins with lower design completion, there are typically more licensing amendments and rework, resulting in delays and cost increases
- **Design maturity:** novel designs with complex materials science requirements that require components that have never been built before will likely have higher costs and risks
- **Cross-site standardization**: the more standardized builds are, the lower the costs of subsequent units as design modifications and engineering evaluations are minimized
- **Orderbook quantity:** bulk order discounts can reduce costs for all reactors, including the first reactor
- **Supply chain proficiency:** a combination of contractor experience and best practices implemented by the contractor
- **Construction contractor proficiency:** contractor's ability to effectively plan and execute nuclear megaprojects
- **Architect/engineer contractor proficiency**: lower proficiency leads to redesigning components, delays, and higher indirect costs

Elimination of rework along with experience and cross-site standardization drive the majority of FOAK to NOAK cost reductions across different scenarios and reactor concepts. Overall, avoiding "negative factors" (e.g., elimination of rework or delays, largely a function of design completion and constructor proficiencies) has a larger impact than "positive factors" (e.g., labor productivity gains from experience).

Figure 26: Investment in pre-construction planning and design standardization are essential for reducing costs

Relative impact of FOAK to NOAK cost reduction levers on overnight capital costs, $/kW



Investing in pre-construction planning reduces costly rework and delays: ensuring design completion and constructor proficiency can reduce construction time and cost

Design standardization maximizes learning: multiple orders of a standardized design increase the ability to realize learning effects between projects

The greatest cost reduction opportunities are likely to come from yard/cooling/installation and EPC costs, as these cost categories primarily represent labor costs:

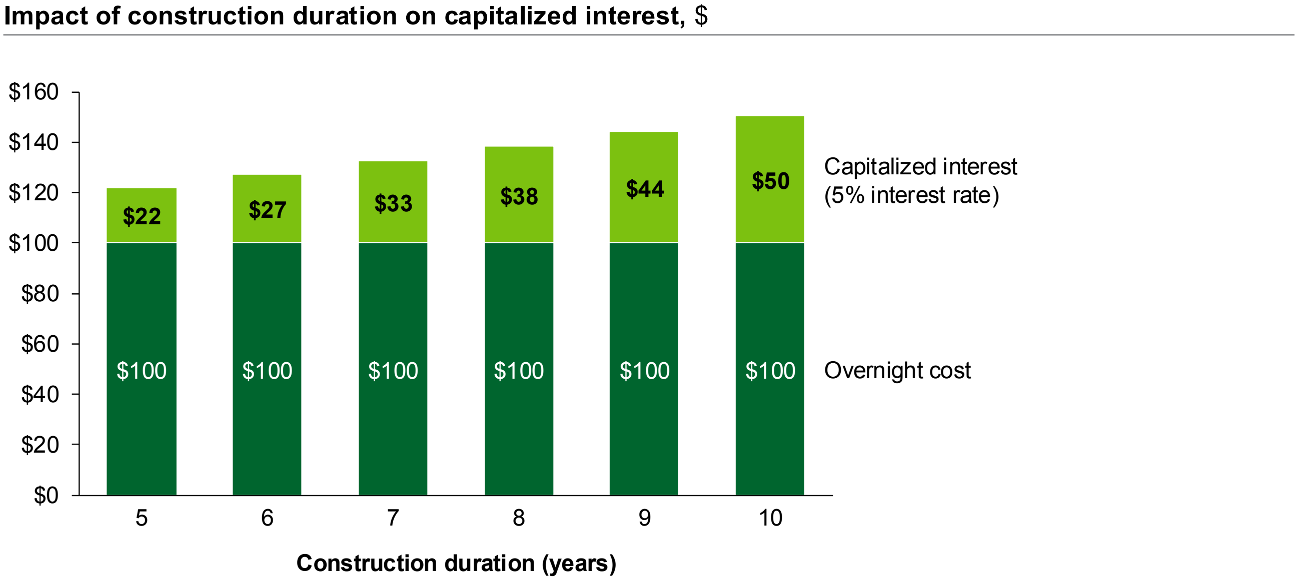
- **Learning by doing:** Experience built across the labor force as it is carried from one project to the next.
- **Standardization:** Codified construction processes or process management that create a “playbook” for project construction.
- **Build-time reduction:** Co-processing of tasks and proper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

- **Supply chain development:** As new manufacturing facilities are built, forward orders of materials 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.

Construction duration can have a material impact on total cost. For illustrative purposes, for $100 in overnight capital costs, 5 years of construction would lead to $22 in capitalized interest at 5% interest rates; 10 years would lead to $50. Shortening construction duration is an important lever for driving to NOAK costs.

Figure 27: Construction duration can have a significant impact on interest expense



Developers need to maintain sufficient orderbooks and minimize lag time between projects to retain experience, increase construction productivity, and allow bulk ordering. Bulk ordering over 10 reactors could lead to a ~15% cost reduction of the first unit compared to a single build without order book.[105] The formation of a consortium with a committed orderbook of 10+ units can significantly reduce the financial risks involved, even helping to negate the effect of cost overruns from the first few plants. Siting multiple reactors at the same location could further lower the cost and increase learnings, given shared construction teams and project management.

Reactor designs should be down-selected and standardized to eliminate rework due to design changes and minimize inefficiencies during construction. Standardization of reactor designs is key for decreasing lead times and costs; innovation can, perhaps counterintuitively, lead to higher capital costs and longer lead times.[106] To achieve higher learning rates, reactor designers, EPCs, and suppliers should pursue modularization and standardization of non-safety components and bring production from field to factory where possible.

The nuclear industry can accelerate the learning curve by following best practices demonstrated in South Korea. South Korea has achieved stable cost decreases over the last 20 years, leading to OCC of ~$2,300/kW on large light water reactors.[107]

- **Limiting the number of reactor designs** helped ensure enough deployment within a design to achieve learning; learning rates are mostly design-specific, so learnings achieved on one design are mostly not transferrable to other designs.
- **Minimizing time between projects** helped establish the supply chain and maintain the same workforce, resulting in better learning rates than those with a new workforce and significant time between builds.
- **Siting multiple units at the same location** reduced site preparation work by sharing the same experienced construction workforce and benefited from learnings from prior projects.
- **Building reactors in series of 10+ units** allowed significant cost savings from bulk ordering and spread costs across a large order book to help reduce burden from overruns in the first few units build.

Figure 28: Seven best practices to steepen the learning curve informed by nuclear and other industries[108,109,110,111,112,113,114]

Levers to steepen the learning curve informed by nuclear and other industries

Design, licensing, and project planning	1 **Down-select and standardize reactor designs** to minimize and streamline licensing 2 **Invest heavily in the project schedule** to minimize unnecessary work, workspace congestion, and delays	• **South Korea and France** constructed nuclear reactors in series of ~10 units of the same design and reduced the cost of NOAK reactors by ~20-30% vs FOAK
Construction and labor productivity	3 **Maintain sufficient book order and minimize lag between projects** to retain experience and increase productivity of construction management, crafts and trades, and suppliers 4 **Site multiple reactors at the same location** to share site preparation costs, construction workforce, and shorten permitting timelines	• **South Korea and France** built reactors in pairs and with less than 2 years between projects • **Palo Verde nuclear plant in Arizona** had ~40-45% capital cost reduction for units 2 and 3 versus unit 1
Material and component production	5 **Shift from field construction to factory** to enable automation, advanced manufacturing, and increase productivity 6 **Modularize and mass produce** components to gain economies of scale 7 **Standardize non-safety components** to leverage existing supply chains	• **Solar and wind** have achieved high learning rates by scaling production of standardized modular components • **Shipbuilding** has shown ~10-20% cost reductions with modular fabrication

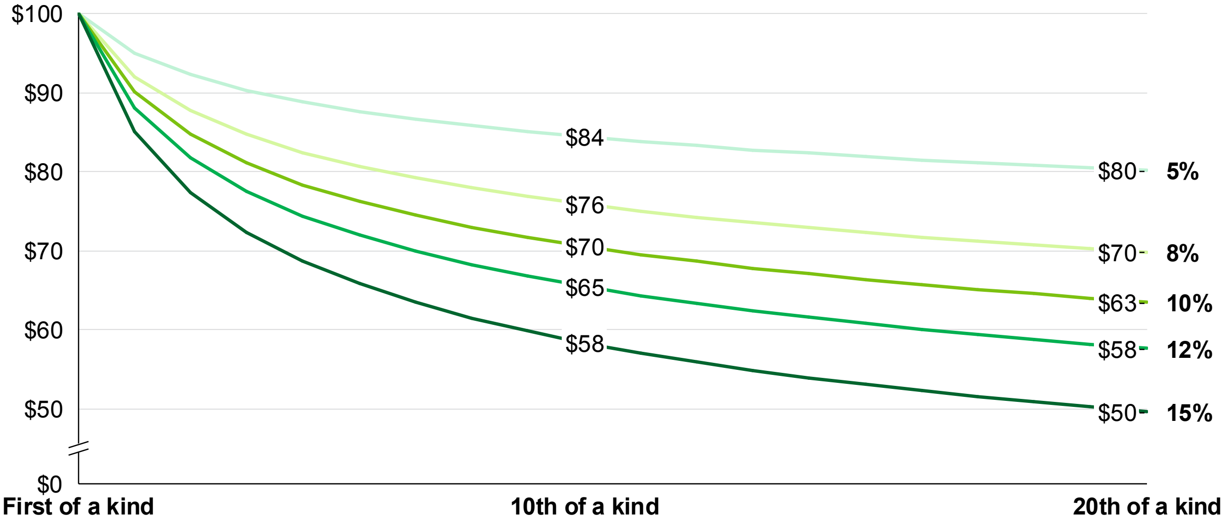
Other power generation technologies have demonstrated significant cost reductions with large scale deployment and substantial investment from the public and private sectors:[115]

- Solar's LCOE decreased from an average of ~$230/MWh in 2010 to ~$34/MWh in 2020
- Wind's LCOE decreased from an average of ~$440/MWh in 1984 to ~$32/MWh in 2020

NOAK cost reductions for nuclear will be impacted by learning rates. Given the infrequency of repeat builds of the same design, there are not large data sets to inform design-specific nuclear learning rates. Figure 29 provides a range of learning rates (observed in nuclear and other energy sources) and their cumulative impact on cost reduction for repeat builds; note these are for relative comparison and are not necessarily representative of the steepness expected from the first to second build.

Figure 29: NOAK costs depend on learning rate and number of units[116,117]

Illustrative cost reductions by learning rate, $



Section 2.c.iii: LCOE limitations and levers

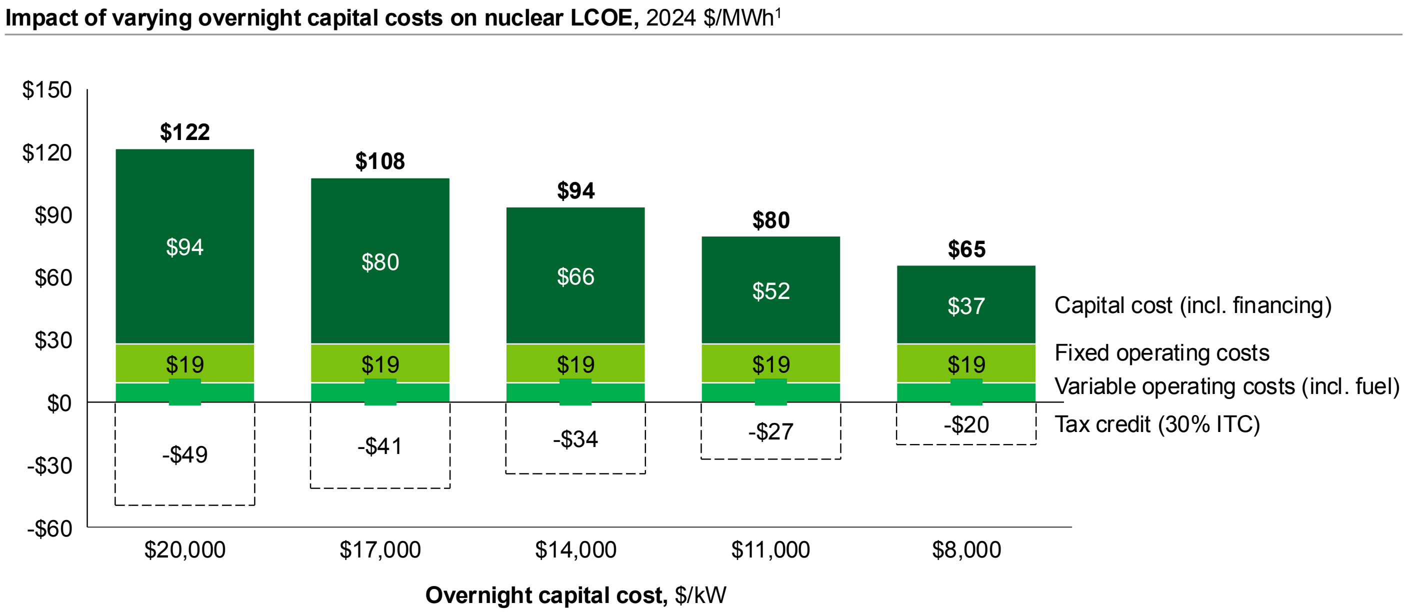
Levelized cost of electricity (LCOE) represents the average revenue per unit of electricity generated that would be required to recover the costs of building and operating a generation plant during an assumed cost recovery period and for a specific duty cycle. Costs include not just operation and maintenance, but also debt financing, equity returns, and tax effects. LCOE also accounts for the discounting of yearly cash flows.[118]

LCOE can be a useful metric for quantifying cost reduction progress, e.g., from FOAK to NOAK, within a technology or for comparing different options that provide the same services, e.g., different clean firm resources. Cost reductions and predictability improvements will be critical for nuclear projects, and LCOE will be a useful metric for tracking progress.

The LCOE of nuclear is driven primarily by construction costs, which can be broken into overnight capital costs and financing costs. Overnight capital cost is the cost to construct a nuclear plant without the impact of financing costs (as if it were constructed "overnight"). As a result, reducing overnight capital cost, construction time, and financing costs are all key levers for reducing LCOE. Construction costs can drive ~70–80% of nuclear's LCOE while operating costs are low and predictable. This contrasts with natural gas, where rather than construction costs, the LCOE is strongly influenced by fuel prices, which can create volatility in operating costs.[119]

In this report, LCOE was calculated using the 2023 NREL LCOE model; a version with a nuclear dashboard that allows changing key assumptions is available here. To see the effects of varying assumptions on LCOE from Vogtle and future AP1000s, see 3.b.i.

Figure 30: Estimated LCOE ranges including 30% ITC[120]



1. LCOE calculated using NREL ATB LCOE model; key assumptions: 6 year construction time, 80% debt, 5% interest, 30% ITC, no adders

Nuclear operating costs are in a predictable band and have decreased over time. In 2022, the average total generating cost for US nuclear was ~$31/MWh: ~60% operating costs, ~15-20% fuel costs, and ~20-25% capital costs. Generating costs declined from ~$51/MWh in 2012 to ~$31/MWh in 2022 with reductions in operating and fuel costs.[121]

LCOE does not capture the full benefits of nuclear as a clean firm resource. 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 average generation irrespective of the time it is produced, which excludes two key categories of cost: delivery cost and firming cost. LCOE also does not capture the benefits of clean carbon-free generation, excluding the costs incurred by fossil fuels of carbon emissions on air pollution, human health.

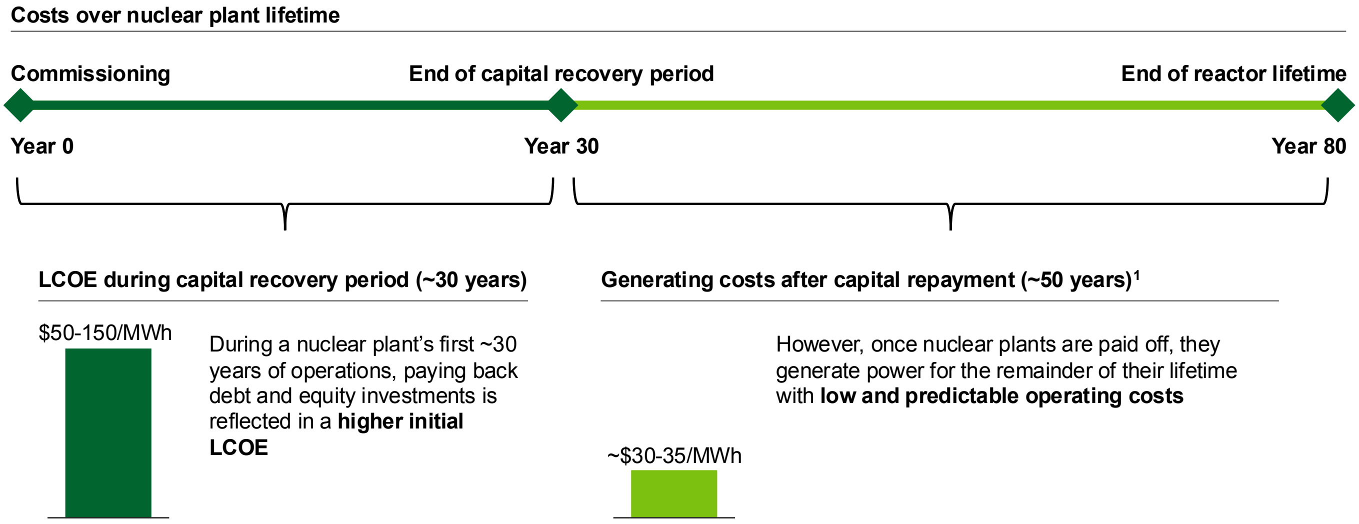
LCOE does not include delivery system costs such as interconnection and transmission. Firm resources tend to have lower overall delivery costs. With higher capacity factors, less delivery capacity is needed for a given amount of electricity generated (the transmission line capacity has a higher utilization). In addition, nuclear is more geographically concentrated; therefore, it can require less delivery buildout, including interconnection costs.

LCOE does not include the cost to maintain additional generation to balance or "firm" the system during times when variable resources are not producing. For variable resources, this firming is provided by natural gas peaking plants, overbuilding with curtailment, or by batteries, which create costs for matching system load. It is challenging to capture system and firming costs to create clean firm comparisons even with modified LCOE, e.g., the Lazard LCOE+ analysis "firms" solar and wind with unabated natural gas (not clean) or four-hour battery storage (not firm).[122] Modeling shows that this firming cost can increase as the penetration of variable renewables reaches high levels.[123]

Nuclear compares more favorably to other generation sources when accounting for full costs of provision and decarbonization. Renewable electricity sources can have higher system costs because of their variability, limited dispatchability, and forced curtailment.[124] As a result, they require either overbuilding of both capacity and storage to meet load. A resilient grid includes a variety of generating assets, not just those with the lowest marginal LCOE.

LCOE fails to capture the value of 80-year operating assets. Capital recovery periods, the time over which the project amortizes the initial construction costs, are likely capped at 30 years. Even if a nuclear plant's LCOE ranges up to $150/MWh during that capital recovery period, once the asset is paid off, it could continue to operate for ~50 additional years, generating electricity within a predictable range of $30-35/MWh for (a range that could continue to decrease over time given efficiencies). Since LCOE doesn't capture the post-capital repayment value, it underestimates the value of multi-decade investments that will provide future generations with affordable clean firm power.

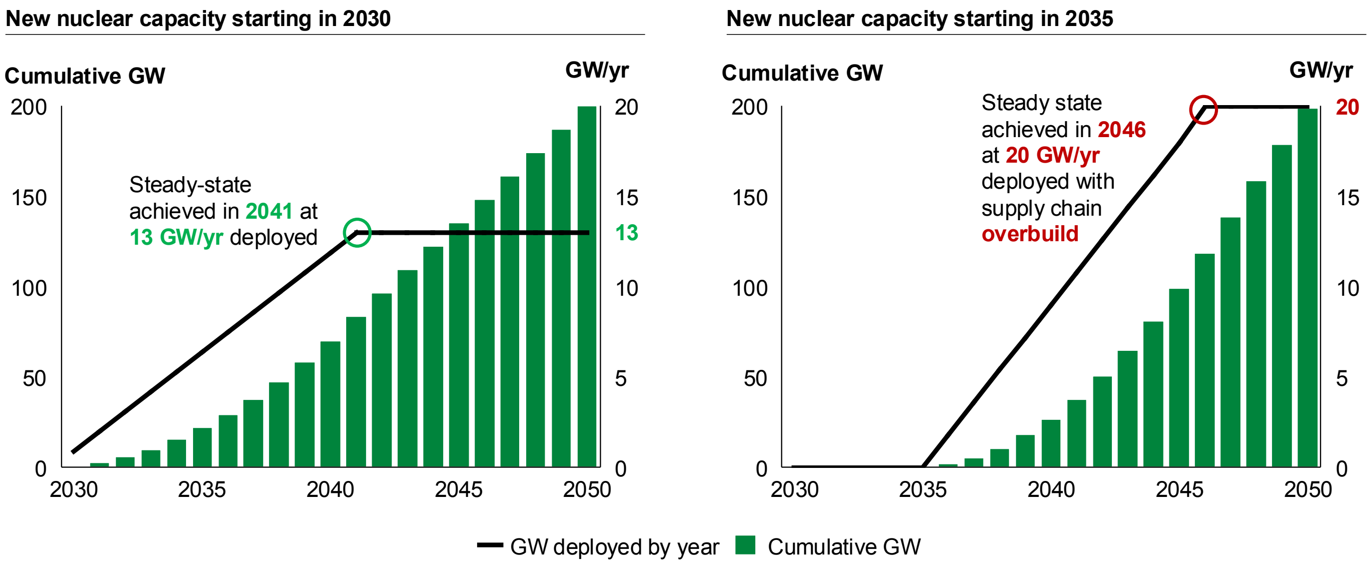
Figure 31: LCOE fails to capture the full benefit of 80-year clean firm operating assets



Chapter 3: Pathways to commercial liftoff

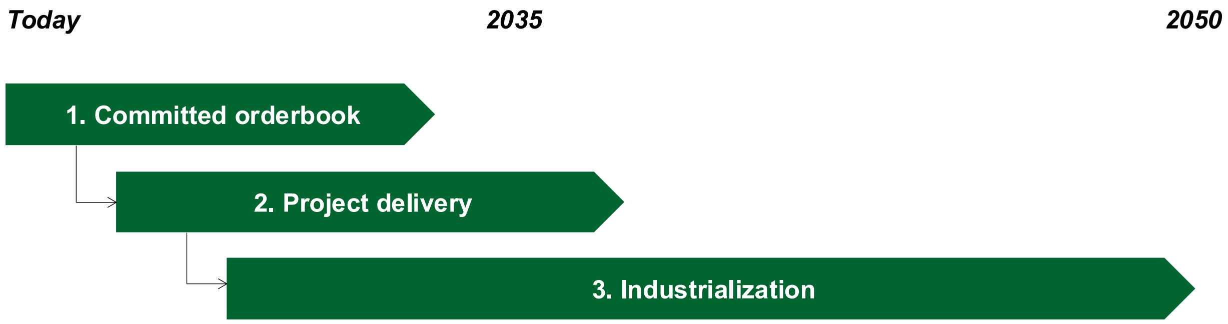
Waiting until the mid-2030s to deploy at scale could lead to missing decarbonization targets and/or significant nuclear supply chain overbuild. Committing to rapidly scaling the nuclear industrial base will increase capital efficiency and enable nearer-term decarbonization. If deployment at scale begins 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. To avoid the cost of a delay in advanced nuclear deployment, the industry will need to begin deploying nuclear by 2030.

Figure 32: Delaying new nuclear deployment could increase the cost of decarbonization



New nuclear liftoff will proceed in three overlapping phases: (1) committed orderbook, (2) project delivery, and (3) industrialization.

Figure 33: Three phases for the nuclear industry to achieve liftoff



Section 3.a: Committed orderbook

A committed orderbook of 5–10 deployments of a single reactor design is the first essential step for catalyzing commercial liftoff in the US. 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 a 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 the 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 September 2024, there are no committed orders, e.g., signed contracts, to construct new nuclear reactors in the US.[xi] 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.

These 5–10 deployments need to be within the same design as overnight costs are largely expected to decrease 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 ARDP are powerful tools in a portfolio of advanced nuclear technologies, Gen III+ reactors may generate the early demand signal. Interviews with utilities and supply chain players suggest they currently feel most comfortable with the Gen III+ designs. Other end-users, including industrial companies and tech companies, may prefer Gen IV designs due to the safety profile and ability to produce high-temperature heat. Regardless of reactor type, generating a demand signal will benefit the entire industry for Gen III+ and Gen IV by building the momentum and infrastructure required for deploying all designs at scale.

[xi] 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.

By 2050, up to ~200 GW of coal assets are expected to retire.[125] As utilities begin to retire these fossil assets, nuclear is uniquely positioned to replace retiring assets with a similar electricity generation profile. The ability to leverage the same transmission, water, and land-based infrastructure as retiring fossil generation could yield substantial savings versus greenfield construction.[126] Communities aiming to preserve the high-paying jobs that fossil plants provide would benefit from transitioning to nuclear to provide similarly concentrated local economic benefits.

Regulated utilities may be the first movers on deploying new nuclear, but likely not without a partner. Because of the risks of cost and schedule overruns, it is unlikely that a first mover will emerge to deploy advanced nuclear without "guaranteed" long term recovery of the asset. Regulated utilities or public power are more likely be first movers as opposed to those with shorter term merchant market exposure. Traditionally, utilities used general rate base to achieve long term recovery; however, the considerations of having ratepayers shoulder FOAK costs and risk makes this model less attractive. Based on interviews, large customers including technology or industrial companies may play an important role in committing to long term offtake at above market prices 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. Therefore, with the support of large offtakers to take long term commitments, utilities or even merchants may be more willing to be first movers. 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 reactors coming online annually. "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 US nuclear industrial base.

Section 3.a.i: Consortium approaches

Consortium approaches aggregate demand and push through the "first mover disadvantage" to realize and share cost reductions. Nuclear has the potential to come down the learning curve through successive builds and achieve competitive prices by NOAK. However, the cost of the first few plants is likely to be higher than is economically competitive. If customers buy plants separately, then there is a disadvantage in being the first customer, so most potential customers express that they would "prefer to be fifth" and take advantage of the lower cost. However, no one can be fifth if no one leans in to be first, second, third, and fourth.

The nuclear industry must solve the issue of spreading early costs over subsequent reactors such that there is no longer a benefit to waiting for the fifth project. A model like this has been executed regularly outside of nuclear. For example, Boeing did not try to sell one very expensive 787 loaded up with all the costs of designing the plane, building production facilities, standing up the supply chain, etc. Instead, Boeing sold 50 787s to their first customer, spreading early costs over multiple planes in a single order.[127] The solution for nuclear requires a committed orderbook large enough to achieve a competitive average price.

Consortium approaches allow customers to all be "one fifth" of the orderbook versus "waiting to be fifth." Spreading costs for these orderbooks could be achieved through one or both of two consortium types:

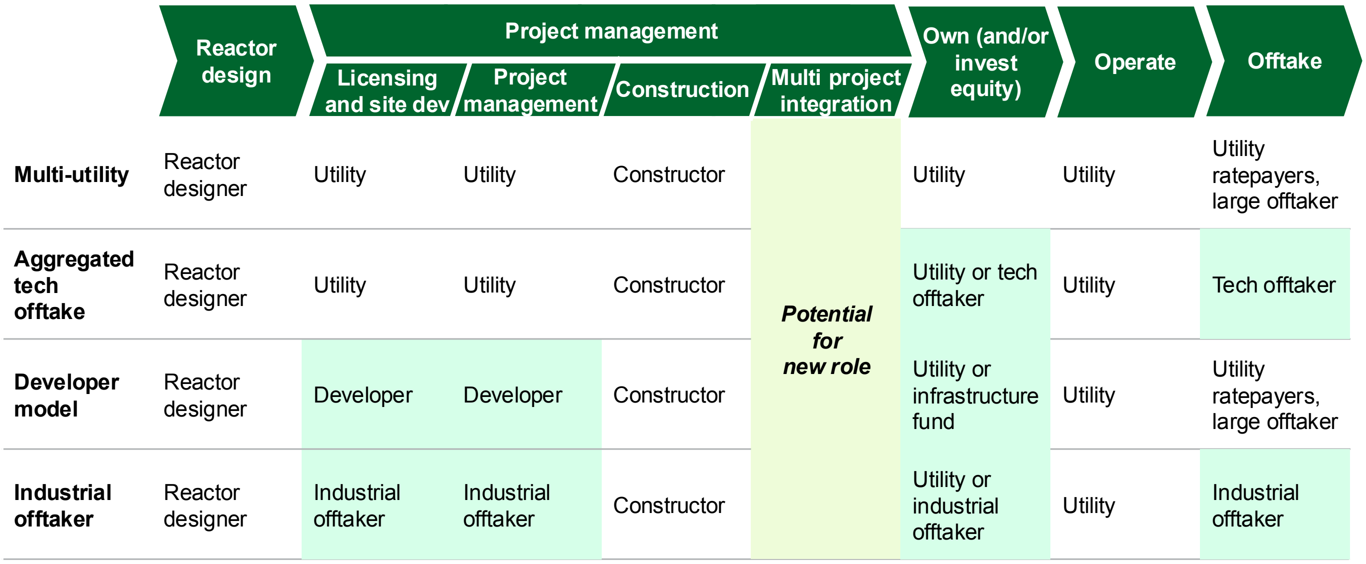
- **Buyers' consortium** in which offtakers pool demand and agree to an average price for the entire set of reactors
- **Builders' consortium** in which asset owners agree to work together (or through a developer) to spread the early costs across the set of reactors

The Energy Futures Initiative (EFI) outlines that a successful consortium will:[128]

- **Pool demand:** Commitment to 5-10 reactors of the same design is easier to aggregate across multiple customers.
- **Share knowledge:** During construction planning and execution, intellectual property and business know-how will be created and integrated among projects, which is essential for realizing cost reductions (versus building five FOAK projects in parallel).
- **Share risk and reward:** The consortium is the legal and commercial arrangement that allows sponsors to share costs among members. Moreover, the consortium model could also be used to share revenues and/or monetary upside from accumulated IP and the ability to deliver projects on-time and on-budget.

Many US nuclear plants have been built and owned as a joint venture among multiple utilities, e.g., Palo Verde. However, consortium models open up more options where a common offtaker or developer and participants can play different roles in the development, ownership, operation and offtake of multiple projects.

Figure 34: Any nuclear project requires many roles to be filled; consortium approaches can help aggregate demand and create partnerships



	Reactor design	Project management				Own (and/or invest equity)	Operate	Offtake
		Licensing and site dev	Project management	Construction	Multi project integration			
Multi-utility	Reactor designer	Utility	Utility	Constructor	***Potential for new role***	Utility	Utility	Utility ratepayers, large offtaker
Aggregated tech offtake	Reactor designer	Utility	Utility	Constructor		Utility or tech offtaker	Utility	Tech offtaker
Developer model	Reactor designer	Developer	Developer	Constructor		Utility or infrastructure fund	Utility	Utility ratepayers, large offtaker
Industrial offtaker	Reactor designer	Industrial offtaker	Industrial offtaker	Constructor		Utility or industrial offtaker	Utility	Industrial offtaker

🟩 Roles that differ from multi-utility

Many key roles must be filled for a nuclear project: reactor design, project development, owning, operating, and offtake. Historically, utilities have been responsible for leading their own reactor design selection, licensing, site development, and overall project management. This model has limited the ability to come down the cost curve through repeat building of the same design because any individual utility does not have sufficient demand for the number of reactors required to come down the learning curve. See section 3.b.i for more on how Vogtle Units 3 and 4 were ultimately completed under Southern Nuclear's management.

Reactor design is managed by reactor designers (or reactor vendors), who design the nuclear reactor and do early engagement with the NRC.

- Occasionally, there is a misconception that reactor designers construct or deliver a complete nuclear power plant; in general, selecting a reactor design only fills the first key role, with many remaining roles to be filled for successful project execution.
- Note that some microreactor designers are intending to provide more of a complete power plant, but larger reactors require extensive coordination with project managers and constructors.

Project development and management includes licensing and site development, project management, construction, and multi-project integration.

- **Licensing and site development** involves applying for approvals from federal and state entities (e.g., NRC, state permits) and leading site evaluation and preparation. Utilities have historically led the licensing and site development for nuclear projects, but this could be carried out by other entities, e.g., developers (in the model of renewable developers).
- **Project management** involves managing all aspects of development and construction, including ensuring all participating parties (reactor designer, EPC, suppliers, etc.) deliver on a successful project.
  - While many participants have interests in project success, no stake is more significant than that of the owner, and it follows that the owner should provide intensive direction, governance, and oversight.
  - The owner takes on the financial risk, which could follow two models: traditionally, ownership begins while the asset is being built on balance sheet; alternatively, a developer could own the asset during construction and then flip ownership to the ultimate owner.
  - Success depends on ensuring the project's structure (including responsibilities and risk sharing) are aligned with the owner's priorities. Risks cannot simply be shifted to other parties, but must be actively managed. The goal should be *ensuring* a successful outcome, rather than just *insuring* against overruns.
  - The integrated project delivery (IPD) model provides a helpful framework for aligning the interests of the owner with their contractors; see section 4.a.iii for more.
- **Construction** of nuclear power plants is typically assigned to engineering, procurement, and construction firms (EPCs).
  - EPCs provide a more integrated approach than used in the earlier nuclear construction wave in which there were separate architect-engineers and construction contractors, where the owner acted as the integrator between the design and construction.
  - The role of the EPC is to complete the scope of work assigned to them by the overall manager of the project. The success of the overall project remains with the entity managing the overall project. Thus, it is critical that the EPC scope is well defined and fully understood.
  - In the 1960s, utilities were offered fixed price "turnkey" deliveries of entire nuclear power plants. More recently, constructors have typically provided cost plus services, as opposed to firm fixed price contracts.
  - Target price contracts based on well-defined scope allow for a detailed cost estimate that can include incentives and disincentives for performance. Cost overruns during construction due to issues in other parts of the project (e.g., licensing or design) typically are not borne by the EPC.
  - There are not many firms with both large project and nuclear experience. EPCs are often formed by joint ventures. The role of delivering a completed nuclear project is a key gap in the new nuclear industry.

- **Multi-project integration** is a role that has not historically been filled in the US, but must be filled to capture learning between builds of the same design at different sites.
    - A standalone entity dedicated to documenting IP/know-how and sharing across projects could unlock higher learning rates. Such an entity could be the vehicle for providing consistent project oversight and management for multiple offtakers.

Offtake has historically been for ratepayers in a utility service territory, but the emergence of offtakers with large power needs, clean energy commitments, high reliability requirements, and an ability to pay a premium has opened up new options for non-traditional development models.

- **Tech companies**, e.g., Microsoft, Google, Amazon, have enormous needs for clean firm power. They can take leadership roles not only on power procurement aggregation[xii] but also the development of the projects.
- **Industrial companies,** e.g., Dow,[xiii] Nucor, have varying requirements for high reliability electricity, high temperature heat, and high-quality steam that could require integrating a nuclear reactor into site operations or simply purchasing dedicated electricity.
- There are multiple options that these offtakers could pursue to catalyze projects, including creating a 24/7 tariff with a nuclear operator, purchasing bulk generation from a developer model, or becoming an equity investor in new projects.

Owning and operating nuclear power plants is managed by utilities in rate regulated energy markets and competitive generation companies in deregulated energy markets. There are also companies that offer nuclear operating services to asset owners with no operating ability. Large offtakers, including many tech companies and industrial companies, have expressed they would prefer existing owners and operators to continue owning and operating assets.

- **Equity investment in project development**, beyond owning the asset, is a way for large, well-capitalized offtakers to catalyze projects and potentially benefit from future development.

New models could accelerate deployment of new nuclear by creating a delivery entity that captures lessons and continuously improves on the deployment approach.

- **Integrated project delivery** aligns financial incentives and improves coordination among key participants, including owners, EPCs, and other contractors. Learnings and intellectual property could be shared across the IPD team. See section 4.a.iii for more.
- **Developer models** would provide an integrated offering where the developer would take full responsibility for delivering a completed nuclear project (or select steps, e.g., the licensing and site development). The developer would take on this risk in exchange for owning intellectual property, allowing the integration of learnings into future projects capturing the increased predictability and profit.

A consortium could be very flexible to the requirements of the participants; a few considerations include:

- **Geographic locations**: More cost savings occur the more co-location can be achieved at a single site, both from construction cost savings and economies of scale in operations, which they will need to weigh against cost differences for transmission, interconnection based on the locations.

[xii] In March 2024, Microsoft, Google, and Nucor announced the Advanced Clean Electricity RFI to "accelerate the development of first-of-a-kind and early commercial projects."

[xiii] In 2023, Dow began working with X-energy to develop high temperature gas reactors to provide electricity and steam at one of its industrial sites in Texas.

- **Intellectual property:** Consortium participants could jointly own (or have unfettered access to) IP and know-how. This would also allow licensing to future customers outside the consortium, potentially at a premium margin, after cost and schedule predictability have been achieved. Currently, reactor designers are often unable to market their reactors with an integrated package of construction schedule and work packages due to diffuse IP ownership.
- **Financial terms:** Sharing costs is foundational to a consortium, but there are other questions, e.g., distributing cost overruns and sharing revenue. See 4.a.ii for more.
- **EPC:** Very few EPC firms have experience with both nuclear and megaproject construction and EPC proficiency is a major driver of delivered cost. Consortiums that can partner with the same EPC are likely to achieve higher cost savings. Consortiums that can create significant IP/know-how through repeat construction could develop an integrated firm fixed price offering at a profit to future customers.

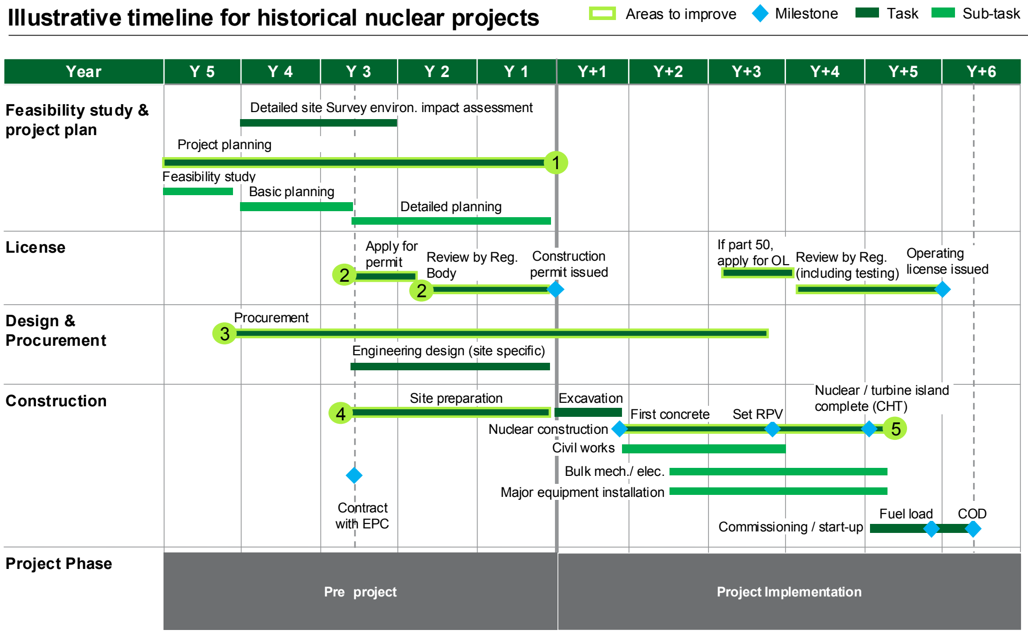
Section 3.b: Project delivery

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:

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 35: Illustrative major steps for building a nuclear power plant from historical LWR projects[129]



Potential improvement areas

1. Consult available project schedules from OEMs and EPCs
2. Engage with NRC early, determine appropriate level of detail, assess Part 50 vs Part 52
3. Use experienced vendors, modularization, and OTS materials when feasible
4. Leverage strong scale effects achieved through multi-unit sites and potential brown field development
5. Capitalize on learning effects by using the same workforce, contractors, and management teams to the maximum possible extent

A composite timeline shows nearly half of the total timeline can be spent planning: preparing for construction and beginning long-lead procurement efforts. Additional time for planning may have been needed for Vogtle given the US had not initiated large nuclear construction in decades. Future projects, when leveraging scale and learning effect to achieve nuclear goals, may be able to achieve improvements across several areas highlighted in the historical target schedule.

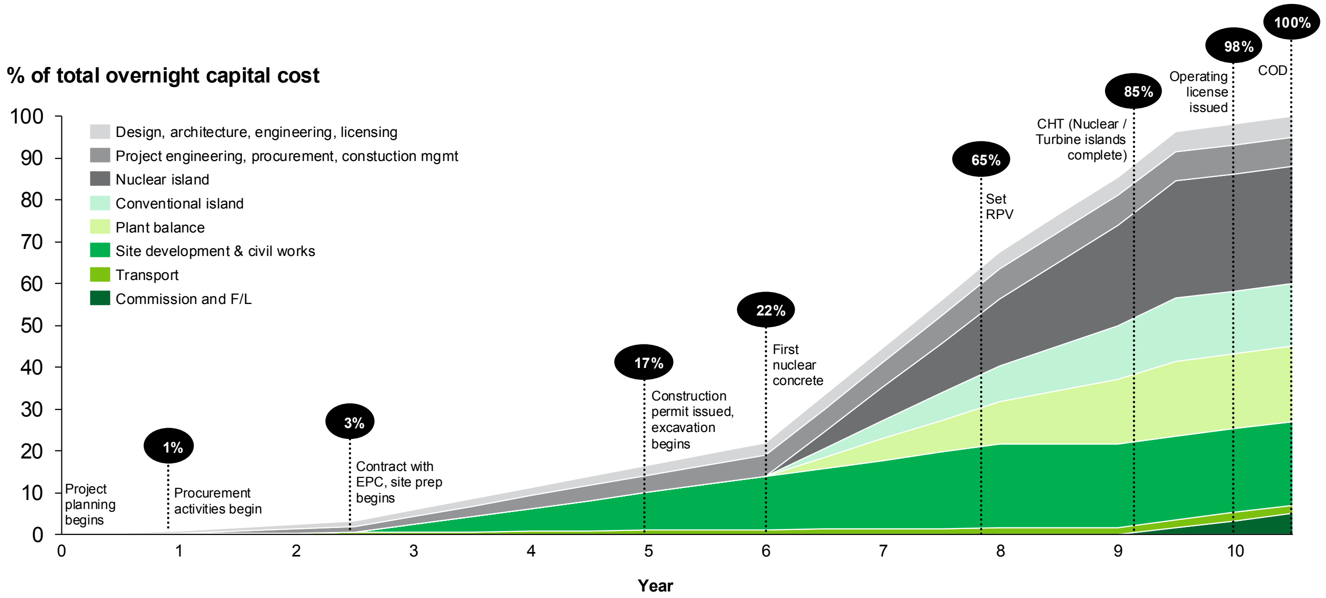
Pre-project: focused on gaining approval from the NRC to begin construction of the plant. This includes demonstration of the safety of the design, the suitability of the site, and the need for the plant. The pre-construction preparation in this phase is critical for successful project implementation. A design that is mostly complete is a key factor in successful construction. Timely construction requires sufficient lead time for components where the supply chain limits the number of vendors who can build them and the time it takes for their manufacturing (e.g., reactor pressure vessels, steam generators). 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.

Figure 36: Illustrative nuclear project costs across a 10-year timeline with milestones

Nuclear project cost vs. potential 10-year timeline & milestones[1]



1 Cost curve is estimated using the IAEA's project activity schedule & milestone timeline and World Nuclear Association's breakdown of percentages of total costs allocated to activities. Costs for each activity are assumed to have even spend across each activity's time duration.

Figure 36's illustrative cost curve from historical composite schedules[130,131] shows relatively low costs are expected for activities that can be frontloaded, e.g., planning, licensing, and select procurement. Relatively low cost activities like establishing project controls and quality assurance are essential for preventing compounded overages in schedule and budget: rework causes delays in schedule, extended the financing period, and paying for labor "again." Nearly half the project budget may go to the nuclear and turbine islands; labor is the largest cost associated with construction.

Section 3.b.i: Lessons learned from Vogtle

Cost overruns are not unique to the nuclear industry and are a feature of most megaprojects. However, to ensure that these overruns are not repeated, it is critical to incorporate lessons learned and megaproject best practices into future deployment. A common root cause of megaproject challenges is not cost overruns but "underestimates" due to insufficient up-front planning. A better approach is "think first, then do," planning slowly (pre-construction) and acting quickly (during construction).[132]

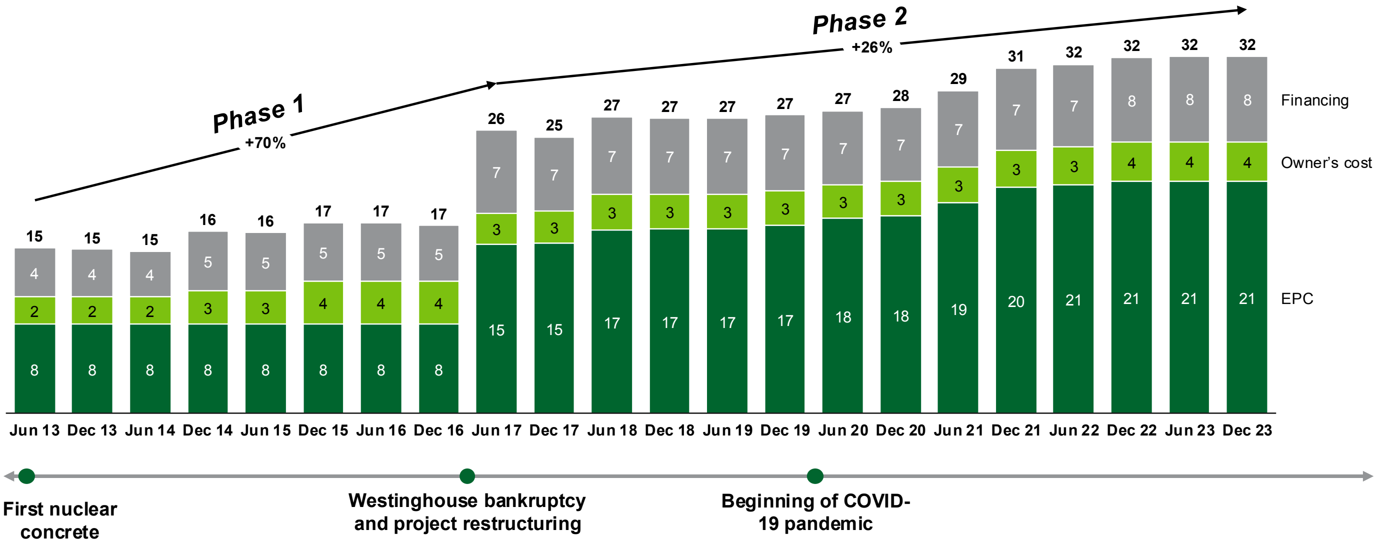
The completion of Units 3 and 4 made Vogtle the largest clean energy generation site in the US (as well as the largest energy generation site of any kind in the US). With ~4,500 MW of capacity and ~35 million MWh generated per year, Vogtle's four units can power ~2 million homes. Vogtle Units 3 and 4 were the first US nuclear reactors to begin construction and reach operation in 35 years,[xiv] beginning nuclear construction in 2013 and becoming fully operational in 2024.

The original budget for Vogtle Units 3 and 4 was ~$14B, while the final cost was approximately ~$32B. An interesting question to consider is how much was "overrun" versus how much was underestimation, given the design was not complete when the budget was originally estimated. The reset of the project budget to ~$26B in 2017 (when Southern took over the project management role), especially after accounting for Covid impacts, was substantially closer to the final cost.

[xiv] The most recent completed plant to begin construction before Vogtle was Shearon Harris Unit 1, which began construction in 1978 and began operations in 1987. Watts Bar Unit 1 began operations in 1996 and Unit 2 in 2016, but began construction in 1973, which was halted for many years.

Figure 37: When Southern took over the project management role, the budget was reset closer to final cost

Projected total cost during construction of Vogtle Units 3 and 4,[1] $B



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)

Vogtle provides important lessons for filling nuclear project roles:

- **Customer consortium model provided strong, creditworthy offtake:** the Vogtle expansion project is owned by four partners: Georgia Power, a subsidiary of Southern Company (45.7%), Oglethorpe Power (30%), Municipal Electric Authority of Georgia (22.7%), and Dalton Utilities (1.6%).
- **Expertise mismatch created challenges:** Westinghouse and CB&I Stone and Webster were contracted to both design and construct the reactors. After CB&I sold Stone and Webster to Westinghouse in 2015, Westinghouse became the sole EPC contractor. In effect, the reactor designer became the constructor and project manager, three critical roles that require different expertise, which exacerbated challenges (see 3.a.i for more on the importance of filling nuclear project roles with the appropriate expertise and incentives). In 2017, Westinghouse filed for bankruptcy protection, driven by the cost of performing under the fixed-price construct of the EPC contract.
- **Subsequent owner-led model ensured project completion:** Southern Nuclear Operating Company, also owned by Southern Company, took over as the project manager and licensee and hired Bechtel to become the prime construction contractor. When Southern took over this project management role (with increased focus and accountability), the budget reset was a substantially more accurate estimate of the total cost and ensured project success.

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

Figure 38: Root causes and systemic issues associated with Vogtle cost and schedule overruns

Root causes lead to…	…systemic issues
🟩 Incomplete design	① Extensive rework/remediation
🟩 Limited constructability review	② Supply chain delivery issues (for modules)
🟩 Inadequate detail in integrated project schedule, inflexible timelines, poor project controls system	③ Low individual productivity
🟩 Inadequate quality assurance / control practices; improper documentation standards	④ High levels of attrition and absenteeism
🟩 Poor risk assessment	
◩ Shortage of experienced labor	
⬜ COVID-19 pandemic	

🟩 *Within project leadership control*

⬜ *Outside project leadership control*

1. **Complete the design before starting construction.** When using NRC's Part 52 licensing process, complete at least 90% of the design (everything that can be completed prior to site selection) before starting construction. While a slightly lower design readiness could be used for the Part 50 licensing process, any reduction in design maturity risks rework and delays when beginning construction. In either case, detailed work packages "Certified for Construction" should be developed for construction execution.

   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 are 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 account for missed dates, ensure it is reasonable, and is 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 initial project delivery, the government could provide grants 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. The use of lean construction techniques (e.g., kitting) should be used to minimize time spent in the field and maximize value-added time.

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

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 meet 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.

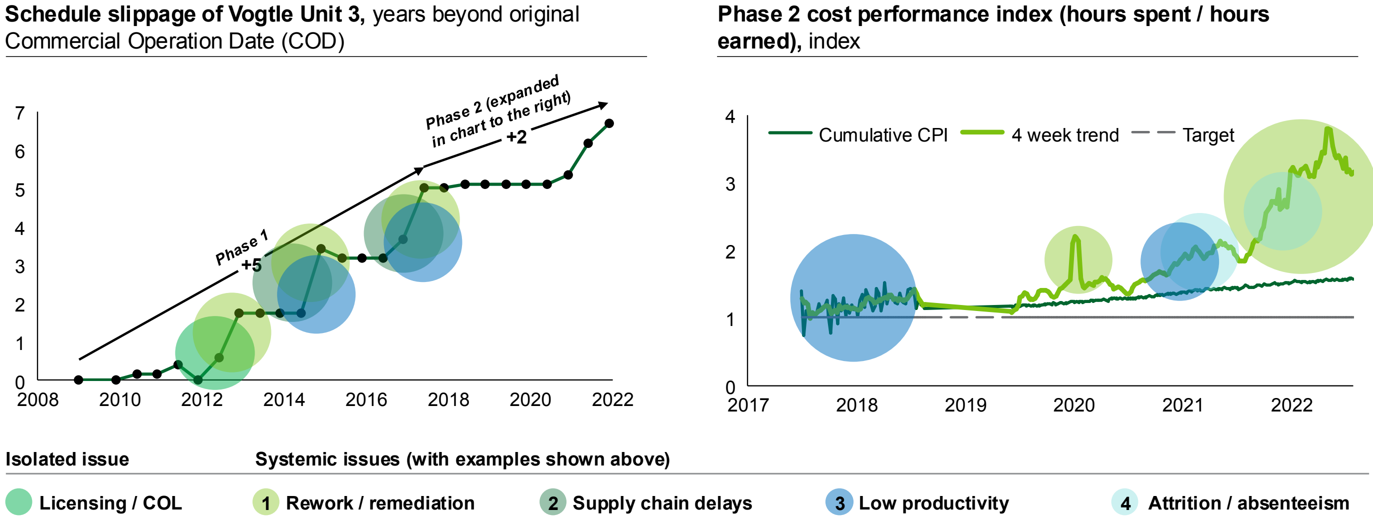
6. **Invest early and heavily in technical and process training for workforce.** Budget for intensive training programs that will be required to train non-nuclear workforce to nuclear standards. Implement a standardized, non-nuclear-to-nuclear construction training program across all functions. Ensure the employment offering is competitive for local labor markets.

   Experienced, consistent labor will be crucial for capturing learning effects, though it may be the most challenging to address. A government task force could evaluate existing construction labor gaps (e.g., welding) and invest in community colleges and 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 could be less stringent. Differentiating requirements like these would need to be balanced with the desire of many project managers to flexibly move workers around the site.

Four systemic issues contributed to the performance against target schedules.

Figure 39: Schedule slippage and performance against cost performance index at Vogtle [133]



Schedule slippage of Vogtle Unit 3, years beyond original Commercial Operation Date (COD)

Phase 2 cost performance index (hours spent / hours earned), index

Isolated issue **Systemic issues (with examples shown above)**

1. **Rework / remediation: original work did not function or did not meet quality standards and had to be redone.** Rework was a significant source of project delay for many years.[134] 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 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 was unavailable when needed, and attrition hindered learning.** Absenteeism was a recurring issue, and 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.

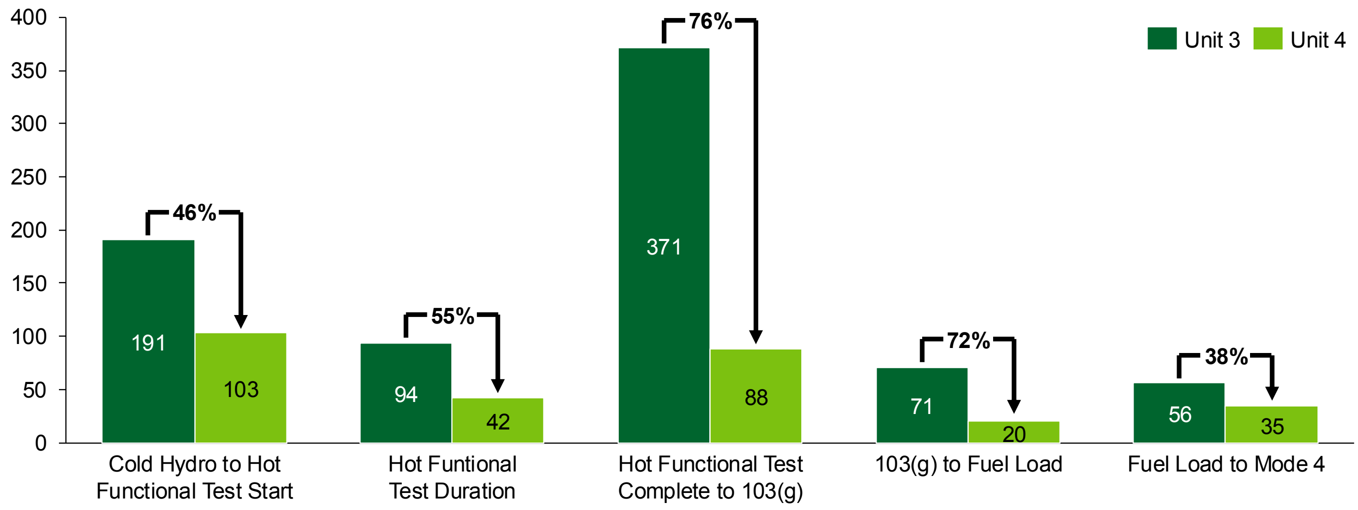
The construction of Vogtle Unit 4 has been reported to be ~30% more efficient and ~20% cheaper than Unit 3, noting it is challenging to disaggregate given shared infrastructure. Southern Company has identified drivers of efficiencies from Unit 3 to Unit 4:[135]

- Key testing milestones were completed ~38-76% faster between Units 3 and 4
- Engineering service requests dropped ~50% between Units 3 and 4
- Work packages, staffing plans, and schedules were improved based on observed level of effort and modified sequencing

- Modular construction methodology, material management plan, and electrical quality inspections were improved through experience
- Supply chain vendor proficiency increased or improved by switching to different vendors

Figure 40: Improvement in time to complete key milestones between Vogtle Units 3 and 4

Days between major milestones for Vogtle Units 3 and 4, days

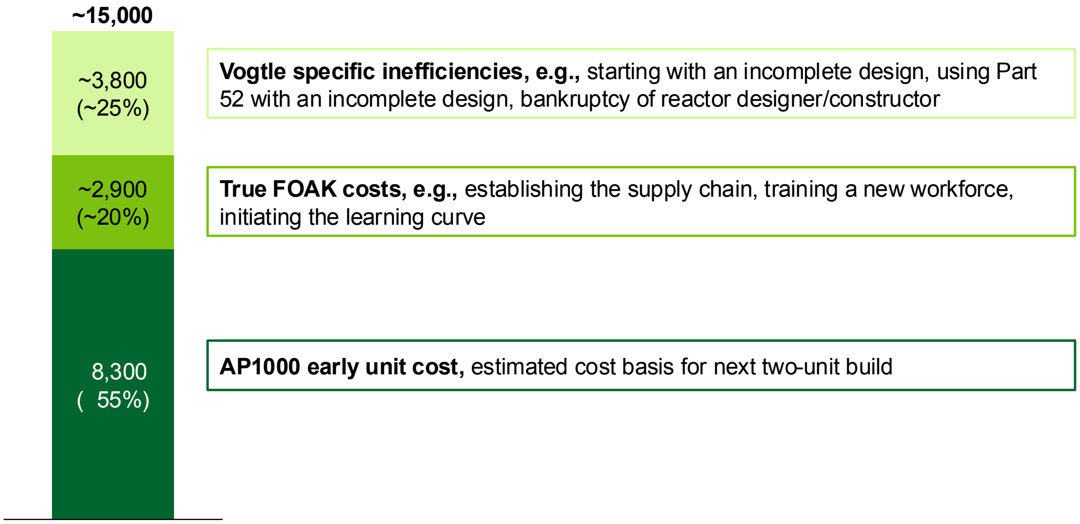


The cost of Vogtle Units 3 and 4 is not the correct anchor point for estimating additional AP1000s given costs that should not be incurred again.[136] Vogtle began construction with an incomplete design, an immature supply chain, and an untrained work force; the AP1000 design is now complete, there is now supply chain infrastructure, and Vogtle trained over ~30,000 workers. The costs can be broken down into three conceptual categories based on bottoms-up analysis (with next-AP1000 cost savings estimated for each):

- **True FOAK costs** that should not recur after the first AP1000 build (~$2,900/kw):
    - Newly trained workforce with nuclear construction experience (~$1,500/kw)
    - Maturity of supply chain and procurement practices (~$700/kw)
    - Initiation of the learning curve (~$700/kw)
- **Inefficiencies specific to Vogtle** that should not apply to additional AP1000s (~$3,800/kw):
    - Using Part 52 licensing without a complete design, which led to ~200 license amendment requests (~$1,600/kw)
    - Starting construction without a complete design or set of work packages, which led to change orders (~$1,000/kw)
    - Changing EPCs during construction given bankruptcy of contractor responsible for reactor design and construction (~$500/kw)
- **Base AP1000 unit cost** that should decrease with future two-unit builds (~$8,300/kw)
    - Further decreases for a four-unit build (~$800/kw)

Figure 41: Much of Vogtle's cost was true first-of-a-kind or project-specific cost that would be unlikely to recur with future AP1000s[137,138]

Vogtle Units 3 and 4 overnight capital cost categories, 2024 $/kW



Vogtle specific inefficiencies, e.g., starting with an incomplete design, using Part 52 with an incomplete design, bankruptcy of reactor designer/constructor

True FOAK costs, e.g., establishing the supply chain, training a new workforce, initiating the learning curve

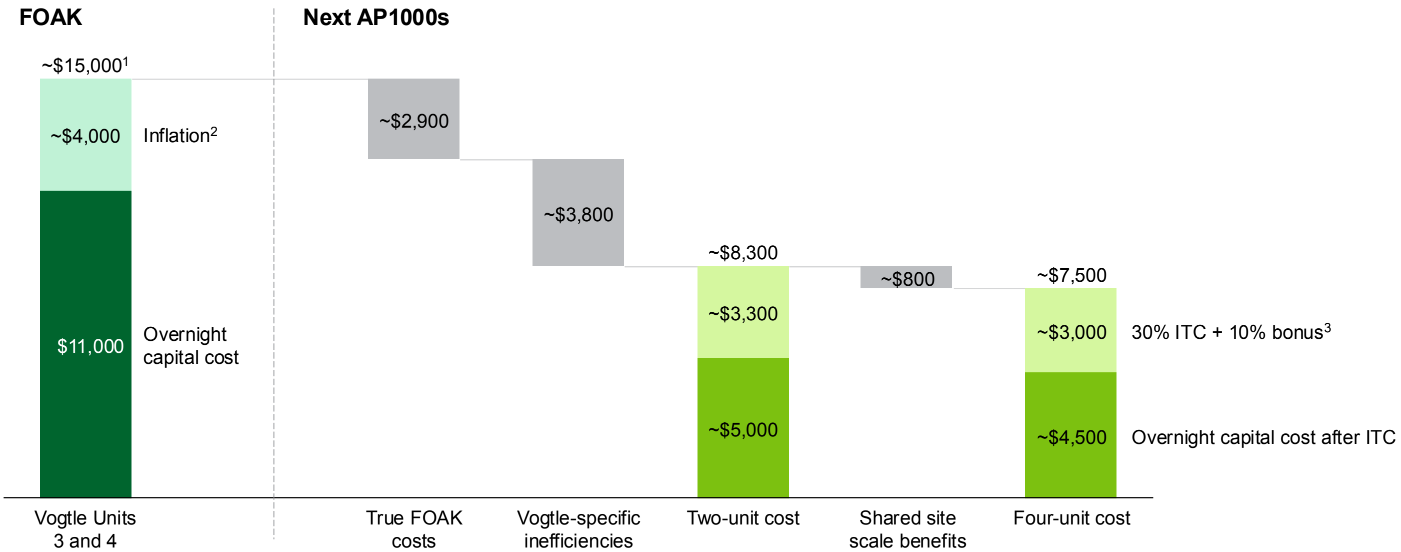
AP1000 early unit cost, estimated cost basis for next two-unit build

Additional AP1000s would benefit from using NRC's Part 52 now that the design is complete. Vogtle used Part 52 for an incomplete FOAK design, which required licensing iteration during construction and rework, causing delays and cost increases. FOAK designs may benefit from Part 50 to accommodate changes to the design during construction; NOAK designs may benefit from Part 52, which is designed to catalyze standardization; see 3.c.v for more.

The overnight capital cost of the next two-unit AP1000s is expected to be ~$8,300/kw. The OCC of Vogtle Units 3 and 4 was ~$11,000/kw; with inflation to 2024 dollars, ~$15,000/kW. Removing true FOAK costs and Vogtle-specific inefficiencies results in a pre-ITC OCC estimate of ~$8,300/kw; adding the ITC (with one adder) further reduces the costs by 40% to ~$5,000. For more on cost reduction drivers for additional AP1000s, see MIT's 2024 Total Cost Projection of Next AP1000.[139]

Figure 42: Projected cost reductions from Vogtle to the next AP1000s; note this is just the "next" AP1000s and NOAK costs are expected to approach ~$4,700/kw[140,141]

Overnight capital cost evolution from Vogtle to next AP1000s, 2024 $/kw



1. Vogtle OCC estimation and projections in 2024 USD from K. Shirvan, 2024 Total Cost Projection of Next AP1000; 2. Vogtle OCC calculated from VCM 30 (actual outlays over the course of the project) then adjusted for inflation to 2024 values; 3. ITC and bonuses are applied to "all-in" costs

Co-locating 4 reactors at the same site is expected to further reduce costs to ~$7,500/kw due to learning effects and economies of scale. Co-locating multiple reactors increases the probability of retaining a trained workforce throughout the construction cycle. This retained workforce also results in easier knowledge transfer and economies of scale from labor repeatability. The same owner (or consortium of owners) allows for shared IP and learnings. It also allows for lower costs coming from a more consistent order book for suppliers and vendors. Finally, there are additional cost savings from shared operations that can be achieved.

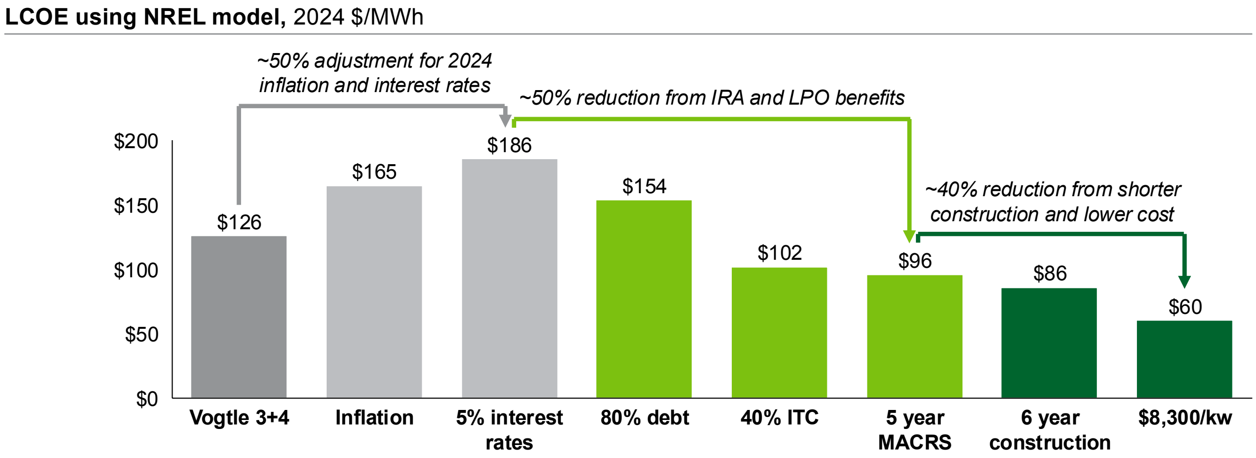
The next US AP1000s would also realize substantial cost reductions with IRA benefits:

- LPO loans of up to 80% of eligible project costs (Vogtle was at a lower percentage)
- ITC of 40% (assuming 30% base with one 10% adder)
- 5 year modified accelerated cost recovery system (MACRS)

Underscoring the impact of IRA benefits, even assuming that overnight costs and construction time do not decrease from Vogtle Units 3 and 4, the LCOE still drops almost 50%, below $100/MWh, even after increased interest rates and inflation. Using MIT's assumptions for reduced cost and schedule further reduces the projected LCOE to ~$60/MWh.

Figure 43: Even assuming Vogtle costs inflated to 2024, next AP1000 could be under $100/MWh with IRA benefits; closer to ~$60/MWh with cost reductions

LCOE using NREL model, 2024 $/MWh



	Vogtle 3+4	Inflation	5% interest rates	80% debt	40% ITC	5 year MACRS	6 year construction	$8,300/kw
Overnight capital cost	$11,000	$15,000	$15,000	$15,000	$15,000	$15,000	$15,000	$8,300
Construction time	11 years	11 years	11 years	11 years	11 years	11 years	6 years	6 years
Interest rate on debt	3.5%	3.5%	5%	5%	5%	5%	5%	5%
Debt fraction	60%	60%	60%	80%	80%	80%	80%	80%
Tax credit	PTC (old)	PTC (old)	PTC (old)	PTC (old)	40% ITC	40% ITC	40% ITC	40% ITC
Depreciation	15 years	15 years	15 years	15 years	15 years	5 years	5 years	5 years

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 scaling up the nuclear workforce, fuel supply chain, component supply chain, licensing capacity, testing capacity, and spent-fuel capacity.

Section 3.c.i: Workforce

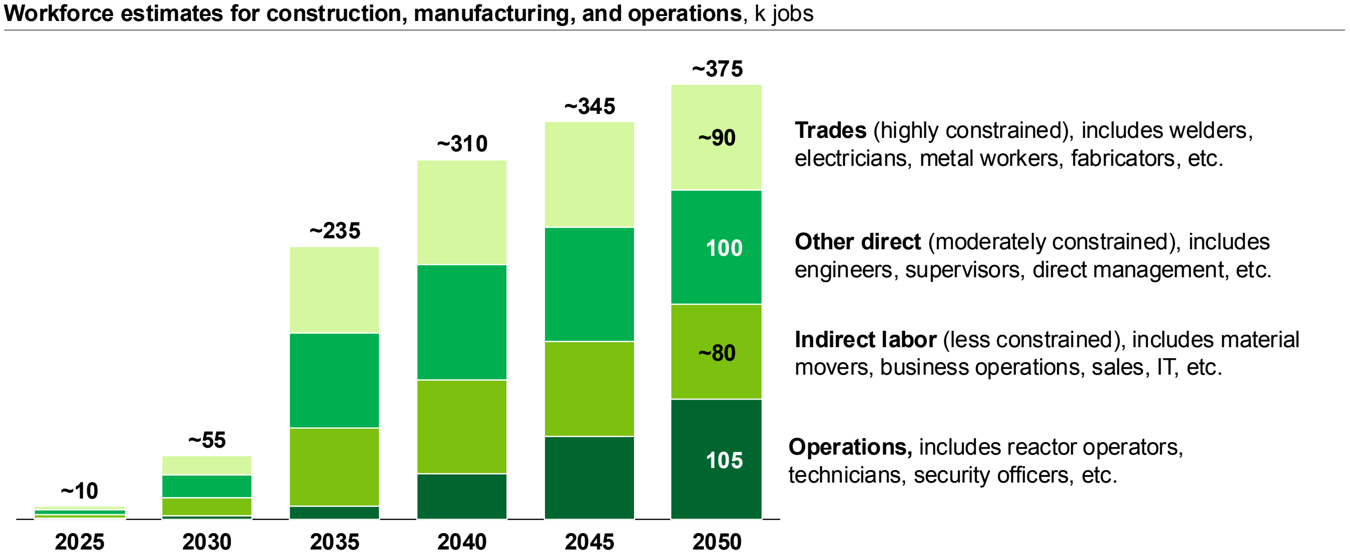
The US would need an additional ~375,000 workers with technical and non-technical backgrounds to support the deployment and operation of 200 GW of new nuclear by 2050; today it has ~100,000 supporting ~100 GW. ~100,000 would be required to operate the 200 GW of new reactors in 2050 and ~275,000 would be required for construction and manufacturing.

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, pipefitters, electricians, mechanics, carpenters); the workforce with this skill set is highly constrained today. Supply of other direct labor (e.g., mechanical, civil, electrical, and environmental 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.

Nuclear power plant construction is particularly reliant on skilled trades workers as typically over two-thirds of the cost and materials involved in building a nuclear unit are associated with the non-nuclear portions of the plant including underground utilities, civil construction, switchyards, and cooling infrastructure. 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.

Note these estimates are directional based on data and projections from the current operating fleet. Many reactor designers are intending to reduce the operators required, but it is not clear where the workers per GW ratio will land given counterbalancing forces of workforce efficiencies for simpler designs versus losing economies of scale on power output, e.g., microreactors will likely require many fewer staff per site than large reactors, but the reduced power output and number of units per site could impact the ratio.

Figure 44: Estimated construction, manufacturing, and operations labor force required for 200 GW by 2050[142]



NE will receive up to $100M to implement a new nuclear safety training program through the FY 2024 Consolidated Appropriations Act. The program will support nuclear safety curriculum development and training implementation through university-led partnerships with industry, national laboratories, technical colleges, community colleges, registered apprenticeship programs, and workforce training providers to help prepare the workforce needed for the existing fleet, but also for a build-out of new plants.

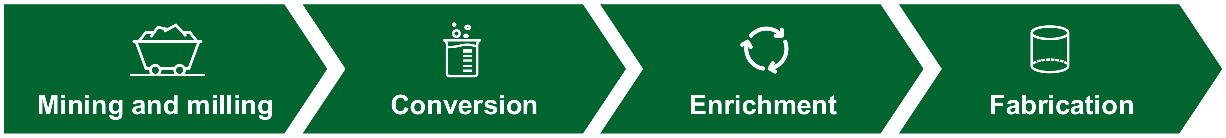
Government could support nuclear workforce needs by identifying, quantifying, and monitoring the most highly constrained trades and labor types, providing financial support to recruit and train new labor in these areas, or providing regional training and education programs to facilitate the development of necessary skills, possibly in collaboration with labor and industry. Collaborating with industry unions can also help ensure the nuclear workforce is trained with sufficient lead time for reactor construction and operation.

Industry should continue identifying and recruiting from other potential talent pools including through partnerships with 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 3.c.ii: Fuel supply chain

Tripling nuclear generation capacity by 2050 would require commensurately tripling the fuel supply chain capacity. The size of different fuel supply chain elements will depend on the mix of technologies deployed. Note the ranged estimates in this section are directional based on a technology mix that includes large LWRs and SMRs that use both LEU and HALEU.

Figure 45: The nuclear fuel supply chain has four key steps



Mining and milling	Conversion	Enrichment	Fabrication
Extract uranium ore and concentrate yellow cake uranium oxide (U_3O_8)	Convert U_3O_8 to uranium hexafluoride (UF_6)	Increase composition of U^{235} isotope to ~5% for LEU (or ~19.75% for HALEU)	Create fuel pellets

Mining and milling: The US would need access to ~55,000-75,000 MT per year of U_3O_8 mining/milling capacity to support 300 GW of nuclear capacity; it currently has ~2,000 MT of capacity and procured ~22,000 MT. Mining/milling of uranium will need to be increased from the US, allies, and partners to ensure a secure supply for the expected growth in nuclear capacity. The US had a recent peak of 2,263 MT U_3O_8 mined in 2014. To support an additional 200 GW, the US would need to expand mining/milling operations by an additional ~71,000 MT per year of U_3O_8.

Conversion: The US would need access to ~70,000-95,000 MT per year of UF_6 conversion capacity to support 300 GW of nuclear capacity; it currently has ~10,400 MT per year of UF_6 conversion capacity. As of January 2023, the Converdyn Metropolis Works facility is the only US facility capable of converting triuranium octoxide (U_3O_8) to uranium hexafluoride (UF_6) required for enrichment and has the capacity to produce ~10,400 MT per year. This facility had been shuttered since 2017 due to market conditions but restarted in July 2023.

Enrichment: The US would need access to ~45-55M SWU per year to support 300 GW of nuclear capacity; existing US uranium enrichment capability is ~4.4M SWU, while current US demand is ~15M SWU. SWU, separative work units, measure the amount of work required to enrich uranium. Current SWU demand for the US operating fleet is for LEU (enriched to ~5%); nearly all Gen IV reactor designs will require HALEU to operate (enriched to ~19.75%). As of 2024, American Centrifuge Operating (a subsidiary of Centrus) is operating the only US HALEU enrichment facility, producing up to 900 kg of HALEU per year. (the only commercial-scale HALEU enrichment capabilities are in Russia).

For many Gen IV reactors to succeed, a domestic supply of HALEU fuel would need to be developed. DOE is working to implement a strategy, consistent with Congressional authorizations and appropriations governing uranium production, which would support the creation of such a domestic supply of HALEU. The DOE is pursuing multiple pathways to produce HALEU through its HALEU Availability Program (Section 2001 of the Energy Act of 2020) and the Nuclear Fuel Security Initiative (Section 3131 of the FY2024 National Defense Authorization Act). Funding for these programs was provided by the Inflation Reduction Act ($700 million for the HALEU Availability Program) and the FY2024 Consolidated Appropriations Act ($2.72 billion for the Nuclear Fuel Security Act of 2023). In the long-term, sufficient HALEU demand is likely to drive commercial expansion without the need for government intervention. Implementing the HALEU Availability Program and Nuclear Fuel Security Initiative, which should include making small quantities of HALEU available in the near term from existing but limited quantities of HALEU from DOE inventories and working with the private sector in the long term to establish a commercial, domestic HALEU production and supply chain. The DOE continues to facilitate 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.

Fabrication: The US would need to access ~6,000-8,000 MTU per year to support 300 GW of nuclear capacity; it currently has ~4,200 MT per year of uranium oxide (~3,700 MTU). In the US, Westinghouse, Framatome, and Global Nuclear Fuel-Americas fabricate fuel domestically and export fuel internationally. It is projected that an additional ~2,500 MTU 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 oxide fuels 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. TerraPower has partnered with GNF to develop metallic fuel required for Natrium reactor deployment, but there is no information on production capacities of such a facility. X-energy has proposed the construction of a TRISO-X facility, which is expected to come online as early as 2025 in Oak Ridge, Tennessee. Its initial capacity is expected to be 8 MTU/year with capacity expansion expected in the early 2030s to 16 MTU/year. To achieve commercial liftoff for Gen IV reactors, fuel fabrication facilities capable of supporting the fuel for both “first core load” and subsequent reloads are required.

International engagement: The US continues to lead a five-nation group (Sapporo 5) that has committed to invest a combined $4.2B in enrichment and conversion services. On the margins of COP28 the United Kingdom, France, United States, Japan, and Canada announced their intent to invest a combined $4.2B. Quickly following this commitment, the French mobilized ~$1.8B, the UK pledged ~$383M, and the US appropriated $3.42B to support the expansion of a secure nuclear fuel supply chain. The US will continue to work with the Sapporo 5 to expand the membership and identify areas of collaboration to support a stable supply of fuel. Unlocking bottlenecks in the supply chain will continue to be a focus of this initiative including conversion and deconversion which is largely based in Canada, France, and the United States in relation to the Sapporo 5 membership.

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.

Gen III+ reactors operate similarly to the existing US nuclear fleet, which are also LWRs. While the supply chain may not be of sufficient capacity as of 2024 to support expansion of Gen III+ reactors, these designs are less of a departure from existing technology and experience compared to Gen IV, and could enable faster scale-up of supply chain support for deployment.

Gen IV reactors operate in different environments (e.g., high-temperature gas, molten salt, liquid sodium). Even with these changes, many of the primary side component requirements are similar to Gen III+ (e.g., canned pumps and large pressure vessels) and use similar materials and alloys. Unique aspects of these Gen IV designs, such as fuel handling systems and equipment, could be a more substantial challenge for supply chain build-out to support wide, multi-unit deployments. The secondary side of Gen IV designs would likely operate in a manner similar to Gen III+ reactors and is less of a supply chain concern.

A common concern of the US nuclear supply chain for all reactor design generations involves manufacturing capacity and capability for large components. As of 2024, there is limited domestic capacity for making nuclear grade forgings and the maximum forging size capability supports only smaller designs. Domestic forging capability to support material needs for larger reactors, such as the AP1000, does not yet exist domestically and currently needs to be sourced from international partners. Once raw material forgings are obtained, further domestic supply chain limitations exist for machining, fabrication, and assembling these forgings into final components for installation in a reactor plant.

With the capacity of domestic vendors that meet the quality requirements of commercial nuclear reactors (N-stamp certified), the US will be strained to provide support for adding 3 GW per year of new nuclear power to the grid. The remaining gap of ~10 GW per year of large forging capacity that would be required to achieve 200 GW of advanced nuclear by 2050 requires thoughtful consideration and actions to close this gap. The process for obtaining an N-stamp can take over a year and cost hundreds of thousands of dollars. Investments in and expansion of the component supply chain may occur with guaranteed offtake agreements and industry growth, and additional actions can accelerate this expansion. In the long-term, the US should build this capacity to ensure energy security.

Figure 46: High level overview of nuclear component supply chain

Step	Supply chain segments to meet the demand of the final product	Significant domestic suppliers	Cost competitive among US suppliers	Cost competitive between US suppliers vs. global suppliers	Is foreign supply source significant secure?	Likely best course of action
Mining and 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, Tungsten, Vanadium, Zirconium	Yes	Yes	Yes	Yes	**Expand existing US capability and leverage intl. markets**
Processing	Steel	Yes	Yes	Yes	N/A	**Expand existing US capability**
	Concrete	Yes	Yes	Yes	N/A	**Expand existing US capability**
	Other	Yes	Yes	Yes	N/A	**N/A**
Component	Large component forging and manufacturing	No	?	?	Yes	**Expand existing US capability and leverage intl. markets**
	Other component forging and manufacturing	Yes	Yes	Yes	Yes	**Expand existing US capability**
Assembly	Module assembly	Limited	N/A	N/A	May be	**Build US capability**

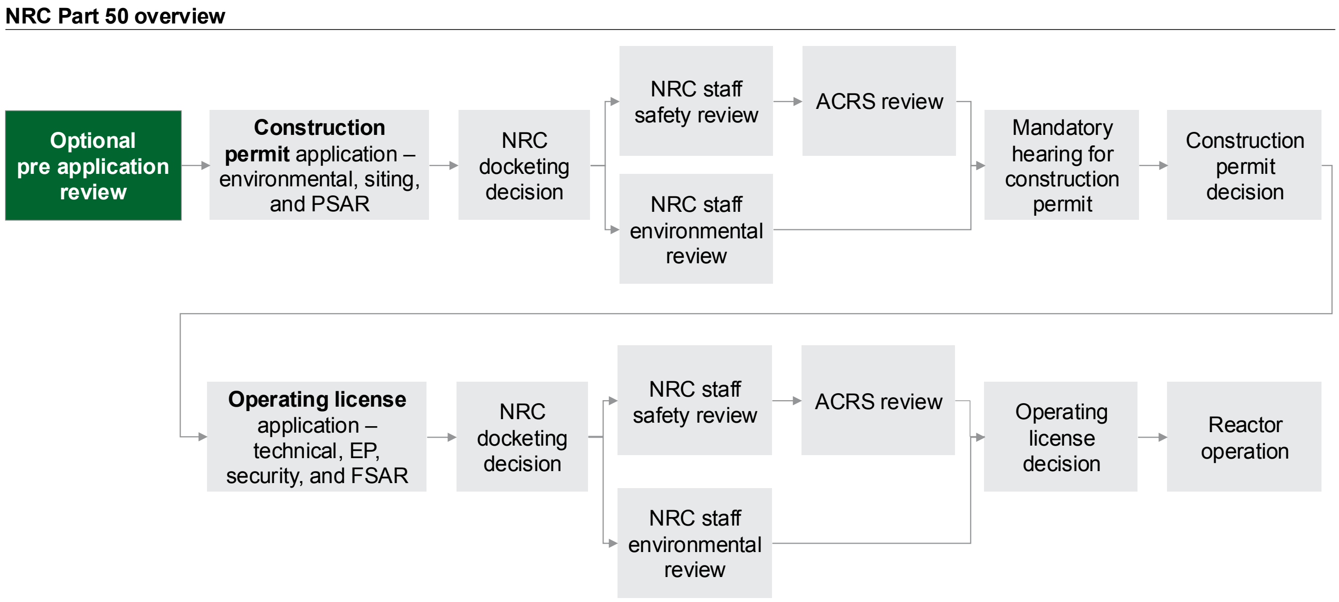
Some of the materials used to construct nuclear reactors have been identified as critical minerals on the US Geological Survey Critical Minerals list;[143] of particular concern are Hafnium, Niobium, Yttrium, Chromium, and Nickel.[144] The Advanced Manufacturing Production Credit under Section 48X of the IRA supports domestic production of these critical minerals.

Section 3.c.iv: Licensing

The NRC has two licensing pathways: 10 CFR 50 (Part 50) and 10 CFR 52 (Part 52). Part 50 is a two-step process, while Part 52 is a combined license. Vogtle Units 3 and 4 were the first reactors licensed under Part 52; all other operating US nuclear power plants were licensed under Part 50.

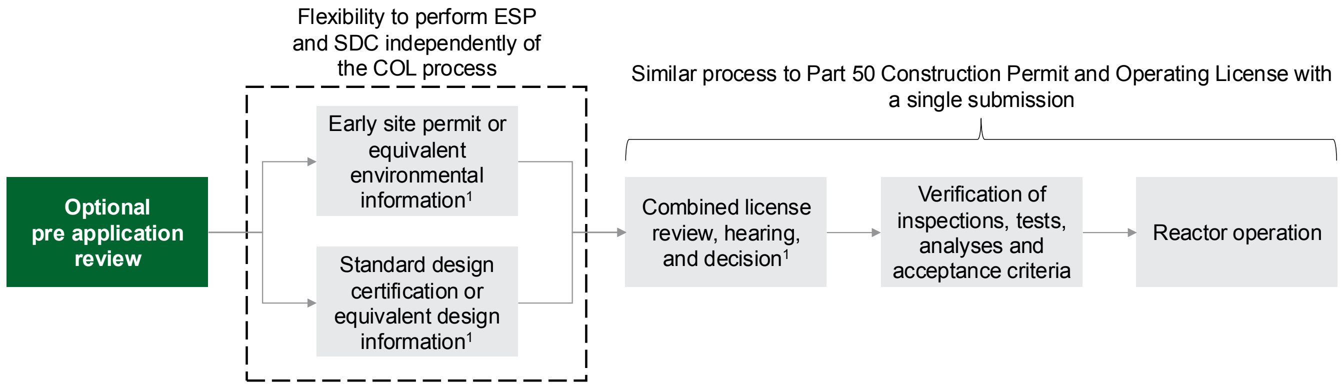
The Part 50 two-step process separates the construction permit from the operating license. The reviews for construction permits and operating licenses have traditionally required several years to complete, as an operating license cannot be issued until construction of a facility has been substantially completed. Recently, NRC staff completed the review of the Kairos Hermes construction permit application in ~2 years. Lessons learned from this project should be consulted for future reviews.

Figure 47: NRC Part 50 overview[145,146,147,148,149]



The newer Part 52 Combined License (COL) process authorizes both construction and operation when issued and was developed to address issues in the Part 50 process. It combines the entire process into a single step with two optional processes, Early Site Permitting (ESP) and Standard Design Certification (SDC), that can expedite the COL review and approval. An ESP can also allow non-safety site preparation activities before a COL is issued. The COL, submitted with approved ESP and SDC, could have a streamlined timeline of 2-3 years. The ESP and SDC process can begin significantly before the start of planned construction, and early communication into this process is highly encouraged.

Figure 48: NRC Part 52 overview[150,151,152,153,154]

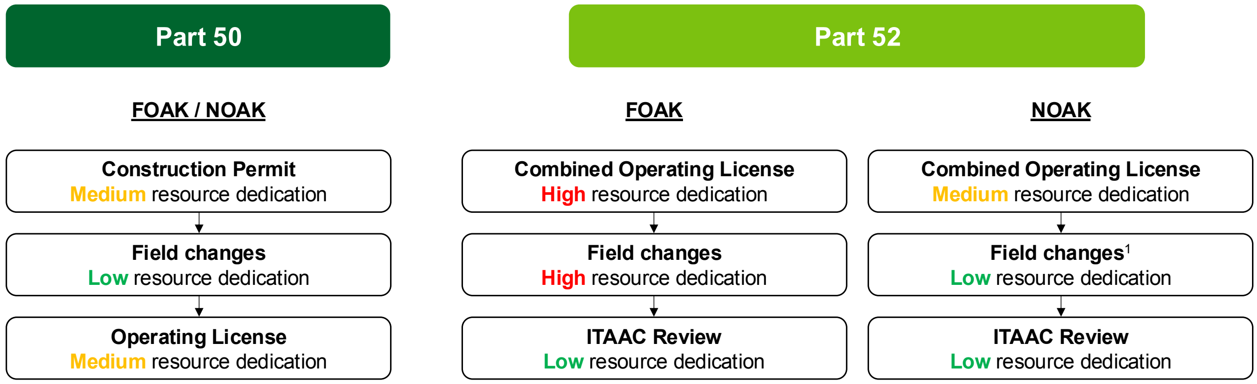


Nuclear projects should consider the maturity of the design and the benefits of NRC's Part 50 versus Part 52 when selecting an NRC licensing process to follow. The two-step Part 50 licensing process allows for ongoing design refinement during the review of a construction permit and construction of the facility. The Part 52 licensing process requires that a final design be submitted as part of a COL application.

FOAK designs may benefit from Part 50 to accommodate changes to the design during construction. A benefit of using Part 50 for FOAK is construction and procurement can begin under the construction permit, while the design details are developed and supporting data is procured during the operating license review phase. This can expedite FOAK deployment as a proof of concept, after which standardization can be leveraged to reduce licensing and construction time.

NOAK designs may benefit from Part 52, which is designed to catalyze standardization. Part 52 is likely to be most effective when the design is finalized and not subject to change. Part 52 requires a robust Field Change Request process to maintain the combined construction and operating license. This could result in costly construction delays if design changes re-initiate the COL review process, similar to what was experienced at Vogtle**.**

Figure 49: FOAK designs may be better suited to Part 50, while NOAK designs may be better suited to Part 52[155]



FOAK designs could benefit from Part 50: Part 50 is more "revision-friendly" for designs that have not yet been constructed

NOAK designs could benefit from Part 52: NOAK designs could experience streamlined licensing; FOAK designs, could have difficult-to-construct design features "locked in"

1 Resource dedication could be significant if changes are required, however, the probability of design changes during construction are lower for NOAK

The NRC is developing Part 53 as part of its efforts to modernize and optimize licensing reviews of advanced reactors. The draft proposed rule would provide a technology-inclusive, risk-informed, and performance-based licensing framework for new and advanced reactors consistent with the Nuclear Energy Innovation and Modernization Act. The Commission approved, in part, the NRC staff's draft proposed rule, and the staff is preparing to publish the proposed rule for public comment.

The NRC is also amending its Part 50 and Part 52 regulatory frameworks for new technologies, including the recent publication of new alternative emergency preparedness requirements.[156] This final rule provides performance-based, technology-inclusive, risk-informed, and consequence-oriented emergency preparedness requirements that acknowledge technological advancements in small modular reactors and other new technologies.

The NRC is optimizing the established construction oversight framework to ensure flexibility and responsiveness to advanced reactor technologies; the Advanced Reactor Construction Oversight Program (ARCOP)[157] is being built around seven guiding principles (risk-informed, performance-based, technology-inclusive, scalable, informed, comprehensive, innovative) to ensure that the program is appropriately scaled to the unique features of advanced reactors, including flexibility for NOAK deployment.

In March 2024, the NRC issued guidance to facilitate the licensing of non-LWR designs. The new guidance emphasizes aspects of design and operation that most directly affect safety and is expected to streamline the review of non-LWR applications and reduce the regulatory uncertainty for Gen IV designs. This guidance includes the NRC's endorsement of an industry-led Technology Inclusive Content of Application Project (TICAP), and interim staff guidance comprising the NRC's Advanced Reactor Content of Application Project (ARCAP).

Given microreactor designers are considering factory fabrication to deploy multiple units of a standardized design, the NRC is proactively engaging with stakeholders and developing licensing strategies to support the effective and timely licensing of microreactors of a standardized design.

To support efficient environmental reviews, the NRC has drafted the Advanced Nuclear Reactor Generic Environmental Impact Statement (GEIS).[158] This draft GEIS uses a technology-neutral regulatory framework and performance-based values and assumptions to determine which environmental impacts could result in the same (generic) impact for any nuclear reactor facility that fits within the GEIS parameters (versus which would require a project-specific analysis).

Licensing resourcing and processes would need a combination of increased efficiency (while ensuring effectiveness) and improved resource planning, budgeting and performance management 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.

The NRC has published generic licensing timelines for new reactors based on historical data.[159] More recently, the NRC staff completed its safety review of the Kairos Hermes 1 construction permit application in 18 months.[160] To consistently achieve this licensing efficiency, the NRC needs high quality applications and may need 10-12 staff members per core review team.

To achieve 13 GW per year, 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 ~500 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.

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. 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.

The ADVANCE Act was signed into law in July 2024.[161] It provides incentives for new nuclear technologies, such as reduced licensing fees and prize awards for deploying such technologies. It directs the NRC to update its mission statement to include that licensing and regulation be efficient and not unnecessarily limit the benefits and civilian use of nuclear energy. The Act requires the NRC to complete reviews of COL applications for new reactors at existing or adjacent sites on an expedited schedule. It also directs the NRC to develop performance-based and risk-informed guidance and strategies for licensing and regulating microreactors.

Possible future actions include:

- Implementing licensing standardization, simplification, digitization, and optimization; all can increase throughput and reduce regulatory resource burdens[xv]
- Ensuring Part 53 results in further standardization of risk-informed licensing criteria, safety-related determinations, and license execution allowances and expedient remediation pathways
- Defining clearly 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

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[xv] 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.

The NRC staff continues to prioritize advanced reactor readiness activities and proactively seeks input from potential applicants regarding their plans for new reactor licensing activities. Robust pre-application engagement with prospective applicants allows for the timely identification and resolution of technical and policy issues and assists the NRC in determining resource and budget needs to support efficient reviews. The NRC is employing several strategies to increase the effectiveness of its reviews, including using core and interdisciplinary review teams, holding early engagement with applicants, conducting pre-application readiness assessments, streamlining environmental review processes, and leveraging lessons learned.

Applicants should commit to pre-licensing activities such as high-quality probabilistic risk assessment engagement 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 should 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 3.c.v: Testing

The US does not have fast-spectrum reactor testing capability to support Gen IV reactors. Testing requirements for Gen III+ designs are relatively modest given their similarities in design and operating conditions to other operating LWRs. However, Gen IV reactor designs employ hardened thermal spectrum to fast spectrum neutrons for power generation that cannot be replicated in existing domestic test reactors. Limited historical data in prototypic conditions will not be sufficient to enable further advancements for Gen IV reactor fuels, materials, and operating capabilities. Access to irradiation testing in prototypic operating conditions will be a key enabler for the United States to be a global leader in advanced reactor technology.

The US had planned on building a fast test reactor, the Versatile Test Reactor; however, funding was eliminated in 2022. The US had extensive fast-spectrum testing capabilities between 1951 and 1994, but there has been no domestic capability for fast-spectrum testing since 1994. There are only a few fast-neutron test reactors globally, and the most extensive capabilities reside in Russia.

To accelerate deployment of Gen IV reactors, the US would need to invest in a fast-test reactor or align with other nations to use their test reactors. 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. 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.

Section 3.c.vi: Spent nuclear fuel

Today, commercial spent nuclear fuel (SNF) from LWRs—currently managed/stored primarily by the nuclear utilities—is safely stored in highly regulated and monitored facilities. Fuel is a solid when it goes into the reactor and a solid when it comes out as SNF. Commercial SNF accumulates 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 currently operating ISFSIs except for one are located on operating or decommissioned reactor sites where the SNF was generated. The NRC licenses dry cask storage systems for 40 years and allows license renewals for 40 additional years.[162] There are over 70 storage facilities at or near a nuclear power plant site in 35 states.

If all SNF generated by US commercial reactors since the 1950s were to be stacked together, it could fit on a single football field at a depth of less than 10 yards, not including shielded packaging. In total, US commercial reactors have generated more than 90,000 metric tons of SNF since the 1950s.[163] The volume of the SNF assemblies is quite small considering the amount of energy they produced. 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.

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 SNF can be moved to final disposal. It will allow for the removal of SNF from sites where the material is currently stored (including 20 sites that no longer have any operating nuclear reactors) 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 FY21-24, Congress appropriated funds to DOE for federal interim storage activities, including preliminary work towards the development of a federal consolidated interim storage facility.[164] Also, in 2021, DOE issued a Request for Information on Using Consent-based Siting to Identify Sites for Interim Storage of Spent Nuclear Fuel and received 225 submissions in response.[165] In 2022, DOE issued a funding opportunity announcement to provide resources for communities interested in learning more about consent-based siting, management of spent nuclear fuel, and interim storage facility siting considerations.[166] In 2023, DOE issued an updated Consent-Based Siting Process for Federal Consolidated Interim Storage of Spent Nuclear Fuel[167] and placed 12 financial assistance awards with 12 Consent-Based Siting Consortia to support the Department's efforts to facilitate inclusive community engagement and elicit public feedback on consent-based siting.[168,169] In 2024, DOE determined that a federal consolidated interim storage facility is needed to help manage the Nation's commercial spent nuclear fuel and approved Critical Decision-0 (CD-0) for DOE's Federal Consolidated Interim Storage Facility Project.[170] CD-0 is the first step of a process that DOE uses to manage capital asset projects and determines a mission need for the agency.

DOE is committed to a consent-based approach to siting federal storage and disposal facilities and a waste management system that enables broad participation. 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 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.

Permanent disposal in a mined deep geologic repository (DGR) is the foremost alternative for SNF and high-level radioactive waste disposition. Five decades of research, development, and demonstration in multiple countries supports the feasibility and safety of disposal of SNF and high-level radioactive waste in DGRs. Many countries have decided to dispose of SNF 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.[172] In 1987, Congress designated Yucca Mountain as the only site to be evaluated for a DGR; however, Congress ceased funding the Yucca Mountain Project in 2010. DOE's policy position remains that a repository at Yucca Mountain is an unworkable option due to lack of public support.

The US has already implemented a DGR for long-lived transuranic waste from defense activities (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 US,[173] cleaning up 22 generator sites nationwide.

The US should continue efforts to identify sites and develop facilities for consolidated interim storage and permanent disposal of SNF. New legislation, however, would be required to build and operate a federal consolidated interim storage facility and pursue siting for a new federal DGR. Until new legislation is passed, DOE should continue undertaking steps towards development of one or more federal consolidated interim-storage facilities including, but not limited to, engagement in a consent-based siting process and development of facility design and operating plans. Construction and operation of a federal consolidated interim storage facility are subject to specific constraints in existing law 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 using DOE's newly developed, consent-based process for siting.[174]
- Once authorized, focus on consent-based siting for one or more DGRs as well as federal consolidated interim storage facilities.
- Once authorized, demonstrate a continued Federal commitment to develop one or more DGRs by preparing and issuing for public comment a draft plan for the consent-based siting and phased development and operation of a repository.[175]

Chapter 4: Barriers to liftoff and potential solutions

Barriers to liftoff	Potential solutions
Market power prices do not consistently compensate nuclear for the value it provides.	System modeling efforts consistently show the cost saving benefits of clean firm sources like nuclear in a low-carbon energy future Innovative power purchasing is a key tool for large offtakers to catalyze new generation States or other entities could create clean firm standards A standard value for clean firm power could help decision makers account for nuclear's decarbonization benefits Broader electricity market reforms could incentivize investment in new clean firm assets
Many potential customers cite cost or cost overrun risk as the primary barrier to committing to new nuclear projects.	Sharing costs to lower barriers to entry, either among private sector companies or with the government Sharing and insuring costs to provide resiliency for project completion Insuring resiliency through different cost scenarios with credit tools Ensuring on-budget delivery by better estimating costs and implementing best practices
The US lacks nuclear and megaproject delivery infrastructure.	The integrated project delivery (IPD) model aligns incentives between owners and contractors to deliver projects on-time and on-budget Funding constructability research could target the drivers of cost overruns and improve project delivery

Section 4.a.i: Quantifying and communicating value

Market power prices do not consistently compensate nuclear for the value it provides. 13 US nuclear reactors closed between 2013 and 2022 despite having years remaining in their operating licenses, largely because there was little anticipated load growth and the operating costs of natural gas were cheaper with little to no standard accounting for the impact of greenhouse gas (GHG) emissions.[184] In 2024, there are planned and potential restarts of closed reactors resulting from dramatic load growth projections and the willingness of some large offtakers to pay more for clean energy, implicitly putting a price on carbon.

Current short-term electricity market incentives can lead to long-term inefficiencies. Competitive wholesale markets with short-term price setting that does not account for GHG emissions can make large-scale investment in clean firm generation challenging; it is not clear they provide incentives to support large scale investment in new clean firm generation necessary in 2024.

Traditional decision frameworks and tools do not adequately value the full contribution of nuclear to the electricity system and to future ratepayers. Current approaches often undervalue nuclear's benefits from decarbonization, reliability, resiliency, and asset life. Integrated resource plans (IRPs) with time horizons of ~15-20 years are evolving to better optimize the cost of low carbon systems, but many still do not account for an explicit cost of carbon or willingness of customers to pay for clean power. Assumptions for nuclear construction costs may be overestimated given limited reference points overweighted by recent experience. Nuclear, with 80 years of operations, provides low priced power for future ratepayers for decades (potentially ~50 years) after construction has been paid off (typically ~30 years); however, most frameworks optimize for current ratepayers. For example, Vogtle Units 1 and 2 were expensive in the 1980s, and now provide clean, affordable power for ratepayers today and could continue to do so for another 40+ years with subsequent license renewals. Similarly, Vogtle Units 3 and 4 are a down payment today on assets that could produce clean firm power into the 22nd century.

LCOE does not capture the full benefits of nuclear as a clean firm resource, does not include delivery system costs such as interconnection and transmission, and does not include other system costs to balance or "firm" the system during times when variable resources are not producing; see section 2.c.iii for more. While system-level analyses show a more complete picture, it can be difficult for individual project decision makers to make comparisons on an asset-by-asset basis.

Nuclear has long time horizons that can be challenging for companies or investors under pressure to produce quarterly or annual returns. Nuclear projects not only have multi-year planning and construction timelines, but they also have operations and value that extend decades past the capitalization period. After repayment of construction costs, even when accounting for major maintenance capital expenditures, the operating costs for nuclear remain affordable and predictable for decades. Federal and state governments and utility commissions have a role to play in ensuring that these multi-generational infrastructure benefits to future ratepayers are captured.

System modeling efforts consistently show the cost saving benefits of clean firm sources like nuclear in a low-carbon energy future. Including nuclear and other clean firm generation allows systems to build less variable renewable capacity, storage, and transmission; see 2.a.ii for more. To better measure system costs and benefits, quantitative frameworks that capture the marginal impact of individual investments on the system could inform better decisions (versus LCOE).

Innovative power purchasing is a key tool for large offtakers to catalyze new generation. Traditional power purchasing arrangements between utilities and large commercial customers are generally insufficient to spur investment in clean firm resources. Clean transition tariffs are essentially "blended rates" that allow customers to purchase existing power and invest in future development of clean firm generation.[xvi] These new rate structures allow for higher payments from customers who want to match clean energy generation with customer load and invest in clean firm sources like nuclear.

Clean firm standards could help drive nuclear deployment. Policies could require that a specified percentage (e.g., 20-40%) of a utility's generation portfolio be clean firm assets. Renewable portfolio standards helped increase wind and solar deployment, diversifying the supply of electrical generation, promoting more domestic energy production and domestic supply-chains, and encouraging local economic development. Similarly, clean firm standards have driven project development and committed offtake: a ruling by the California Public Utilities Commission mandating the procurement of clean firm power encouraged the signing of new conventional and next-generation geothermal power purchase agreements.[185]

A standard value for clean firm power could help decision makers account for nuclear's decarbonization and reliability benefits, e.g., by increasing its competitiveness with fossil sources in integrated resource planning. System modeling by Pacific Northwest National Laboratory found that $100 per ton of carbon dioxide increased the deployment of new nuclear and mostly decarbonized the electricity sector.[186]

[xvi] In May 2024, Duke Energy, Amazon, Google, Microsoft, and Nucor announced agreements to develop new rate structures. In June 2024, Google and NV Energy asked Nevada regulators for permission to use a clean transition tariff to support new geothermal generation.

Broader electricity market reforms could incentivize investment in new clean firm assets, e.g., longer term capacity markets and other revenue sources for clean firm generation. Capturing and quantifying the full system and multi-generational benefits of nuclear assets is a complex challenge; this is only intended as a starter list and will require further innovation.

In 2024, a growing majority of Americans now support new nuclear.[187] To build further support, industry and government should continue to engage with communities and provide education communicating nuclear's value proposition and safety record.

Section 4.a.ii: Sharing and allocating costs and risks

Many potential customers cite cost or cost overrun risk as the primary barrier to committing to new nuclear projects. As discussed in 4.a.i, it is essential to capture the full value of nuclear when weighing costs, but even assuming a fair accounting of benefits, the absolute amount of capital required creates a barrier to entry for all but the very largest companies. In addition to the dollar amount, the historic and perceived unpredictability of nuclear construction costs have contributed to emotionally charged fears of cost overruns.

To realize economies of scale and get to NOAK costs, at least 5-10 reactors of one standardized design need to be built. However, 5-10 reactors generate so much power and require so much capital investment that it is difficult for any one company to do alone. Additionally, the market has not yet down-selected and standardized reactors, making it challenging to aggregate enough orders of a single design.

To structure solutions, it is helpful to disaggregate three different avenues for managing costs and risks:

- **Sharing** costs and benefits across multiple projects and participants
- **Insuring** resiliency through cost scenarios
- **Ensuring** project management best practices

Figure 50: Nuclear projects have a variety of tools to share and reduce costs and risks

	Sharing costs across projects and participants	Insuring resiliency through cost scenarios	Ensuring project management best practices
Function	Lowers barrier to entry and facilitates critical mass of orders	Defines cost distributions for project resiliency	Promotes on time and on budget delivery
Cost impact	Shares expected costs	Shares unexpected costs	Reduces unexpected costs
Examples	• Consortium committing to 5-10 (or more) reactors • Financial assistance, e.g., grants • Government build and ownership	• Completion or debt guarantees • Contingent equity • Contingent debt • Flexible PPA prices	• Mature cost estimates • Construction best practices incorporating lessons from Vogtle • FOAK to NOAK cost levers
	• Investment tax credit or overrun insurance (*both sharing and insuring*) • Government-enabled offtake certainty (*both sharing and insuring*)		

A common question is who should bear overrun costs. Cost overrun is not a monolith: costs are divisible for sharing among stakeholders who are able to manage project risks and who stand to benefit from project completion. Consortium arrangements and partnerships can reduce the financial exposure of any individual participant.

There are four key questions to consider when determining how to allocate risks in a construction contract:[188]

- Which party can best foresee the risk?
- Which party can best control the risk (and/or its associated consequences)?
- Which party can best bear that risk?
- Which party ultimately most benefits or suffers when the risk eventuates?

For new nuclear projects, large offtakers including tech companies who need power to fuel the growth of their operations may stand the most to lose if projects are not completed. Given their size, they may also be well positioned to bear risks. However, constructors and project managers (who have less to gain or lose and are less well capitalized) may be the best positioned to foresee and control the project risks.

Construction risks ultimately reside with the owner. Assigning risk to other parties is a form of risk management, not risk avoidance. Attempting to shed risk to other parties can create a false sense of security for the owner and corrodes project cohesion and performance. There is no scenario where a contractor or subcontractor fails and the project succeeds.[189]

Sharing costs to lower barriers to entry, either among private sector companies or with the government:

- **Consortium committing to 5-10 (or more) reactors:** A group of companies, e.g., utilities and large offtakers, could enter a cost sharing agreement to pool demand for the same reactor design, 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 scale the supply chain. See section 3.a.i for more.
- **Financial assistance, e.g., 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. Ensuring that first-movers receive the best deal could induce customers to commit earlier.
- **Government build and ownership**: The government could construct and operate nuclear power plants directly. SMRs and microreactors could be well-suited for providing resilient and reliable off-grid power directly to military installations and other national security infrastructure.

Sharing and insuring costs to provide resiliency for project completion:

- **Cost overrun insurance: note that the ITC already provides "cost overrun insurance" given it covers 30-50% of total capital cost, regardless of initial budget:** 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 US utilities and other customers.
- **Government-enabled offtake 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[xvii]). In areas with a utility service monopoly for the government site, a government entity could purchase power indirectly through the utility service

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[xvii] The USG is limited to a 10 year term for most utility contracts. See 40 U.S.C. § 501(b).

monopoly if the service monopoly agreed to enter into a power purchase agreement with the project owner for the government.[xviii] 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.[xix]

Insuring resiliency through different cost scenarios with credit tools:

- **Guarantees:** Completion guarantees or debt guarantees (full or partial) can ensure alignment of interests of the project owner, investors, lenders, offtakers, and other parties.
- **Contingent equity:** The commitment of additional funds to cover unexpected costs is another tool for ensuring project completion and could be provided by the project owner, investors, offtakers, or other parties.
- **Contingent debt:** LPO loans can be structured with substantial contingency that, when paired with contingent equity, can provide flexible financing for project completion through cost increases. The contingent loan amount could be drawn on only as needed.
- **Power price agreements:** Long term PPAs with attractive pricing help support debt financing and potentially provide a cushion for cost overruns. Pre-payment on PPAs can help provide upfront construction capital as a form of offtaker equity.
- **Contract provisions:** Liquidated damages, price caps, warranties, and guarantees from suppliers can help align interests with the project.

Ensuring on-budget delivery by better estimating costs and implementing best practices:

- **Mature cost estimates are essential for delivering projects on budget.** One of the biggest failure points for megaprojects is reliance on immature point estimates. *How Big Things Get Done* highlights that framing the problem as "overruns" of money and time prevents considering that in many cases, "the real source of the problem is not overruns at all; it is underestimation." According to the Association for the Advancement of Cost Engineering standards for nuclear construction, a Class 5 cost estimate has an expected accuracy high range of +60% to +200% over the point estimate; the Class 1 range is only +6% to +30%.[190] Too often, nuclear projects have begun with immature estimates, so large departures from the point estimate should not be unexpected. Quality cost estimates require time and money, but yield more predictable results.
- **For construction best practices, see Section 3.b.i Lessons learned from Vogtle:**
  - Complete the design before starting construction.
  - Conduct a detailed "constructability review" of the design to ensure the project is executed in the most efficient manner.
  - Create a resource-loaded, achievable, and detailed Integrated Project Schedule and project-controls processes to support execution.
  - Ensure quality assurance (QA) / quality control (QC) and documentation standards are clear and consistent.
  - 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.
  - Invest early and heavily in technical and process training for workforce.

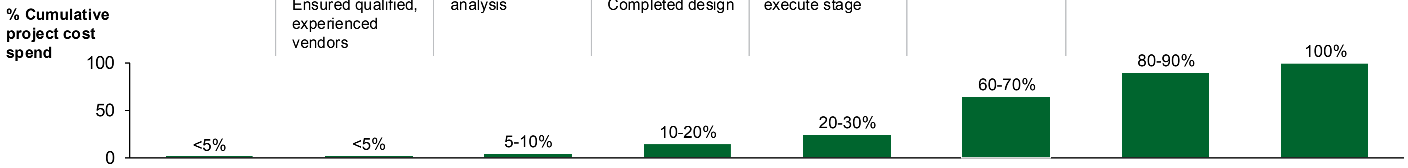
[xviii] See 40 U.S.C. § 591.

[xix] 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.

- For FOAK to NOAK cost levers, see Section 2.c.ii FOAK to NOAK:
  - Down-select and standardize reactor designs to minimize and streamline licensing.
  - Invest heavily in the project schedule to minimize unnecessary work, workspace congestion, and delays.
  - Maintain sufficient book order and minimize lag between projects to retain experience and increase productivity of construction management, crafts and trades, and suppliers.
  - Site multiple reactors at the same location to share site preparation costs, construction workforce, and shorten permitting timelines.
  - Shift from field construction to factory to enable automation, advanced manufacturing, and increase productivity.
  - Modularize and mass produce components to gain economies of scale.
  - Standardize non-safety components to leverage existing supply chains.

Figure 51: Best practices to consider implementing prior to major project milestones

Stage	**Apply for NRC licensing**	**Begin procurement**	**Contract with EPC**	**Start of construction**	**First nuclear concrete**	**Set reactor pressure vessel**	**Complete nuclear and turbine islands**	**Commissioning**
Best practices to incorporate prior to beginning next stage	Engaged NRC early for thorough pre-application guidance Detailed Part 50 vs. Part 52 considerations Streamlined Field Change Request process and syndicated with NRC Leveraged lessons learned, collaborated with NRC to reduce timeline	Completed design specs for long-lead components Codified QA/QC processes; solidified understanding with intensive training Leveraged previous projects' documentation processes Ensured design constructability by involving construction professionals Ensured qualified, experienced vendors	Determined contract structure to align incentives with EPC Created Level 3 Integrated Project Schedule Leveraged successful project schedules Designed & budgeted for extensive nuclear contractor upskilling program Conducted design-to-construct and design-to-operate analysis	Implemented rigorous and transparent project controls Ensured documentation standards surface risks early Planned project activities accounting for workspace congestion and contingency Completed Certified for Construction work packages Completed design	Promoted culture of quality and transparent reporting Ensured avenue for direct labor feedback on quality Verified schedule rigor and ability to manage contingency Evidenced ability to execute verbatim compliance with design standards Validated overall workforce readiness to execute stage	Demonstrated application of lessons learned for milestone preparation Trained, rehearsed, and simulated execution to certify process Validated overall workforce readiness to execute stage	Demonstrated application of lessons learned for testing sequence Trained, rehearsed, simulated testing and sequence execution to certify process Validated overall workforce readiness to execute stage	Established intensive nuclear operator training and certification program Certified / licensed operator workforce Risk registrar updated for outstanding ITAAC / OL mitigations



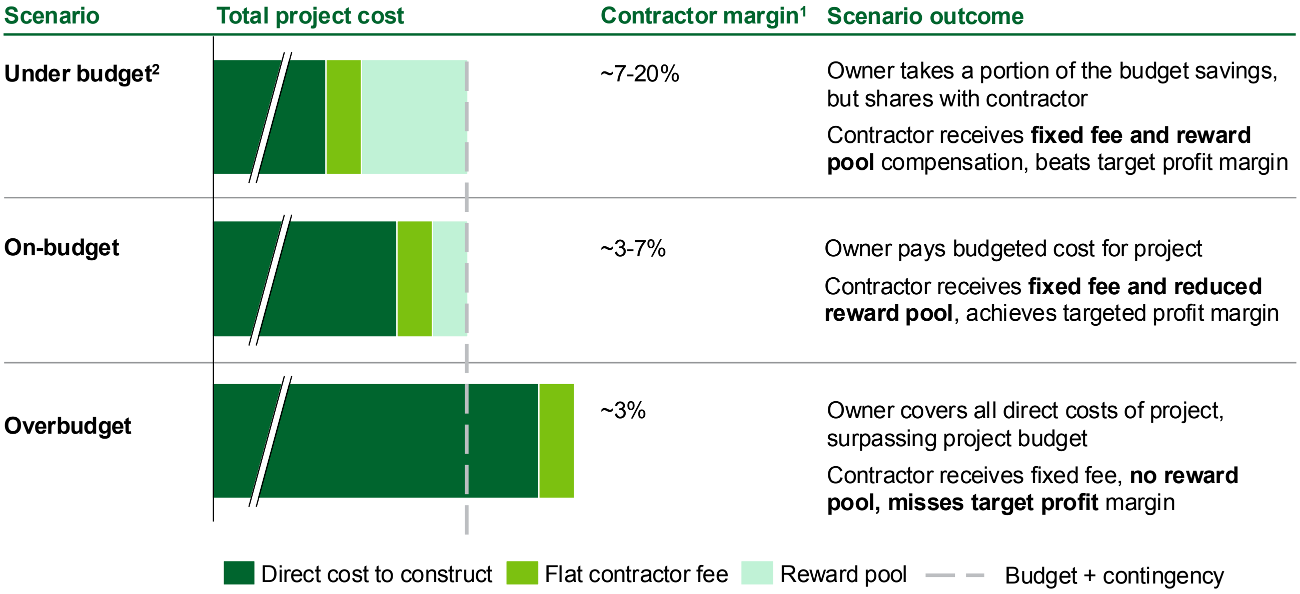
Section 4.a.iii: Building and sustaining construction infrastructure

The US lacks nuclear and megaproject delivery infrastructure. Vogtle was the first start-to-finish nuclear construction in 35 years. The dearth of new projects has resulted in a lack of "muscle memory" and a reduction in the nuclear industrial base required to successfully execute nuclear construction projects. There are very few EPC firms with experience in both nuclear and megaprojects. Much of the nuclear-trained workforce is aging and/or moving into other industries given the lack of new nuclear projects. There are no established developers to integrate and optimize roles and project participants have limited experience with appropriate contract structures.

Many of the issues at recent nuclear construction projects suffering from cost overruns are general megaproject issues rather than nuclear-specific difficulties and are largely preventable. By investing early in the proper planning and processes, project management can avoid the common pitfalls of megaprojects and nuclear construction.

The integrated project delivery (IPD) model aligns incentives between owners and contractors to deliver projects on-time and on-budget. The IPD model avoids adversarial contract models and facilitates a “one team” approach. In nuclear projects with a cost-plus compensation model, contractors are not strongly incentivized to deliver projects on-time and on-budget, e.g., they can “keep getting paid to miss the schedule.” In the IPD model, the contractor receives a flat fee that does not adjust based on costs and has the potential to capture additional reward if the project comes in under contingency (either on-budget or under budget). In the case cost overruns, the contractor will still be compensated a flat fee, but their margin is significantly diminished.

Figure 52: The integrated project delivery incentivizes delivery on or under budget with shared reward pools



Scenario	Total project cost	Contractor margin[1]	Scenario outcome
Under budget[2]		~7-20%	Owner takes a portion of the budget savings, but shares with contractor Contractor receives **fixed fee and reward pool** compensation, beats target profit margin
On-budget		~3-7%	Owner pays budgeted cost for project Contractor receives **fixed fee and reduced reward pool**, achieves targeted profit margin
Overbudget		~3%	Owner covers all direct costs of project, surpassing project budget Contractor receives fixed fee, **no reward pool, misses target profit** margin

1. Examples are shown with single contractor, but this structure would be applied across multiple contractors and hypothetical ranges are shown to illustrate directional incentives 2. This is an illustration of the benefit of a target cost model, where the contract price is intentionally set higher than the expected cost of the project to incentivize contractors to beat the target price and capture the surplus margin

All parties involved in an IPD contract have an incentive to minimize cost and to collaborate to ensure overall project success. IPD requires collaborative decision making, requires contractors that are willing to assume some cost overrun risk, and requires project owners to build out the capability to produce a detailed budget and project schedule with a high level of accuracy.

Figure 53: The integrated project delivery model can help nuclear projects avoid historical challenges[191]

Historical challenges with nuclear construction	Integrated project delivery model approach
Insufficient early-stage planning	Financial incentive structure requires **extensive, collaborative planning and budgeting** in early project stages involving all major stakeholders
Non-collaborative contractor set up creates siloed scopes of work	**Multi-party agreement** between owner and major contractors creates **incentives based on total project cost,** encouraging contractor collaboration to minimize total cost
Poor alignment of incentives does not discourage contractor from overrun	Owner agrees to **flat total fee** on top of project direct costs and contractor is incentivized to minimize cost to maximize profit margin
Litigation between contractors and owners	Owner and contractors sign **"no suit" provision** to avoid adversarial relationship
Poor balancing of financial risk destabilizes contractor	**Cost overrun risks are shared** between multiple parties with the capability to take on the potential overrun

A dedicated entity to share project management knowledge across projects, including integrated project schedules, work packages, lessons learned, and risks could be a possible collaboration between the public and private sectors. Once a project is executed successfully, it will be important to use the knowledge gained from the project to improve the performance of all follow-on projects.

Funding constructability research could target the drivers of cost overruns and improve project delivery. The National Academies[192] recommended that "while it is vital to demonstrate that advanced reactors are viable from a technical perspective, it is perhaps even more vital to ensure that the overall plant—including the on-site civil work—can be built within cost and schedule constraints… the ~$35M in DOE funding for advanced construction technologies R&D is small in comparison to the hundreds of millions spent on nuclear island technology research… more should be done over an extended period to research technologies that may streamline and reduce costs." At INL, the National Reactor Innovation Center (NRIC) Advanced Construction Technology Initiative aims to reduce cost and schedule overruns for nuclear construction projects by developing technologies and approaches through industry partnerships. Sample areas of constructability research that could benefit from increased funding include:

- Risk-informed regulations for constructing advanced nuclear facilities
- Digital engineering and twins for designing and deploying advanced nuclear facilities
- Construction and testing of structural elements using high temperature concrete
- Diaphragm wall construction testing and demonstration
- Testing of robotic and 3-D printing of reinforced concrete techniques
- Full-size demonstration of steel/concrete composite modular walling systems
- Seismic isolators in advanced nuclear reactor construction

The National Academies[193] also recommended that a whole of government partnership to address workforce needs, including the Departments of Energy, Labor, Education, Commerce, State, and Transportation, "would team with labor organizations, industry, regulatory agencies, and other support organizations to identify gaps in critical skills and then fund training and development solutions that will close these gaps in time to support more rapid deployment."

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