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Small Modular Reactors: A Realist Approach to the Future of Nuclear Power

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Standard large nuclear reactors won’t achieve scale or cost competitiveness with alternative energy sources. DOE should focus its resources on small modular reactors, which are a more promising technology with the potential to achieve price and performance parity.

KEY TAKEAWAYS

- Small modular reactors (SMRs) are the future of nuclear power, and they could become an important strategic export industry in the next two decades.
- SMRs must get to sufficient scale so they can become cost competitive with other energy sources including large reactors, renewables, and fossil fuels.
- DOE needs to develop independent assessment capabilities for SMRs (and other technologies) that focus on the pathway to price and performance parity (P3). All major investments must be reviewed through the P3 lens (see box).
- DOE should maintain and expand its strong support for basic and applied nuclear research through the Advanced Reactor Development Program (ARDP) and DOE’s GenIII+ program, including new test and demonstration sites at INL.
- DOE’s Office of Clean Energy Demonstrations (OCED) must provide critical funding to help provide commercial viability, and the Loan Program Office (LPO) will need reform and restructuring to focus specifically on scale-up.
- Nuclear Regulatory Commission (NRC) reform is under way, but more is needed. Innovation requires iteration, and that requires new thinking. NEPA reform is also needed, and so is improved interconnection of new energy sources to the grid.
- SMR markets will be global, so NRC and DOE must not ignore international regulation. United States, Europe, Japan, and other allies can align their regimes to help counter competition from Chinese and Russian state-backed enterprises.

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EXECUTIVE SUMMARY

If nuclear power is the future, small modular reactors (SMRs) are the pathway, potentially offering a flexible, scalable, always-available, potentially cost-effective means of generating clean energy. U.S. companies are currently at the cutting edge of SMR development and deployment, but competition from China, Russia, South Korea, and certain European companies is intensifying. For SMRs to achieve widespread adoption, they must eventually reach price and performance parity (P3) with conventional energy sources, especially fossil fuels. And to do that, they need to scale.

Unlike large reactors, initially high SMR costs may fall because they are designed to be built—partly or completely—in a factory, rather than constructed on-site. Large-scale factory production can exploit economies of scale and can also lead to faster production, another key advantage. That is the endgame for SMRs. The question is how to get there, and the role the U.S. government should play along the way.

It's useful to think of technology development as following a four-phase pathway, although, of course, all the boundaries are fuzzy, and not all technologies go through all four phases:

- Initial basic and applied research eventually leads to a prototype or the equivalent.
- Testing and further development leads to a fully complete design whose components have been successfully tested.
- First-of-a-kind deployment demonstrates that the protype and related components can be scaled up to commercial size, and the first reactor of its kind can be built.
- During the scale-up phase, multiple copies are produced and sold, allowing costs to fall and eventually the technology to become competitive with existing energy sources. Scale-up requires finally settling on a design, developing a fully functioning factory, and building an order book deep enough to support production at scale.

Today, large reactors have reached the scale-up phase but have largely stalled there, and show no sign yet of successfully reaching P3. There are simply not enough orders in the United States to generate sufficient scale economies. Proponents hope that a coalescence of orders around the Westinghouse AP1000 design (which is now a standard model for large reactors) will get large reactors to scale, but that seems unlikely. SMRs are at a much earlier stage, only now reaching the end of the testing and further development phase, with leading-edge designs preparing for first-of-a-kind deployment in the United States and elsewhere.

As a result, we don't yet know whether SMRs will crack the scale-up problem; that question cannot be answered for at least a decade. But we can say that unlike large reactors, there is a greater *possibility* that SMRs will indeed scale, costs will fall, and P3 will be achieved. This is in part because SMRs have significant advantages, including that they may be able to expand the market for reactors very substantially. Because they can be sized from 1 megawatt (MW) to 300 MW or more, they can meet very different needs in different markets. Because some designs at least are well suited to the production of thermal energy, they can play a role in industrial decarbonization, and could also align well with desalination. Also, because they are modular, they can be aggregated to meet the specific amount of energy required. Some designs, for example those using molten salt and thorium promise cheaper fuel, lower refueling downtime requirements and have enhanced passive safety features that further reduce costs. In some cases, they use different fuels that are less expensive and easier to produce. And in contrast to wind and solar, they generate energy 24/7. That, combined with being clean, has attracted significant attention from Big Tech firms looking for power for their rapidly growing data centers.

Of course, first-of-a-kind SMRs are going to be expensive. They will likely cost more per megawatt hour (MWh) than existing large reactors, and certainly more than competing fuels (solar, wind, and natural gas). Expensive new technologies that will take a decade or more to reach scale (if they ever do) are very high risk, and SMRs face four distinct kinds of risk:

- **Technology risks.** Until the reactors are up and running, we won't know whether in practice they meet the anticipated specs. Because we don't have operational experience yet, SMR technology could fail to translate from the drawing board on pilot projects to full commercial operation in multiple ways—they could generate less power, use more fuel, require more downtime; there is a long list of things that could go wrong.
- **Market risks.** SMRs as a business face risks on both the supply side and the demand side. Aside from the technical risks, SMR companies may find that the competition is more intense or effective than anticipated; that some assumptions about their supply chain are wrong; or even that key patents don't hold up. And of course—as with large reactors—companies may simply find that producing and siting SMRs is much more expensive than expected, or takes much longer, or that interest rates shift sharply upward, or indeed that inflation suddenly hits key inputs. On the demand side, it may be that expected markets simply don't materialize, or that there is no market for SMR energy at the price it needs to charge. It's hard to predict energy markets a decade out.
- **Regulatory risks.** SMRs must navigate multiple layers of regulation. They need to get their designs certified for safety (in the United States, by the Nuclear Regulatory Commission (NRC)). They need to get NRC safety approval for their operating plan for a specific site. They then need to get site approval via the National Environmental Protection Act (NEPA) process to ensure that environmental issues have been addressed. That may well also involve a defense against NIMBY ("not in my backyard") lawsuits. And as SMRs will need to scale globally, they will also need to address regulators in other countries.
- **Political risks.** The reality is most nuclear reactor purchases involve national governments in some way (the United States is perhaps an outlier here, although the U.S. Department of Energy's (DOE's) Office of Nuclear Energy (ONE), Office of Clean Energy Demonstrations (OCED), Loan Program Office (LPO), and other programs will still be key enablers for nuclear). Government commitments to nuclear power have been subject to intense political conflict in some countries, leading to reversals, as in Germany, and to a double reversal and then reapproval in Japan. Government support will likely be critical, but governments can also be fickle. And in the United States, while there now appears to be a growing bipartisan consensus at the federal level in support of nuclear power, that is not the case at the state level, where environmental concerns, NIMBY issues, and waste management continue to generate opposition.

It is therefore not surprising that derisking has been at the heart of policy discussions. How can governments mitigate or perhaps even eliminate these risks in ways that don't simply shift them entirely onto the backs of taxpayers?

It’s helpful to consider risk mitigation in terms of financial and nonfinancial risks, as the related policies are quite different.

Financial risk mitigation means finding ways to share risks between different stakeholders, including vendors (that sell reactors), constructors (that build plants), utilities (that usually own them), lenders, ratepayers, large end users, state and local governments, and national governments (and their taxpayers). Just listing the stakeholders indicates the complexity of possible risk-sharing models.

These stakeholders can also support nuclear construction through a wide variety of mechanisms. In the United States, funding comes from three primary sources: government grants for research and development (R&D) and eventually deployment; tax credits for either investment or production (Investment Tax Credits (ITC)/Production Tax Credits (PTC), with the latter currently set at $30/MWh; and—potentially though not yet in reality for SMRs—loan guarantees from LPO.

Other countries are using or exploring quite different approaches. The U.K. government has effectively been forced to become the owner of a plant being built at Hinkley Point, so taxpayers are largely on the hook there. The United Kingdom is also exploring rate-asset-based support, where ratepayers are required to pay a contribution during the construction period rather than just paying for electricity. In Finland, cooperative structures link vendors, construction companies, utilities, and large end users. In several European countries, Contracts for Difference (CfD) provide flexible operating subsidies that are tied tightly to market conditions, offering government subsidies where operating costs are higher than market prices. Many government have provided loans at below-market rates, while in Asia in particular, China has offered very attractive funding packages for new nuclear plants. The United States could clearly benefit from reviewing these options in a systematic way and aligning them with a much stronger emphasis on P3 assessment.

On the demand side, risk mitigation usually involves a long-term power purchase agreement (PPA), wherein a utility or large end user will agree to buy power at a more or less fixed price for a fixed number of years (often as long as 20 years). PPAs are effectively mandatory for large reactors; lenders will not take the risk of simply funding a huge speculative project. They will likely be mandatory for large SMRs, for the same reason. Microreactors—20 MW or less—may however be different; the amounts at stake are smaller and some microreactor companies aim to build and operate reactors themselves, simply delivering energy to clients.

The U.S. model for financial risk mitigation emerged largely because it was the approach that could get through Congress at the time, not because it was clearly the best approach. Indeed, it has many weaknesses especially over the long run, if only because it is exceptionally vulnerable to political risk.

Mitigating nonfinancial risks is also important. Technological risk is being mitigated by the close alignment between SMR companies and the National Labs, which provide critical expertise and capabilities in the form of facilities that can be shared by different SMR companies. Simulation, modeling, and physical test sites are all important, and can play especially helpful roles both at earlier stages of R&D and later in preparing designs for NRC certification. While this work is not glamorous or particularly visible, it is an important building block for the U.S. nuclear sector, and it would be devastating over the medium term if this work were not fully supported. Indeed, as SMR opportunities expand, it is likely that more SMR companies and designs will emerge, and they too will need access to and support from Idaho National Laboratory (INL), Oak Ridge National Laboratory (ORNL), Pacific Northwest National Lab (PNNL), and Argonne National Laboratory (ANL).

There are nonfinancial production risks to consider also. For example, many SMR designs require enriched uranium fuel (High-Assay Low-Enriched Uranium (HALEU)), and that supply chain is both global and insufficient. DOE is working on this, but other companies will likely have to follow TerraPower and cut their own deals with foreign entities and governments.

Regulatory risk is still substantial, despite recent efforts at NRC, where a new rulemaking aims to provide an optional alternative path for safety and operational certification for advanced reactors, replacing the existing model designed for existing GenIII large reactors. This pathway will however not be operational until at least 2027, although the current exemption-based process seems to be working better than SMR companies initially expected. More worrying, there has been no public discussion of a pathway for iteration: innovative products do not usually reach the market without substantial iteration and tweaking, or even full-scale pivots, and we simply have no idea how NRC will address a world that is so different from the “design once, build often” world that it is encouraging for large nuclear reactors. And regulatory risk is not limited to NRC: NEPA plays a significant role in delaying infrastructure projects (including SMRs), although fairly radical amendment is increasingly likely. State policy too impacts deployment, although antinuclear feeling is reversing, and this is being reflected in changes in state regulations for nuclear.

There are plenty of other regulatory concerns as well. SMR transportation and siting will be regulated and will likely need different approaches than those used for large reactors, and so will waste streams, all of which are in some state of flux.

Based on this analysis, the U.S. government has plenty still to do to support SMR development. Key recommendations cover the following areas:

- **Expanded funding for basic and applied research.** The Advanced Reactor Demonstration Program (ARDP), which spans several phases of development, has clearly been successful in supporting SMRs. Early funding—through this program or others—is critical, especially for a newly emerging sector such as SMRs; the discovery phase for this technology will require significant help in the form of grant funding and access to National Labs expertise and capabilities.
- **Testing, certification, and further development.** At this stage of development, new nuclear technologies are a decade or more from deployment at scale. They are therefore high-risk technologies, and federal funding in the form of matching grants will be crucial, as will access to testing and validating facilities at the National Labs and support for beginning the regulatory pathway.
- **First-of-a-kind commercial deployment.** This critical step marks the conclusion of the research and testing phase and the beginning of commercialization. Despite the missteps of OCED under the Biden administration, OCED funding will be absolutely critical for SMR deployment at this stage. We strongly recommend that OCED be reset to focus only on technologies that have reasonable prospects of reaching P3, but that support should

be renewed and possibly expanded. DOE must also fully accept the need for much improved transparency across contracts, milestones, and both technical and economic outcomes from supported projects. Public funding should generate publicly available results.

- **Scale-up.** Here too existing mechanisms will play a key role. LPO should also be reoriented, mandated to focus explicitly on scaling up promising new technologies that are within reach of P3. It should avoid funding projects on either the supply or demand side that have no pathway to sustainability, and subsidies should be explicitly designed to support projects in reaching scale and hence P3. Subsidized loans and tax credits are, however, not the only mechanisms available; the administration should explore multiple alternatives including, for example, risk tiering, the use of CfD, and vertically organized consortia.
- **Regulation is key to SMR success.** NRC must both find ways to reduce the time lag before designs are certified and—especially critical for SMRs—develop ways to support design iteration, a key feature of innovation. Distinguishing between iteration that has safety impacts and those that don't will be central, and NRC will also have to make significant strides in certifying factory-built reactors (and components) and addressing the need for new approaches to waste management and the transportation of SMR reactors, components, and fuel. SMRs will also need resolution of the current problems with interconnection, but it seems likely that these may be addressed before SMRs reach scale-up. Finally, international regulation matters; SMRs must work within global markets to achieve scale, so DOE should work to align certifications and safety regulations with other regulators.

SMRs are a promising technology with the potential to reach P3, in contrast to standard large nuclear reactors, which will not achieve scale or cost competitiveness with alternative energy sources. DOE should therefore focus its nuclear resources primarily on SMRs.

Box 1: Price/Performance Parity: "P3"

Climate change is global, so solutions must be global. In particular, they must meet the needs of low-income countries where demand for energy is rising fastest, and where ability and willingness to pay a green premium is low to nonexistent.

There is no evidence that forcing change with regulation, subsidies, or exhortation will work. Low-income countries will not adopt clean energy at the expense of growth. Neither will richer countries.

The market is the only lever powerful enough to drive the transition at the scale needed—and it will only work when clean energy technologies can outcompete dirty ones without subsidies or regulations. They must reach P3.[1]

Renewable energy is inherently variable. To succeed, especially in lower-income countries, Variable Renewable Energy (VRE) must deliver with reliability and costs that are broadly similar to fossil-generated energy. The United Kingdom recently announced that it is the first Organization for Economic Cooperation and Development (OECD) country to halve its emissions by effectively replacing coal-fired power generation with wind and solar. Nuclear and gas have remained largely constant over the past decade, but gas has now become the backup to VRE.

INTRODUCTION: WHY SMRS COULD BE IMPORTANT

SMRs are clearly having a moment. Publicly traded companies such as Oklo and NuScale have seen both recent stock booms and several major investment announcements, and Big Data companies are buying into or supporting a range of SMRs as a partial solution to their energy needs. The new secretary of Energy, Chris Wright, is an investor in and board member of Oklo, and is clearly a fan of growing nuclear, having written when he was CEO of Liberty Energy, "Nuclear appears to be the most viable option to add sizable new energy resources in the coming decades."[2]

DOE's liftoff report is remarkably optimistic, and more generally, nuclear proponents have argued that using a standardized design (e.g., Westinghouse's AP1000) and building a series of reactors using that design will reduce costs, as a trained construction workforce can be employed for multiple projects, and projects benefit from learning by doing across an increasing number of projects.[3] DOE's report also notes other potential cost drivers such as reduced capital costs and of course clean energy subsidies from Biden administration programs.

These arguments, however, fly in the face of experience with the construction of large reactors. Between 2002 and 2017, 11,833 MW of U.S. nuclear generating capacity closed or announced retirement (11.9 percent of U.S. nuclear capacity), mostly because of unfavorable market conditions.[4] There are no major new reactors under construction or in review by regulators in the United States today, and the most recent completed plant, at Vogtle in Georgia, came in years late and massively over budget.[5] More generally, the cost of constructing large nuclear reactors has increased significantly in recent decades, partly because components have become much more expensive (notably steel and concrete), partly because no settled design has emerged, and partly because safety regimes and regulatory burdens expanded sharply after Three Mile Island and Chernobyl.[6] But the fact is recent construction of large nuclear plants in the United States and elsewhere has suffered from dramatic cost overruns and delays. As a result, no large nuclear plants are planned or under construction in the United States. Planned nuclear plants in Europe, meanwhile, are a response to the need for energy security in the face of Russian aggression, plus a stronger commitment to clean energy even if it costs more.

Initially, SMRs will likely cost as much per kilowatt as large reactors do, or perhaps even more. But SMR companies have developed to the point that they are close to commercial deployment in the United States (and elsewhere). Investment is pouring into the sector, and innovative new SMR companies are popping up like mushrooms after a rainstorm. Why?

SMRs do have plenty of potential ancillary advantages—site flexibility, size flexibility, modularity, possible new markets—and of course, like big reactors, they offer reliable baseload energy 24/7. But most important of all, SMRs could generate clean reliable power much more cheaply than large reactors *if* major components or the entire reactor (for smaller SMRs) can be manufactured in a factory, not on-site, which could open the door to economies of scale and declining costs. That promise is driving interest in SMRs, and Deloitte has identified more than 150 SMRs in development around the world.[7]

However, right now, there are only two commercially operating SMRs, one in Russia and one in China. Only three designs have been approved for construction by NRC. Investments and hype are fueled by the *promise* of SMRs, not the current reality. However, innovative new designs are emerging very rapidly, ranging in size from 1 MW to more than 300 MW, including new technologies, new configurations, new fuels, and new production systems.

This report explores the case for and against SMRs, and offers policy pathways that would give SMRs their best shot at making it to scale in the United States, becoming relevant in reality and not just in theory. Even though public views on nuclear are getting steadily more popular, they have a long way to go, and they will need a lot of help along the way, but it is potentially a very important technology.

What Are SMRs?

SMRs generate power just like other reactors—by using a nuclear reaction to heat a liquid that then generates steam, which in turn powers a turbine that creates electricity (see box 2). Today, SMRs are being developed with different technologies that offer variations on this theme, using different fuels, different coolants, and new safety features.

All SMRs have three key characteristics that differentiate them from standard large reactors: they generate lower levels of energy (usually defined as 20–300 MW, compared with large reactors that typically generate 1,000 MW or more) (reactors generating 20 MW or less are "microreactors"); they are modular in that multiple SMRs can be hooked together to provide the necessary level of power for a particular application; and they are designed to be made at least partly in a factory, rather than completely built on-site like large reactors.

Smaller scale and modularity make SMRs more flexible and hence a potential option for different applications, while factory production offers the tantalizing prospect of mass production and the potentially radical decline in cost that might bring.

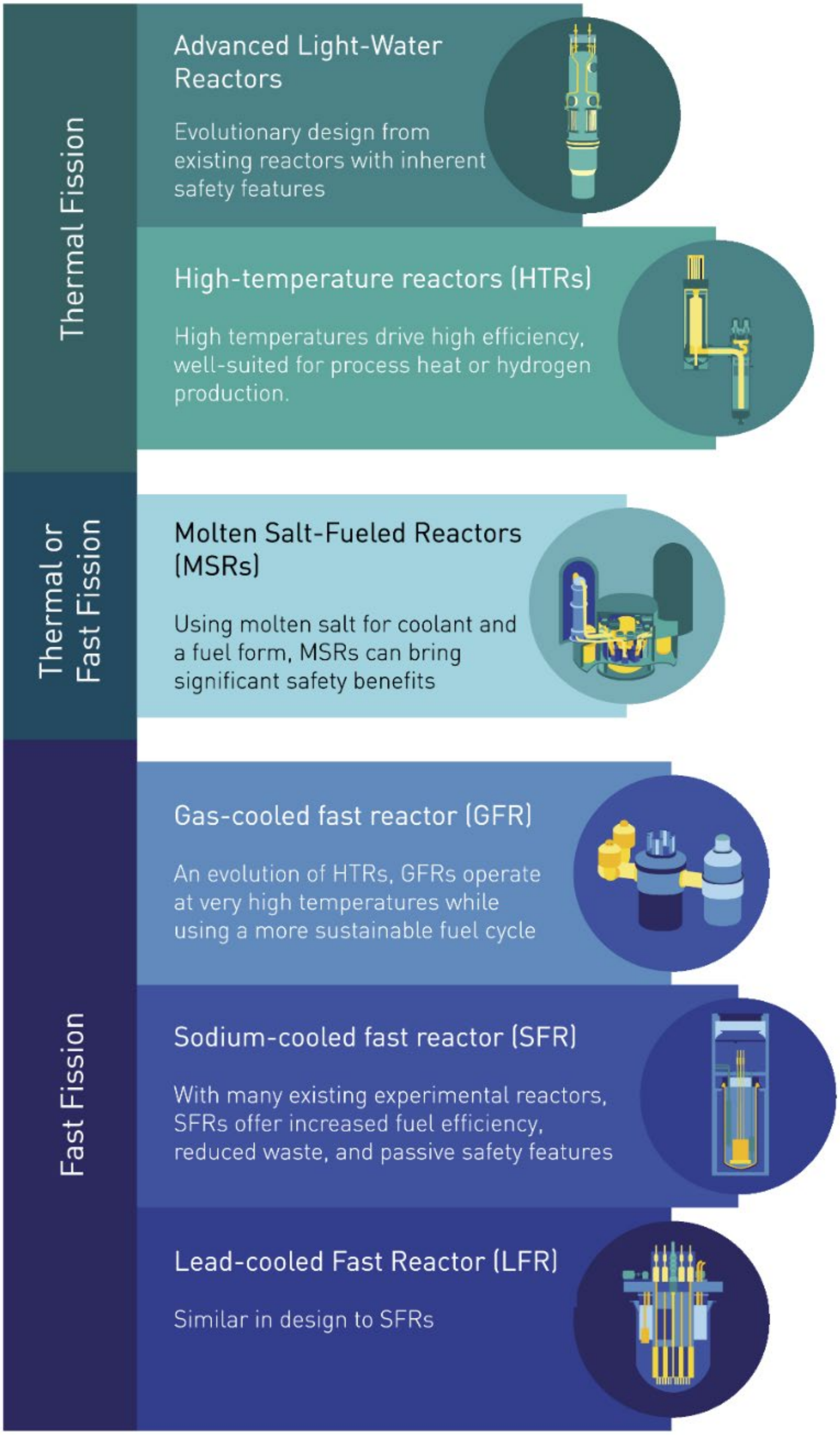
Although there are around 150 SMR companies worldwide, most offer no more than designs on paper. To become relevant globally, the SMR sector must go through the discovery phase to figure out which technologies and business models are winners and which are not, and both are still in flux. For example, at least six quite different designs are being developed (figure 1).

SMRs have plenty of promise, which is why Google, Meta, and Amazon are all exploring their use to power data centers. To become fully relevant in the green transition, SMRs will need to traverse the discovery phase of technology development quite quickly, settling on only a few dominant designs and companies. That's necessary if SMRs are to exploit the promise of factory production, and perhaps then generate true economies of scale. But as shown later in this paper, getting to scale will take time, lots of investment, and plenty of government help.

Box 2: Generating Nuclear Power Using Pressurized Water Reactors

Pressurized Water Reactors (PWRs) operate on two isolated coolant loops. In the primary loop, water under intense pressure (15–17 megapascals (MPa)) flows through the reactor core, heating from 290°C to 325°C while remaining liquid. Main coolant pumps circulate this water through steam generators, where heat is transferred via tube walls to a separate secondary coolant loop. In this secondary loop, the water boils into steam at 6 MPa, then expands through the turbine to near vacuum (0.008 MPa). This pressure drop drives the movement of steam through the turbine-generator assembly, producing electricity.

Figure 1: SMR Reactor Types[8]



Advanced Light-Water Reactors

Evolutionary design from existing reactors with inherent safety features

High-temperature reactors (HTRs)

High temperatures drive high efficiency, well-suited for process heat or hydrogen production.

Molten Salt-Fueled Reactors (MSRs)

Using molten salt for coolant and a fuel form, MSRs can bring significant safety benefits

Gas-cooled fast reactor (GFR)

An evolution of HTRs, GFRs operate at very high temperatures while using a more sustainable fuel cycle

Sodium-cooled fast reactor (SFR)

With many existing experimental reactors, SFRs offer increased fuel efficiency, reduced waste, and passive safety features

Lead-cooled Fast Reactor (LFR)

Similar in design to SFRs

THE POTENTIAL FOR SMRS

SMRs are a powerful energy source that generate no carbon emissions from operations; they are energy dense; they can be constructed flexibly; and—like wind and solar—costs could decline significantly as they gain scale. But that's just the start. This section describes in more detail some of the advantages that SMRs might develop over both large reactors and competing energy sources.

New Markets for Nuclear

Because they are smaller and modular, SMRs may be able to expand into or develop new markets, across several dimensions:

- **Geography.** SMRs can go where large nuclear cannot. They could be used for off-grid and remote applications, for sites close to population centers, for locations where other clean power sources would require a lot of expensive transmission infrastructure. Atomic Energy of Canada Limited, for example, is developing a very low-powered SMR that can run for 15 years without refueling.[9]
- **Industries.** SMRs could support industrial decarbonization applications across many industries, as they can be located closer to existing industry clusters or—for microreactors at least—actually on-site. Entire new industry segments with distinct energy needs could open up: data centers, for example. And new approaches to existing needs are also potentially significant: SMRs could, for example, provide district heating, and could also power container ships.[10]
- **Scale.** SMRs can operate at scales from 1 MW to 1,000 MW or more because they are modular and hence stackable. Therefore, SMRs could work for applications that require 300 MW, for example, while standard large nuclear plants are usually around 1,000 MW.
- **Existing infrastructure.** SMRs don't need a strong existing grid to distribute power, so they have applications in regions with weak or nonexistent grids, or where demand is growing faster than the grid can manage (especially in fast-growing low-income countries).
- **Load following power.** TerraPower emphasizes that, unlike large PWR reactors, which provide baseload power, its Natrium reactor uses molten salt energy storage; that could open the door to use as variable power, especially as a complement to wind power. That is in part the motivation for its first plant in Wyoming.

Some of the relevant potential markets are shown in table 1, although all of these are just "potential" markets right now, and SMRs will need to avoid the "Swiss Army Knife" problem: being the second- or third-best solution everywhere. But there are significant opportunities.

Table 1: Potential markets for SMRs

Potential Markets	Examples
Developing economies with growing energy needs	▪ India, Indonesia, Philippines, and South Africa are attracted to SMRs' lower up-front capital costs, limited infrastructure demands, smaller physical footprint, and potential for incremental expansion.
Maritime and transportation applications	▪ Floating nuclear power plants, maritime propulsion systems ▪ E.g., Russia's floating nuclear power plant and emerging designs for maritime nuclear propulsion. ▪ Nuclear submarines have demonstrated some options.
Countries seeking energy security	▪ Countries around Russia seeking to avoid dependence on Russian gas and oil
Countries needing to diversify energy sources	▪ Countries such as Japan and the United Arab Emirates
Big data	▪ SMRs are a potentially important option for owners of data centers that require large amounts of very reliable energy, clean if possible.
Industrial process heating	▪ SMRs generate heat as well as power and can be located close to end users or on-site. ▪ E.g., desalination, synthetic and unconventional oil production, oil refining (for use in >700°C)
Remote communities and off-grid applications	▪ Remote mining operations ▪ Military bases and installations ▪ Off-grid communities ▪ Island nations
Developed economies seeking green transition	▪ U.S. utilities may see SMRs especially as a way to replace coal with low emissions while maintaining grid stability. ▪ E.g., the Tennessee Valley Authority and NuScale Power.

A 2014 study in the United Kingdom estimated that the global market for SMRs could be 65–85 gigawatts (GW) annually by 2035 (assuming that they are economically competitive).[11] And TerraPower's vision is explicitly focused on bringing competitive SMR power to developing countries: "This century, we would expect to see hundreds of Natrium reactors deployed around the world in nations that don't even have nuclear today: nations in sub-Saharan Africa, where there's tremendous population growth, or in Indonesia where we think Gen IV technology will be ideal."[12]

SMRs for Data Centers

Much of the recent excitement around SMRs is built on the rapidly growing demand for firm, reliable energy for data centers. Even before the explosion of demand for artificial intelligence (AI), data centers were growing rapidly in the United States (and elsewhere), helping to transform electricity trends from decades of flat demand to significant projected growth. Demand from data centers is now expected to turbocharge that growth, and major data center owners are scrambling to find the substantial new electricity supply that will be needed.

The structure of electricity markets in the United States makes nuclear an attractive proposition, for two main reasons. First, it seems unlikely that huge new demand from data centers can be accommodated by existing sources of electricity supply. Amazon's efforts to acquire priority access to the Susquehanna nuclear plant has been rejected by the Federal Energy Regulatory Commission (FERC), and while lawsuits are ongoing, it appears that Big Tech companies and other data center owners have accepted that they will likely have to bring their own power sources rather than simply using electricity from the grid, as regulators will likely not allow utilities to disadvantage existing customers in favor of this new demand, so new generation must be built. In tight electricity markets, the sudden withdrawal of a significant part of electricity supply for data center use would cause substantial and persistent spikes in the price of grid electricity, and that will likely not be permitted.

Second, grid interconnection is a problem on two fronts. It currently takes on the order of five years for FERC approval for interconnection to the grid. And grid connections carry a substantial per-MWh cost in terms of fees and taxes. So avoiding interconnection where possible is attractive—and SMRs or nuclear more generally offers a good solution *if* nuclear can provide electricity at a reasonable price and within a reasonable timeframe. Evidence so far suggests that data center operators are willing to pay a substantial but not exorbitant premium for new nuclear energy, whether it is SMRs that will enter service in the next decade or refurbished existing large reactors that can be reactivated for use more quickly.

All the Big Tech companies have signed nuclear power agreements of some kind. Amazon is investing $700 million in X-energy and SMR deployment in the Northwest United States; Google is funding Kairos; Microsoft has agreed to a 20-year PPA that will pay for the restart of a reactor at Three Mile Island. Meta has released a Request for Proposal seeking 1–4 GW of nuclear power. Google, Microsoft, and Nucor are working with Duke Energy to build a data center next to Duke's Surry nuclear plant. Oklo is partnering with RPower to provide a hybrid solution that offers gas generation until Oklo's SMRs can be deployed.

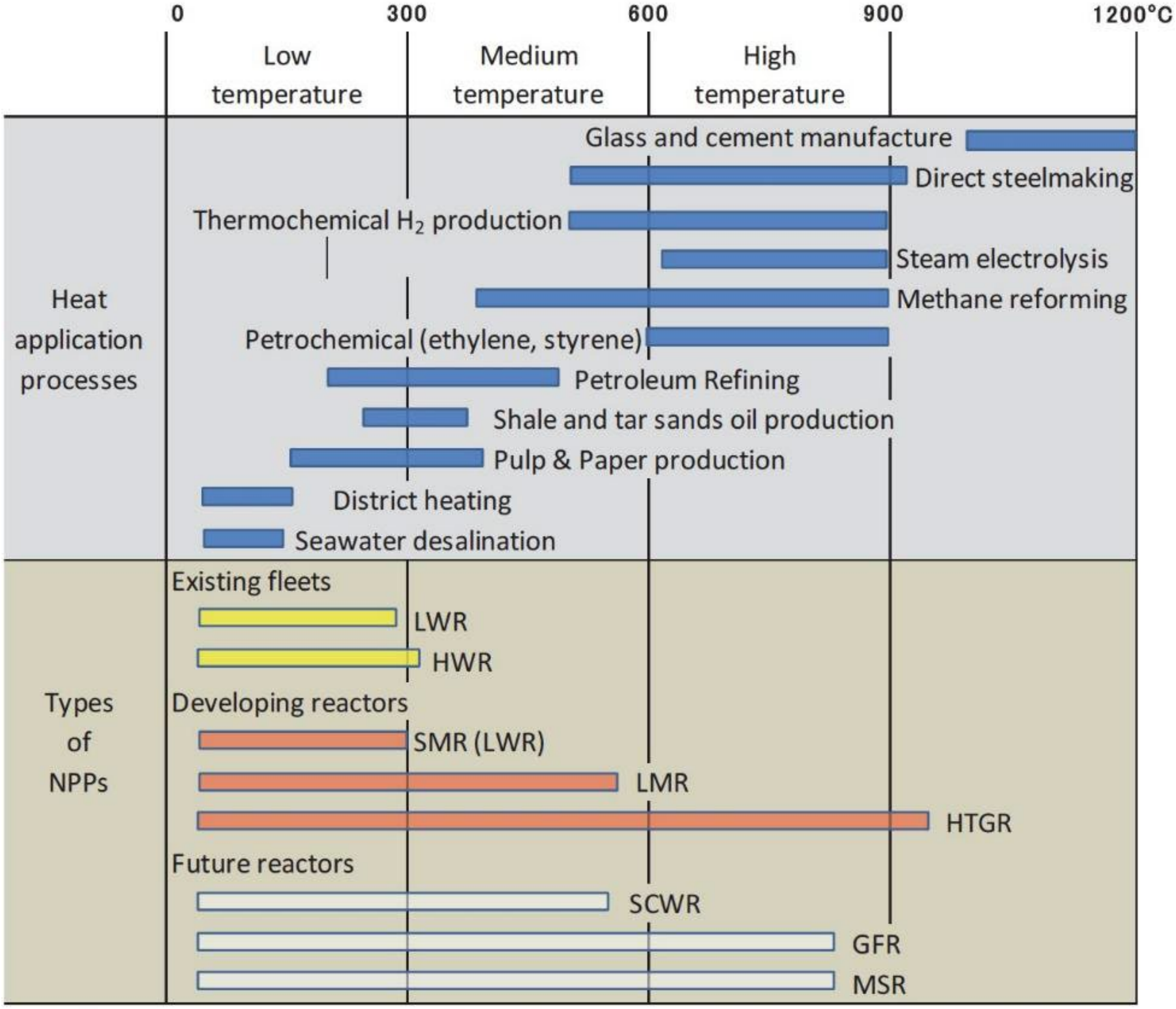
Moreover, data center buyers seem especially likely to fund innovative new ideas. They may offer a uniquely helpful combination of very deep pockets, need for reliable 24/7 clean power, long timeframes, and a willingness to accept risks. Endeavor Energy, for example, has signed a deal with Deep Fission to power its expanding fleet of data centers with energy from 2 GW of SMRs located one mile underground.[13]

Markets for Thermal Power

Unlike wind and photovoltaic (PV) solar, nuclear power generates heat as well as electricity. That heat can be used directly in various industrial processes, or perhaps for district heating, and is especially relevant to SMRs, which could be sited near industrial end users, opening up potential new markets. Figure 2 shows both the range of potential heat industrial processes that could use nuclear power and the temperature range of existing and emerging nuclear technologies.

Some high-temperature applications will probably not be served by nuclear energy (e.g., glass and cement manufacturing), but others are potentially accessible targets, especially for high-temperature gas reactors (HTGRs), which generate very high levels of heat. Emerging new technologies—gas-cooled fast reactors (GFRs) and molten salt reactors (MSRs) in particular—may operate at high enough temperatures to be useful for the chemicals sector, petroleum refining, and pulp and paper production. Both GFR and MSR technologies have been proposed for SMRs.

Figure 2: Temperature ranges of heat application processes and types of nuclear power plant[14]



Note: GFR — gas cooled fast reactor; HTGR — high temperature gas reactor; HWR — heavy water reactor; LMR — liquid metal reactor; LWR — light water reactor; MSR — molten salt reactor; NPP — nuclear power plant; SCWR — supercritical water reactor; SMR — small modular reactor.

Desalination

Given the obvious need for clean water in many parts of the world and the growing pressure on water resources, desalinization will be a critically important technology. SMRs and desalination could be a very good fit.

Most analysis of SMRs is based on the assumption that they will provide firm baseload energy. That is a natural consequence of SMR economics: because reactors are so capital intensive and so reliable, it makes sense to run them at the highest possible capacity factor. That's why nuclear power plants usually run at well over 90 percent capacity today. But SMRs could work differently: They could be linked both to a grid and to a desalinization plant, supplying energy to the grid when demand (and hence prices) is high, and redirecting energy to the desalinization plant when demand (and grid prices) is low. The desalinization plant could also be the offtaker for energy when the grid has no use for it at all (i.e., when the grid curtails the flow of energy from the plant to the grid). This alignment would put a floor under the price for reactor energy (the price at which desalination makes sense) and guarantee high capacity utilization even if grid demand fluctuates.

In effect, the desalinization plant would be an economic battery attached to the SMR, storing excess energy in the form of clean water when grid prices are low. Of course, the same strategy could be applied to other energy technologies such as solar or wind, and the growing curtailment of clean energy in California may provide a real-world test of this opportunity. However, the siting advantages and other flexibility features of SMRs mean that if this model works out economically, it could be applied in areas where excess solar, wind, or both are not so easily found, and especially where water is a scarce resource. For example, a Texas consortium is exploring nuclear for desalination at the Texas Tech SMR cluster.[15]

Several new technologies are also emerging for desalinization, some of which use heat-based desalination (evaporating water to lose contaminants such as salt). It seems quite plausible that nuclear plants—especially those using high-temperature technologies—could be well suited for this approach.[16]

Manufacturing and Economies of Scale: Getting to P3

Factory manufacturing and scale are critical SMRs: Without reaching scale and driving down costs, they have no future. Getting there involves settling on a technology, finding enough customers initially willing to pay a premium, and then successfully exploiting factory production, which does not necessarily require millions of units annually. Boeing builds approximately 500 planes per year on its production lines, and can build them vastly cheaper than if it built them one at a time.

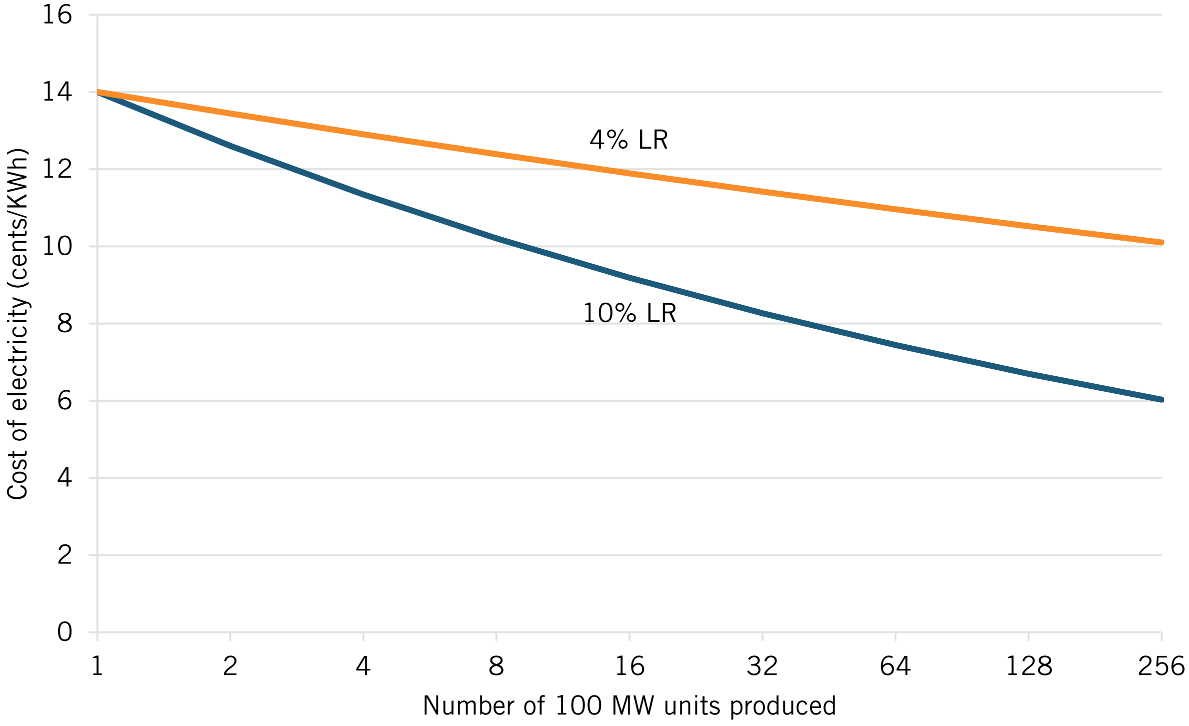
Because SMRs have not yet been produced in a factory, we have only educated guesses about cost savings. And because many variables play a significant role in eventual costs—including the technology adopted, the size of the plant, and financing methods and costs—estimates are unlikely to be accurate.

Wright's Law

Still, in the context of SMRs, the literature provides useful estimates of potential learning effects from scale. In the 1930s, Theodore Wright found that the cost of aircraft production at Boeing fell 10–15 percent each time production volume doubled.[17] This is known as Wright's Law. It has held up fairly well (to different degrees) across other industries (e.g., solar and batteries) and seems a reasonable rule of thumb for scaling nuclear as well; the United Kingdom's National Nuclear Lab used it in a report for the U.K. Parliament in 2014, for example.[18] Other studies, however, offer more pessimistic conclusions, as Wright's Law is not a fixed constant, and doubling the installed base for a technology does not inevitably reduce costs by a fixed percentage.[19]

The potential impact of Wright's Law on the cost of SMR electricity is shown in figure 3, which shows two hypothetical learning rates (LRs)—at 10 percent and 4 percent—for an SMR starting at $0.14/kilowatt (KW), with one initial unit deployed. The chart shows hypothetically that a 10 percent learning curve reduces the cost of electricity by around two-thirds as deployment reaches 256 units, at which point SMRs would be a competitive energy source. These curves show just how important the learning rate will turn out to be—something we won't know for at least two decades. They also underscore the critical role of scale in cost reduction.

Figure 3: Hypothetical scale economy curves for SMRs



How Quickly Can Demand Scale?

We are really talking about two distinct markets at least, one for quite large SMRs (perhaps 100 MW+), where costs and deployment limitations suggest that it will take several decades before 256 units are deployed, and smaller SMRS and microreactors, where take-up could be much faster and where companies are planning to roll out large numbers of units annually (Copenhagen Atomics, for example, anticipates that it will be building plants in multiple countries; each plant is expected to produce more than 300 units annually, and the company aims to eventually deliver reactors at a levelized cost of energy of $20/MWh—well below the cost of competing technologies for new build plants, including gas).[20]

Even if we hypothetically begin rollout with three SMRs deployed in their first year of operation, 30 years of 10 percent compounded growth in deployment will generate a total of only 53 deployed units; growth rates would have to reach more than 15 percent annually to 256 units within 30 years. Of course, early-stage growth could be much faster—the current excitement suggests that it will be. So, while sufficient scale is possible, it could take considerably longer than a decade of rapid growth for SMRs to reach P3 with competing fuels, especially for larger SMRs.

What Will the Rate of Cost Decline Turn Out to Be?

Looking directly at the process improvements available, several detailed studies show how different components of SMRs can be modularized for factory production. One study, for example, estimates that full modularization alone can reduce overnight capital costs by more than 40 percent—and also that the opportunities are greater for smaller reactors.[21]

Another detailed analysis suggests that 60–80 percent of SMR production by value could be accomplished with a factory.[22] That in turn could allow for the application of advanced manufacturing techniques such as electron beam welding and diode laser cladding.[23] It has also been claimed that because SMRs are smaller, they can become more standardized in that there is less need to adapt to local conditions. But this remains unproven.

It's worth noting that larger SMRs likely will to be completely built in a single factory. TerraPower's 345MW Natrium reactor will have all its large components built by fabricators in its factories, and those components will then be assembled on-site and lowered into the ground to their final position. TerraPower still expects to build hundreds of reactors, so component-level economies can become substantial if they succeed.[24]

A high rate of production has other advantages. Workers (both white collar and blue collar) remain employed, and their experience will help drive learning rates. And SMRs can design in features that could reduce the cost of production in other ways. Passive safety features enabled by SMRs (which have a higher surface-to-volume ratio than large reactors do and consequently a lower need for additional features such as large cooling towers) could cut containment costs substantially, while fuels can be designed to be lower costs (e.g., molten salt using thorium).

It's also worth noting that because SMRs are still in the discovery phase, we don't even know what factory production will look like. For example, both Core Power in the United Kingdom and Blue Energy in the United States are looking at converting shipyards to SMR production, aiming to build reactors for sea-based deployment.[25]

To summarize, we do not yet know how all the excitement about declining cost curve and factory production will translate to the real world. But low-cost nuclear power via SMRs has a foundation both in the history of technology and in the specifics of SMR production, and is a tantalizing possibility.

Shorter and Potentially More Predictable Construction Timelines

If SMR production can become standardized to include a substantial factory-built component, that should shorten construction timelines significantly. Optimistic SMR companies claim to expect deliveries and operations in 2–4 years, not the 7–10 years or more that's now standard (at best).

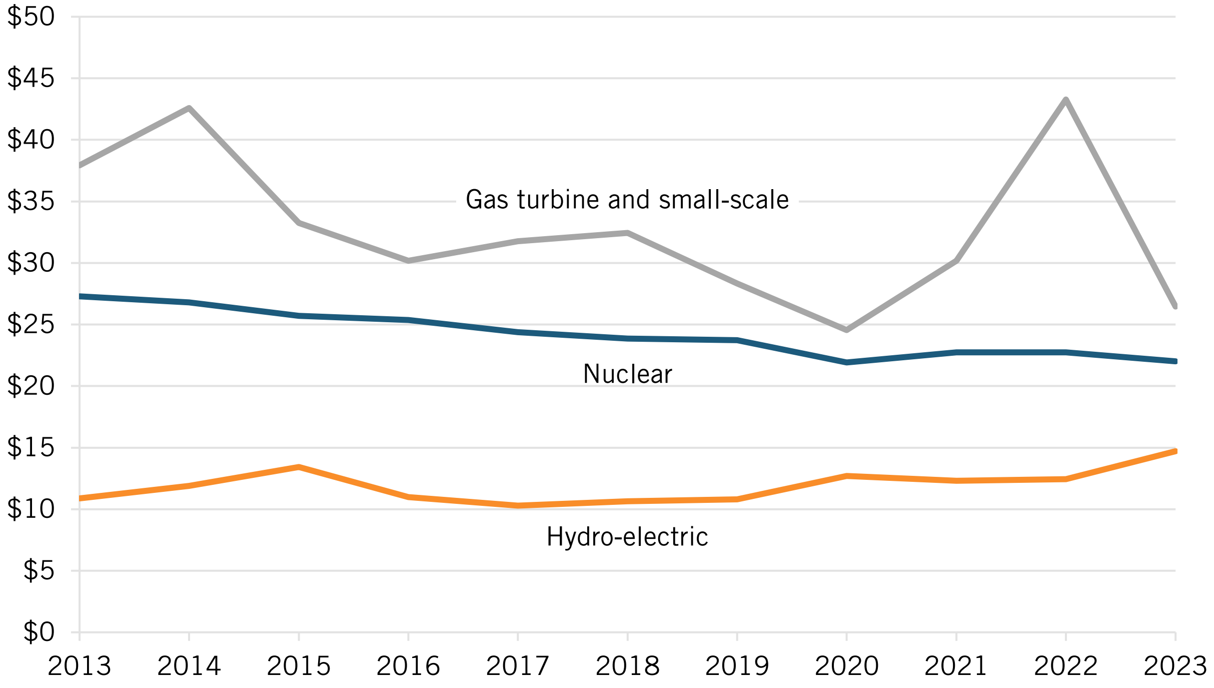
Lower Up-Front Capital Costs

While SMRs have not yet proven that they can generate energy at a lower levelized cost (per MWh) than large nuclear plants (or other competing energy sources), they will definitely require less capital expenditure up front. First-of-a-kind construction is expensive, but even so, a 300 MW SMR facility will require much less up-front capital than a standard 1,000 MW nuclear plant will. Even if overnight costs for first-of-a-kind construction are $10,000/KW (similar to the cost of recent large plants in the United States and Europe), a 100 MW SMR would require on the order of $1 billion in overnight costs, rather than the $10 billion potentially needed for a 1,000 MW plant.[26] Lower capital investments mean lower risks, and create opportunities for projects financed from a wider range of partners.

Low Operational Costs

A survey from the Nuclear Energy Institute indicates that both operational and fuel costs for nuclear reactors have been falling fairly steadily in the United States, and amounted to about $24/MWh in 2022.[27] That’s similar to data from the U.S. Energy Information Administration (EIA), which compares operating costs for nuclear, gas, and hydroelectric power (see figure 4). Fuel and operating costs for combined cycle gas turbines (CCGTs) (the most widely used and cheapest gas technology) vary based on factors such as the price of gas, the turbine technology being used, the maintenance schedule, and even the ambient temperature. Typically, fuel accounts of 60–70 percent of CCGT operating costs, and fuel costs—perhaps especially gas—can spike unexpectedly, as they did in Europe after the Russian invasion of Ukraine. Operating costs for gas have historically been at least $4/MWh more expensive than nuclear (and are currently just over 20 percent more expensive). However, it is also possible that new kinds of fuel for SMRs will be more expensive, at least initially, especially ais most currently propose to use HALEU, which requires more-expensive processing.

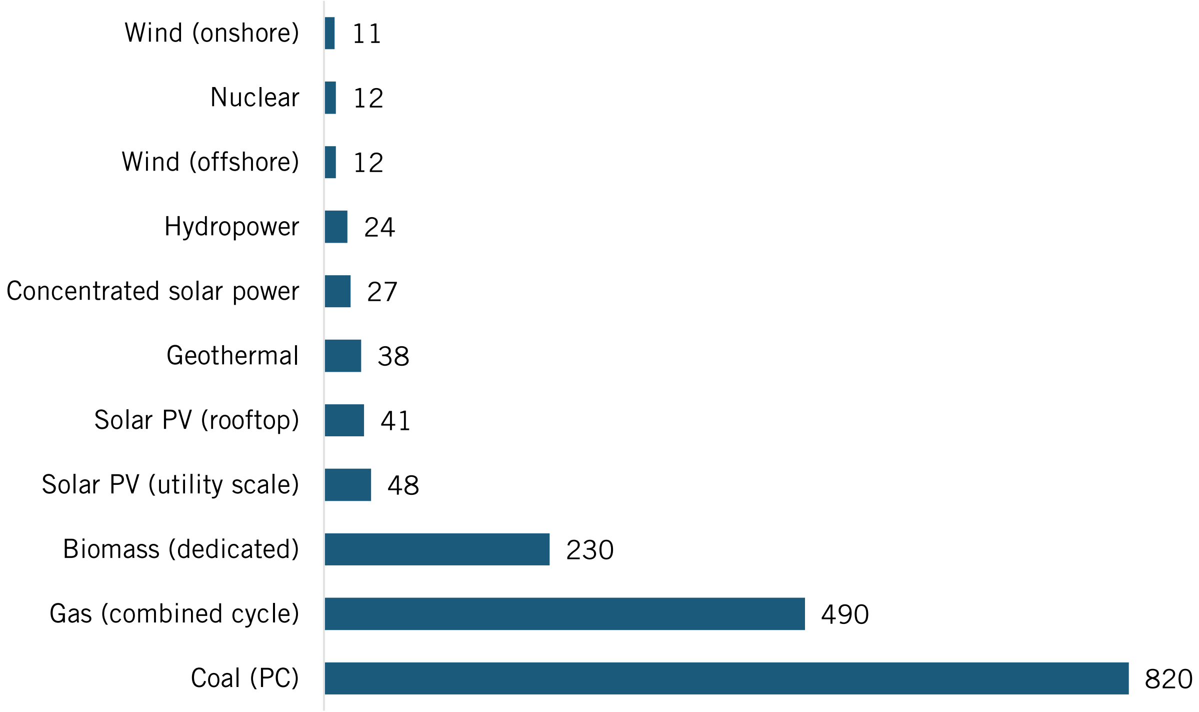
Figure 4: Operating costs per MWh for selected technologies in the United States[28]



Low Life-Cycle Emissions

SMRs produce zero greenhouse gases from operations, so their life cycle emissions come from mining and enriching uranium and also the construction of SMRs. Emissions from large nuclear reactors are far lower than those for fossil fuels, and are around one quarter those of solar. It's reasonable to expect that life cycle emissions for SMRs will be roughly similar. Critically, therefore, SMRs offer clean power—much cleaner than fossil fuels do (see figure 5). If they didn't, there would be little reason to pursue them.

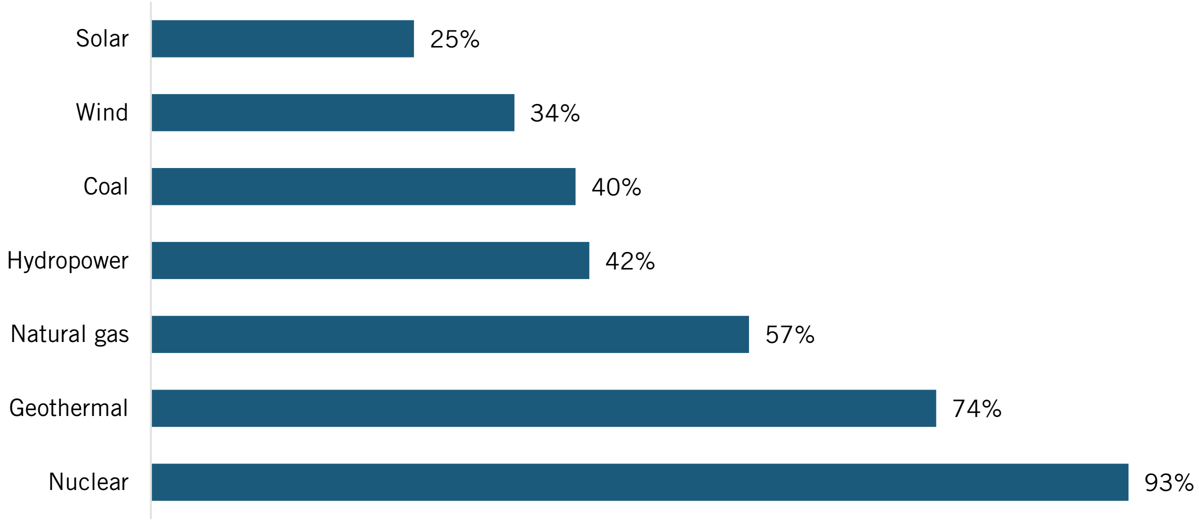
Figure 5: Average life cycle of carbon dioxide (CO_2) emissions (grams of CO_2 equivalent per KWh)[29]



Firm Power, Reliability, High Capacity Factors, and Low Systems Costs

In sharp contrast to wind and solar, nuclear plants are extremely reliable—they provide firm power that's available almost all the time: their capacity factor averages 92.5 percent in the United States, far higher than other energy sources (see figure 6).[30] That offers certainty about electricity supply, which is especially important for certain users. Data centers offer their customers contracts that guarantee more than 99.9 percent uptime; they will need correspondingly reliable energy sources to meet that level of performance.

Figure 6: Capacity factor by U.S. energy source[31]



Downtime for reactors is almost entirely predictable. (Almost! France recently suffered unexpected problems with some of its reactors, as did TVA in the United States.) Downtime is usually caused by scheduled maintenance or refueling time (about every 18 months for large reactors, lasting about a month). SMRs are designed to require less-frequent refueling (or swap out): mostly every three to seven years, depending on the design. Refueling outages should therefore be less frequent, and capacity utilization correspondingly higher.

Further, unlike wind and solar, power output from nuclear is highly predictable. Adopting nuclear—either large reactors or SMRs—can reduce the need for balancing capabilities such as banks of lithium-ion batteries for short-term storage, or the use of natural gas to address long-term variation.[32] The additional system costs for nuclear are much lower than those of wind and solar as well, especially as transmission costs may be lower because of siting flexibility.

Footprint and Siting Flexibility

Both wind and solar require a large land footprint. Of course, the United States has a lot of land, but a PV solar plant generating 1,000 megawatt electrical (MWe) would require 5–10,000 acres, depending on location, according to the National Renewable Energy Laboratory (NREL).[33] A similar-scale nuclear plant would require only about 640 acres. And SMRs have a much smaller footprint than large reactors; for example, a proposed NuScale 920 MW plant would require about 35 acres.[34] A radically smaller footprint also opens the door to a much wider array of potential sites.

Longevity

Nuclear plants last far longer than any other source of energy except possibly hydro. We are seeing plants lasting beyond 60 years now, and it seems likely that, for some at least, the operating lifetime is 80 years or more, based on research on nuclear plant sustainability conducted by DOE. In December 2019, NRC staff approved a renewal application for Turkey Point Nuclear Units 3 and 4 in Florida, allowing operations until 2052 and 2053, respectively—the first time NRC extended a plant lifetime to 80 years.[35] This could transform the financing of nuclear plants; longer lifespans reduce the average lifetime cost of energy by spreading the heavy capital costs of nuclear plants over a much longer period of operation. In contrast, CCGT gas plants have a nominal lifetime of 25–30 years.[36] However, it remains to be seen whether SMRs last as long, especially as there may be trade-offs between longevity and higher temperatures.

Avoiding Costly New Transmission Lines

The need for new transmission lines has become a major concern in the United States as well as other countries such as the United Kingdom, where curtailment caused by lack of transmission has become a real problem. The United Kingdom generates most of its wind energy—which is quickly becoming the dominant source of power for the grid—in Scotland and the north of England, while most demand is in the south. As a result, Scottish wind farms were paid £1.4 billion in 2023 to not produce electricity because there was no room on transmission lines to the south. The new state-owned U.K. grid operator estimates the cost of grid expansion to fix this at £40 billion pounds annually through 2030 (the gross domestic product (GDP) equivalent of about $360 billion annually in the United States).

New transmission lines are needed for many reasons: they make the grid more reliable and resilient by interconnecting regional grids, and that could also help to balance the variability of wind and solar, and to provide markets for variable power that may be produced hundreds of miles away from eventual users (as in the United Kingdom). But the United States currently builds only a fraction of the transmission lines it already needs for these purposes. The interconnection queue waiting for approval at FERC is currently five years long, while the UK example shows how expensive building out sufficient transmission might be.[37]

SMRs could avoid both the cost of transmission, by collocating them with end users such as data centers, and by avoiding the FERC interconnection queue by locating them "behind the meter" (i.e., entirely off the public grid). Those avoided costs are major benefits not captured in simple formulations focused on the immediate levelized cost of energy production.[38] Hence, the interest from data centers.

Nuclear Power and National Security

Civilian nuclear power plays a minimal role in U.S. national energy security; domestic fossil fuel reserves are enormous, and the United States has substantial (and by global standards, reasonably efficient) wind and solar resources as well. Civilian nuclear power plays a much more prominent role in national security for other countries, as it offers the promise of independence from energy sources that can become too expensive or unreliable. The Russian gas crisis after the invasion of Ukraine underlines the fragile state of energy security in much of Europe. Unsurprisingly, countries around the periphery of Russia—Romania, Poland, Hungary, Czech Republic, Finland, Slovakia—are exploring or building new nuclear reactors. Slovakia, Czechia, and Hungary already depend on nuclear for at least one-third of their energy supply.

- Poland is buying three reactors from Westinghouse (at $16 billion), and three more from South Korea's KHNP. It aims for a 30 percent nuclear share in the energy supply mix.
- Hungary is building on nuclear links to Russia, expanding the Russian-built Paks site with two new 1,200 MW reactors (estimated cost: €12 billion, but now years behind schedule). This is partly a like-for-like replacement for existing capacity.

- Czechia aims to phase out coal by 2033, replacing it in large part with nuclear by adding one or possibly two reactors to the existing Dukanovy plant, plus two more reactors at Temelin. The first contract has been let to KHNP.
- Slovakia recently completed a new 471 MW reactor at Mochavce (under construction since 2008), and another unit is planned this decade.
- Romania is adding two 700 MW units at Cernavoda (estimate cost $8 billion), for completion in 2031. The engineering contract has been signed with Canyu. The Romanian state is providing a full guarantee of costs, as well as operating subsidies via a contract for difference. A joint venture with NuScale is exploring an SMR at Doicesti.

In this context, it is perhaps not surprising to hear that "Romania is taking firm steps towards energy independence and becoming a net energy exporter," according to then-PM Nicolae Ciuca.[39] More generally, provided that the nuclear supply chain can be globalized away from dependence on Russia, nuclear power offers significant national security benefits: the energy effects of Russia's invasion demonstrate to these countries the need for more energy autonomy very clearly. Those benefits could apply to SMRs once they are price competitive with large nuclear reactors.

RISKS FOR SMRS

The dramatic cost overruns and delays on recent large nuclear projects in the United States, United Kingdom, France, and Finland explain why building nuclear is regarded as a high-risk operation. A lot can go wrong, and capital costs are huge to begin with. Risk therefore provides a useful lens through which to explore the challenges facing SMRs.

Investors in SMRs face four kinds of risk:

1. **Technology risks** are inevitable as companies introduce new technologies to the market. Sometimes technologies just don't work as expected.
2. **Market risks** can be divided into supply-side risks (the possibility that a company will be outcompeted, or that critical supply chains will fail, for example) and demand-side risks (e.g., the possibility that expected markets will not materialize at the right price, or perhaps at all).
3. **Political risks** reflect the reality that—as Germany and Japan demonstrate—the political appetite for nuclear power can change, sometimes dramatically.
4. And because nuclear power is tightly regulated, there are substantial **regulatory risks** as well, especially as the regulatory pathway for SMRs is not yet well defined.

All these risks are real, as the main U.S. nuclear contractor (Westinghouse) can confirm (it went bankrupt in 2017).

Technology Risks for SMRs

SMRs have already divided into two broad technology pathways. Some companies, such as NuScale, have decided to use existing technology scaled to the needs of their smaller reactors; it uses existing PWR technology. That's partly why NuScale has already had its design certified by NRC. Others (e.g., Copenhagen Atomics) have opted for more innovative non-PWR designs

(Copenhagen is based on molten salt as a coolant). However, even reactors using PWR technology will need significant innovation such as helical coil steam generators, internal control rod drive mechanisms, new in-vessel instrumentation, and perhaps new fuel combinations and configurations.[40]

In contrast, alternative technologies offer a range of potentially significant performance benefits beyond possibly lower long-run costs:

- **Higher operating temperatures** potentially increase efficiency (reducing fuel costs and increasing output per reactor) and could allow for more uses for industrial heating and thermal applications more generally.
- **Potential for improved fuel utilization** that would reduce fuel consumption, which in turn reduces fuel costs and—perhaps more important—extends the period before refueling (and hence downtime) is needed. Innovative SMRs may use different fuels altogether: molten salt breeder reactors can for example use thorium instead of uranium, and can act as a breeder reactor using spent nuclear fuel (SNF) from other reactors.
- **Lower operating pressures** would potentially reduce containment requirements and hence both construction costs and perhaps regulation-related compliance costs.
- **Some designs offer inherent proliferation resistance** by using fuel formulated in ways that are resistant to easy extraction and would require considerable further processing before they could be used for weapons.

These new designs are likely to be higher risk. They do not have decades of use behind them, and the technology trade-offs pale in comparison to the primary risk: that the design will not work as expected, and will either fail or require substantial revision (and associated delays). That risk is lower for SMRs based on well-understood existing technology; advanced design SMR companies are betting that the benefits of new designs will outweigh the additional risks. We will find out who was right sometime in the mid-2030s.

Is Enough Iteration Possible?

Today, SMRs are at a stage of development roughly analogous to the U.S. auto industry in 1900—when there were more than a thousand companies making autos, using multiple technologies, in a frenzy of experimentation. By the early 1930s, internal combustion engines (ICE) had won out over electric and steam, the industry had consolidated into three dominant companies (Ford, GM, and Chrysler) plus a handful of others, and mass production led by Ford had opened the door to the cheap cars that drove the American Dream. To get there, the 1,000-plus auto companies operating in 1900 raced to iterate—new designs, new technologies, new ways of manufacturing, new marketing strategies.

In SMRs, not only are there no clear winning companies yet, but also the basic technology has not yet been defined. In 1900, steam-powered cars outsold ICE and electric vehicles, but we all know what happened after that.[41] Today, SMR designs include at least four different kinds of coolants, for example, and multiple different fuels among many other varying design choices. We still don't know what the SMR equivalent of internal combustion will be.

Further, there are clear tensions between innovation and cost certainty. In order to find the best technologies, markets, and solutions, SMRs will need to innovate—probably many times. But innovation is the enemy of replication and hence scale: Building the first of a kind is both more expensive and riskier. The experience with nuclear more generally shows that the path to reduced cost is through focused exploitation of a selected technology which can be replicated and (for SMRs) manufactured rather than stick built.

Clients have clearly gotten the message, and nuclear power suppliers are now being forced to address this tension. EDF, the French national champion in nuclear energy, has now abandoned years of work on innovative SMR designs and will return to PWR technology to meet the demands of its customers who require certainty that energy will be produced at a levelized cost of €70–€100/MWh. To do that, it will use only proven technologies.[42]

Box 3: Early Auto Industry Technology Innovations in the United States

In the first three decades of the 20th century, the auto industry developed and then adopted scores of important innovations, including the following:

- Electric ignition starters: Invented in 1911 and made standard by the late 1920s, these allowed drivers to start the engine with a button instead of a manual hand crank.
- Drive-in service stations: The first drive-in opened in Pittsburgh in 1913, offering services such as lubrication, tire repairs, and washing.
- Automatic transmission: The Sturtevant brothers of Boston developed an early automatic transmission in 1904.
- Air-cooled engine: General Motors developed an air-cooled engine with copper fins to disperse heat for the 1923 Chevrolet.
- All-steel body: This innovation was adopted by the Dodge Brothers in 1914.
- Hydraulic brakes: These were invented in 1919 and first adopted by Duesenberg in 1921 to replace mechanically actuated drum brakes.
- Synchromesh transmission: This easier-shifting device was invented in 1924.
- New pyroxylin-based paints, eight-cylinder engines, four-wheel brakes, and balloon tires: These innovations were the biggest trends for 1925.[43]

Iteration is also difficult in a tightly regulated environment, as every significant design change will presumably need to be approved by the NRC, and could potentially reopen NEPA litigation pathways. This will tend to make SMR iteration *slooooow*. And because it takes many years to deliver even first-of-a-kind reactors, cross-pollination between companies is also drastically slowed. Hydraulic brakes were invented in 1918, and had become industry standard a decade later. It's hard to believe anything similar will occur so quickly for SMRs.

Finally, it is not clear how the NRC will handle iteration. In general, reactor designs are tightly specified, and only those exact designs are approved when replicating. It is not obvious how the NRC would even begin to think about what is a "significant" design change and what is not, especially as regulation has moved toward a probabilistic model where cascades of small problems are seen as important. However, if all design changes are important, then any change could perhaps trigger the need for NRC review and potentially recertification. Of course, firms will need to do their own due diligence on safety, but we don't know how much extra work will be demanded by the NRC. It’s also possible that AI will play an important role in the development of simulations to carry some of the regulatory burden.

Transporting SMRs

The point of SMRs is that they are at least in part built in a factory. Smaller microreactors could perhaps be built entirely in a factory and then loaded onto a large tractor-trailer for transport. Larger ones will be partly built on-site. Rolls Royce’s huge 470 MW SMR is in part built using Rolls’s turbine manufacturing skills and technologies in a factory. But it will require 2,000 container loads to deploy, and will then be assembled on-site. Microreactors, in contrast, can be designed around the limitations of a single large container-sized truckload.

Transportation for small nuclear reactors is not new. Eighty-three nuclear powered ships and submarines are currently operated by the United States, for example. Submarines seal radiation behind a heavyweight barrier at an aft bulkhead while allowing radiation to escape in other directions (into the sea—hence, divers cannot safely operate while the reactor is running). Nuclear powered aircraft carriers are essentially small floating cities, big enough to accommodate the enormous amount of shielding and the multiple layers of safety provisioning that are required.[44] There have been smaller experiments as well: The U.S. Army built truck-mounted reactors in the 1960s (the ML-1), but that project failed. It is now trying again with Project Pele.

Box 4: The U.S. Army’s Portable Nuke: The ML-1

The ML-1 was an experimental mobile nuclear reactor developed by the U.S. Army in the early 1960s, featuring a unique design: a nitrogen-cooled, water-moderated reactor with a nitrogen turbine energy conversion system.

It was engineered to be highly portable, transportable in six containers weighing approximately 38 tons total. It could be moved by C-130 aircraft, trucks, or rail. Its low weight, however, meant reduced protection, and it required humans to stay 500 feet away.

The ML-1 project faced significant technical challenges. The experimental heat engines generated only two-thirds of planned power output. There were other issues as well: poor compressor performance, cracked moderator water tubes, and failure of internal regenerator insulation. The project was ultimately abandoned due to increasing Vietnam War expenses, budget constraints, technical difficulties, and caution regarding premature field testing.[45]

SMRs face several transportation challenges, including:

- potential mechanical stress during transportation;
- radiation shielding during transit;
- securing nuclear materials against potential accidents or external threats; and
- maintaining reactor integrity during movement.

The physical challenge of transporting reactors. SMRs range from 20 to 300 MW—one third to 1/50th the size of large reactors.[46] But even the smallest are still large pieces for equipment. Trucks are the most flexible and cheapest form of transportation for reactors but face significant size constraints.[47] Trains and barges can handle much bigger equipment in one trip, but are far less flexible. Barges can work only where the infrastructure is available to offload heavy machinery. Trains work only where there are train tracks.[48] Both still require additional transportation after delivery, in most cases. Vessel size determines whether a reactor can be transported in one piece. The 77 MW NuScale VOYGR SMR modules are smaller than many SMR designs, but will still weigh 700 tons in total, and must be shipped in at least three different segments.[49]

DOE's nuclear fuel management program has funded development of new railcars for transporting SNF to the consolidated interim storage facility. The railcar project took 10 years to complete and cost approximately $33 million before receiving regulatory approval.[50] It is also providing $16 million for R&D of containers specifically designed for transporting HALEU fuel. Presumably, this research will be completed in time to meet demand when HALEU SMRs become commercially available.[51]

Security in transit. The transportation of a nuclear reactor presents new security vulnerabilities. SMRs may be fuel loaded before transit, and there will (if successful) be many SMRs on the move, so there will be a lot more nuclear material in transit to protect.

Radiation leakage is the greatest risk from the transportation of SMRs. While most SMRs will be transported in pieces and fueled on-site, some will be fabricated and fueled in a factory.[52] Radiation exposure for those reactors must be limited to safe levels throughout transit, but the NRC and the International Atomic Energy Agency (IAEA) have yet to provide meaningful guidance, and DOE does not appear to have committed to following IAEA's international standards on nuclear packaging covering its composition, material categorization, documentation, and labelling.[53]

The U.S. Environmental Protection Agency (EPA) is the regulator for nuclear transportation (once it meets a threshold of radioactivity). Highly radioactive packages must be encased in specially designed casks that are tested against extreme accident conditions (e.g., being dropped from 30 feet in the air, or onto a steel spike, or burned in a gasoline fire for 30 minutes, or submerged in water for eight hours).[54] However, EPA has not yet offered even draft regulations for SMRs, and it is not even clear whether a fully fueled reactor should be regulated as a reactor (and hence perhaps by NRC) or as a fuel package to be regulated by EPA. The former would be a new approach for regulators.

The transportation of SMR fuel is a source of additional concern. Because the HALEU fuel required by most new SMRs is more highly enriched than fuel used in large PWR reactors, new packaging for that fuel will likely be necessary.[55] It is not yet clear how IAEA—or U.S. agencies—plan to adjust existing transportation regulations for these new more radioactive technologies.[56]

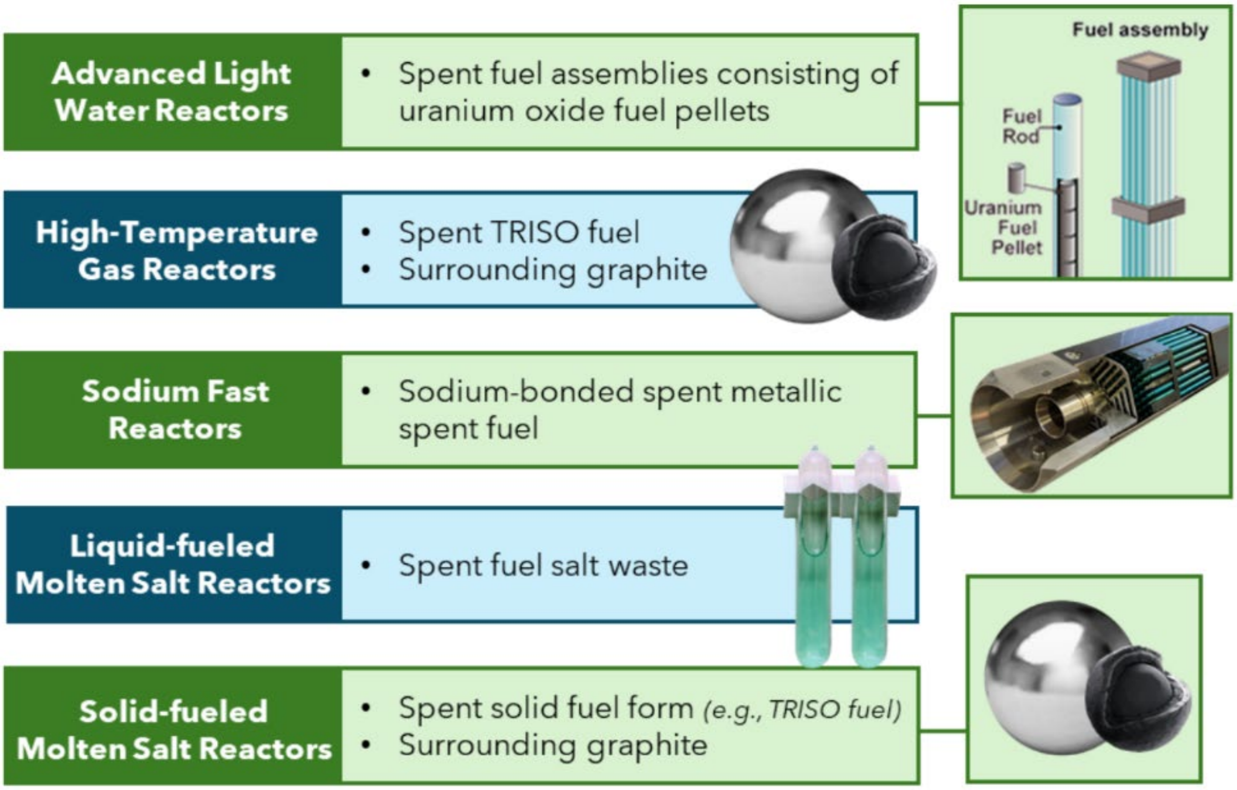
Transportation issues have been largely avoided by SMR companies in their public statements, while regulatory agencies are just beginning to address SMR-specific issues in transportation. Radiation risks, size and mobility, security, cost implications, and regulatory peculiarities are just the tip of the iceberg, suggesting that there will be a lot of work to do, even though nuclear fuel and nuclear waste have been transported across the United States for many years, and the absence of nuclear incidents suggests that these regulations are effective.

How Will SMRs Handle Their Waste?

Nuclear waste will vary substantially depending on the nuclear technology used and a company's design (see figure 7). Broadly, nuclear waste is divided into three categories: low-level nuclear waste (LLW or Class C); intermediate-level waste (known as “greater than class C waste” or GTCC); and high-level nuclear waste (HLW).[57] LLW can include protective clothing and equipment (e.g., gloves, coveralls, and shoe covers); filters used to clean air and water systems; tools and instruments used in reactor maintenance (e.g., wrenches, gauges, and monitors); and materials from decommissioning as plant systems, structures, and components are removed, including concrete, piping, wiring, and metal structures, all of which may become contaminated.

GTCC waste includes used fuel from commercial nuclear power plants, from radioactive medical waste, industrial and research activities, and from DOE itself (especially from nuclear armaments and the cleanup of legacy facilities).

Figure 7: SNF generated by different kinds of reactors[58]



Advanced Light Water Reactors	• Spent fuel assemblies consisting of uranium oxide fuel pellets
High-Temperature Gas Reactors	• Spent TRISO fuel • Surrounding graphite
Sodium Fast Reactors	• Sodium-bonded spent metallic spent fuel
Liquid-fueled Molten Salt Reactors	• Spent fuel salt waste
Solid-fueled Molten Salt Reactors	• Spent solid fuel form *(e.g., TRISO fuel)* • Surrounding graphite

As of 2024, there were four U.S. intermediate disposal sites that could take LLW that is not suitable for local disposal. LLW from advanced reactors (including SMRs) should be accommodated within these four sites. In May 2024, NRC issued a proposed rule that would authorize the near-surface disposal of some GTCC, but there has been strong political opposition to constructing a facility, particularly from the governors of Texas and New Mexico. Currently, DOE needs congressional action before it can move forward on GTCC disposal, under the Energy Policy Act of 2005.[59]

HLW includes both SNF and waste products from the reprocessing of that fuel. [60] The United States, under intense political pressure, has abandoned efforts to build an HLW facility at Yucca Mountain in Nevada. However, other countries are moving forward.

Finland’s Onkalo repository is the first HLW site to begin trial operations. Originally designed to accommodate 6,500 tons of SNF, it has since increased capacity to 9,000 tons, and new tunnels will be constructed in parallel with operations.[61] In France, the Cigéo project aims to store waste in a 500-meter-deep clay layer, and should be operational by the late 2030s.[62] Canada's Nuclear Waste Management Organization is developing a repository expected to open by the 2040s, with site selection now completed in partnership with local communities. [63]

Sweden's Forsmark repository will encapsulate waste in copper canisters and then store it in bedrock. It will have 500 tunnels at 500-meter depth, with the capacity to store 12,000 tons of SNF. It is designed to last 100,000 years. Construction has been approved, but will take approximately 70 years to complete. Other countries such as Slovakia are looking to Sweden's approach as a model.[64]

Hungary, Bulgaria, and the Czech Republic are also making progress. Hungary is expanding its geological disposal plans, while Bulgaria is exploring deep borehole technology.[65] The Czech Republic is reviewing sites for a final repository, with a decision expected by 2030.[66]

In contrast, Germany and Belgium are struggling. Germany is looking for ways to store approximately 28,000 cubic meters of HLW. A search for a final repository began in 2013, but a location decision is not expected until at least 2074, with construction expected to take another 20 years.[67] Belgium has begun construction of a surface disposal facility in Dessel for LLW and GTCC but has not found permanent storage for more hazardous materials.[68] The Netherlands is not expected to commit to a final disposal site until around 2100, focusing instead on storing HLW from its Borssele nuclear power plant in solidified glass containers.[69]

China has 46 nuclear reactors currently operating, with 11 more under construction. It will store high-level waste in a stable geological formation 500–1,000 meters underground, and is expecting construction of a final repository around 2050.[70] Industrial-scale disposal of LLW and GTCC occurs at three sites, the first phase of five planned regional disposal facilities.[71]

China is also exploring a closed nuclear fuel cycle strategy wherein SNF is first stored and then reprocessed for use in fast reactors. It operates a pilot reprocessing plant in Gansu, and is partnering with France to build a new plant capable of producing mixed oxide fuel for PWRs. China is also exploring fast (breeder) reactors; construction of the first commercial unit (1,000–1,200 MWe) could start in December 2028, with operations expected in 2034.[72]

In the United States, NRC is still seeking a deep geological repository for permanent storage. But no such facility exists for commercial nuclear waste, and none is currently under development since the collapse of the Yucca Mountain project in 2010. The only operating deep geologic disposal site in the United States is the Waste Isolation Pilot Plant (WIPP) in New Mexico, created to store defense-related transuranic waste. WIPP experienced a major accident in 2014, leading to significant delays and repair costs. Estimated costs to fix the facility are up to $2 billion, and full operations cannot resume until a new ventilation system is completed—perhaps in 2026.[73]

In the absence of any permanent deep geologic sequestration site, SMR companies are developing plans to store SNF indefinitely in interim storage facilities that they will build on-site. TerraPower and X-energy have both submitted relevant plans to NRC for approval, which suggests that this could be a model at least for larger SMRs.[74] DOE has also announced plans to develop a federal consolidated interim storage facility for SNF, with an initial capacity of 15,000 metric tons (with expansion potential).[75] However, it is much less clear how SNF will be managed for much larger numbers of microreactors.

Overall, while significant progress has been made in certain countries, the safe, permanent disposal of nuclear waste remains a pressing challenge across Europe as facilities fill up and new solutions are developing slowly. The United States has essentially abandoned efforts to find a permanent deep geological storage facility for HLW, and is focusing instead on intermediate storage.

For SMRs in particular, there appears to have been minimal thinking about waste disposal, in part because locations have not yet been decided on. SMRs that use standard fuel will presumably fit within the basic schema currently being operated by DOE, with waste stored at interim facilities. Some more-innovative designs may generate substantially less waste, and in particular less HLW. MSRs, for example, could be designed as breeder reactors.

SMRs and Security

The cost of security for nuclear reactors is nonlinear. Protecting a 1,000 MW site is not 10x more expensive than protecting a 100 MW site, and that in turn is not 5x the cost of protecting a 20 MW site. Some critics have argued that these nonlinear costs will make SMRs relatively more expensive. While most site-level security costs are hidden behind corporate privacy, analysis suggests that for large nuclear sites, direct security costs account for roughly 5 percent of annual operating expenses.[76]

Aside from providing for physical security, SMRs can also be less-attractive targets for acquisition and capture—they can use lower levels of uranium enrichment and can also make fuel extraction very difficult (e.g., by integrating fuels into other materials). But they may still be targets for *destruction*, acting as a kind of radiation bomb for bad actors. Site-level security is therefore another area where regulators and companies will have to develop suitable programs and metrics specifically for SMRs.

Market Risks

SMEs face substantial risks on both the supply and the demand side of the market.

Supply Side

Supply-side risks encompass all the possibilities on the production side that could lead an SMR company to be outcompeted and eventually fail. In part, these risks are a story about the competition, to which we will return shortly. But they is also a story about construction.

Construction Risks

Bluntly, the construction of large nuclear plants has been a story of relentless overpromising and under-delivering, of construction that takes much longer and costs much more than expected. The time to construct a large reactor grew from around 5 years during the 1960s nuclear boom to more than 10 years. That led to a tripling of overnight CapEx in real terms.[77] It is now estimated that Sizewell C in the United Kingdom will cost £40 billion for 3.2 GW of power—up from £16 billion at inception. French, Finnish, and U.S. plants have suffered similar though not as extreme delays. Even in France, where nuclear is the largest source of power and where EDF has been building plants for decades, costs have ratcheted up significantly. More broadly, a 24-month delay in plant construction is associated with about a 10 percent increase in the levelized cost of energy.[78] Thus, SMRs operate in a world where the likelihood that nuclear construction will be delivered late and well over budget is a very present risk.

SMRs should avoid some of this construction risk, as they are partly or wholly built in a factory and then simply delivered and installed on-site. This process should be much shorter overall than large nuclear construction. Of course, SMRs still need containment and control structures, and connection to the grid, but the cost of the actual reactor might be cut substantially. However, that does not mean SMRs can entirely avoid construction risks: the failure of NuScale's pilot project in Utah is explicitly tied to inflation in construction costs (see box 5).

Box 5: NuScale's Failure in Utah

NuScale's proposed flagship SMR project in Utah has closed because it became uneconomic, as the projected cost of construction increased by 75 percent (to $9.3 billion) between 2021 and 2024. As a result, the estimated cost of electricity per MWh increased from $58 to $89, even after including a $30/MWh subsidy under the Inflation Reduction Act (IRA).

NuScale is seen by industry critics as the canary in the SMR coal mine, arguing that the most advanced commercial deployment for SMRs in the United States has failed, and therefore SMRs are a failure. This seems premature at best.

Scaling Risks

For SMRs to reach P3, they must scale, and costs of production must fall dramatically. One primary market risk is that this promise simply will not be fulfilled. Any of the following could happen:

- No single company gains enough market share to build an order book sufficient to justify factory production. It's also possible that the SMR market as whole will not reach that level of production.
- Factory production doesn't generate the necessary savings. Just saying "factory" isn't sufficient. Production lines don't have to churn out millions of copies to be efficient at reducing costs—Boeing only makes about 500 planes a year. But companies do need enough throughput to justify setting up a production line. And then that production line has to generate real cost reductions.
- Learning by doing—one important component of cost reduction—delivers less savings than expected. We won't know until we get there, but the assumptions and related results in DOE's Liftoff report seem ambitious.[79]
- The factory-built share of total cost doesn't contribute enough to cut overall costs sufficiently. Ironically, as the cost of factory-built reactors falls, the importance of other costs rises. It was massive increases in the cost of cement and steel that primarily sank NuScale's first-of-a-kind demonstration project in Utah.
- Supply chain problems derail production. DOE is well aware that constricted supply of uranium could squeeze out SMRs. TerraPower, for example, has already delayed deployment because it could not get sufficient access to HALEU fuel (it has since made new agreements with South African sources).[80]

In short, factory production is doing a lot of heavy lifting in the anticipated reduction in SMR costs; so far, there is no data against which to assess these projections.

The Competition Is Too Strong

Beyond costs, competitive energy technologies offer a different supply-side challenge. In the United States, that competition comes from multiple directions:

- **Gas.** Natural gas is by far the cheapest source of firm 24/7 power in the United States. It's relatively quick and simple to build more CCGT and peaker plants, and natural gas is almost ubiquitous. However, this is largely a U.S. phenomenon. Europe is suffering because gas is expensive and it is largely dependent on flows from Russia. The latter may be mitigated by more liquefied natural gas imports, especially from the United States, but those won't be cheap.
- **Coal.** While coal is cheap, it is clearly on the way out—but only in the United States and perhaps Europe. Germany is turning to coal for dispatchable power when its wind-based generation fails. In India and China, coal use is growing rapidly, and remains the cheapest form of energy—and hence the most formidable competitor—in much of the developing world.
- **Large nuclear reactors.** It's possible that, in the end, SMRs won't have significant cost advantages over large reactors. Big reactors do have economies of scale in site construction and operations. Those could perhaps more than balance out reactor cost advantages for SMRs, even if cheaper factory-built reactors become a reality.
- **Other clean energy.** Wind and solar are widely expected to eventually dominate the energy matrix. While their total system costs must include necessary storage and often new transmission (both costs that are often ignored by wind and solar enthusiasts), energy from wind and solar is cheap now, and getting cheaper.
- **New technologies.** There are promising new technologies on the horizon that could provide firm dispatchable energy, notably geothermal and fusion. Geothermal could become important within a decade, if the initial results from Fervo prove out.
- **Transmission.** If out-of-area energy from across the grid became cheaper and more available, the need for localized firm power would decline, reducing the market incentives for SMRs.
- **Batteries.** Similarly, continued rapid cost declines and capacity growth for batteries—perhaps especially in combination with improved transmission—might also make SMRs less competitive.
- **International competition.** Nuclear construction is currently dominated by China (CNNC), Korea (KEPCO), and Russia (Rosatom). China currently has 58 reactors built and 29 under construction. Rosatom is expanding into 13 countries. And KEPCO is building plants in the UAE and countries near the border with Russia. These are all large reactors; Russia and China are working hard on SMRs as well.[81]

It's worth noting that the competition in each of these areas is not standing still; wind and solar and batteries, for instance, are all still getting cheaper. And evidence from the U.S. nuclear investment winter of the late 1990s indicates that financial investors seek to avoid exposure to performance risk for nuclear plants.[82]

Can Costs Fall to P3?

The eventual sustainability and success of SMRs hinges on the cost of the energy they can eventually provide. The promise of SMRs is that they will become cheaper at scale via a combination of factors: 1) multiple production of essentially identical units; 2) increased factory production and learning; 3) reduced construction schedules; 4) plant design simplification; and 5) unit timing.[83] We hope that those factors do drive down SMR costs. But because only two SMRs are currently operating at commercial scale, and they are in Russia and China, we have no actual operating data with which to work.

We do know a few things though:

- **Diseconomies of small scale.** While the case for SMRs is based on the potential to make all or large parts of each reactor in a factory, thereby generating genuine economies of scale, existing large nuclear plants will in some ways be cheaper than SMRs. The cost of control, operating, and safety does not scale linearly; it is not 10 times more expensive for a 1,000 MW reactor than for a 100 MW reactor. So per unit of energy, these nonlinear costs are higher for SMRs.[84]
- **First-of-a-kind penalty.** All the companies currently racing to get operational must pay the additional cost for implementing a first-of-a-kind reactor. The academic literature says that this is likely to be around 20 percent, but it could be much higher, especially if genuinely new designs are being implemented (e.g., not using pressurized water technology).[85] And costs do not magically then sink to nth of a kind (NOAK) as some proponents seem to suggest: costs decline along a curve as scale increases, steeply at first and then more gradually. The 2nd of a kind reactor will be cheaper, but probably still a lot more expensive than the 10th and then the 100th.
- **The baseline cost of nuclear.** SMRs will not just need to match the costs of large nuclear plants; they will have to become much *less* costly. Large plants have become more expensive in recent years—cost disasters have struck in the United States, United Kingdom, Finland, and France; only Chinese and Korean firms seem able to build large reactors at an overnight cost of approximately $4,000/KW, or $4 billion for a standard 1,000 MWe reactor. And even that is not directly price competitive—building equivalent gas generation costs around $775/KW, while similar costs for solar are $1,500/KW (not including batteries and other system costs), although assessing the levelized cost of energy for any fuel is an exceedingly inexact science once the cost of required complementary system investments are included.[86] And SMRs face an obvious chicken and egg problem: costs must come down very quickly to attract customers, but they can only become cheaper through scale, which requires sales.
- **Contingency costs.** Because construction costs for large nuclear plants have massively exceeded estimates, and SMRs are in any event a new approach, there are real risks that costs of construction and deployment will balloon, and deadliness will be missed. There are ways to insure against this, but the experience to date on contingency costs and delays with large nuclear has made it very unattractive to investors.[87]

- **Transitioning from a project to a product basis will be critical for cost reduction.** Once projects are completed, project teams typically dissolve. Products are managed differently, with sustained management and workforces. SMRs will need to get beyond project structures into products as quickly as possible.
- **Cost of capital.** Nuclear plants are highly capital intensive, so their overall costs are sensitive to the cost of capital. The Nuclear Energy Agency (NEA) estimates the projected impact of interest rate changes on the eventual cost of electricity produced, and it substantial. For example, a shift in interest rates from 4 to 8 percent leads to an increase in levelized cost of energy from <$60 MWh to more than $90 MWh.[88]
- **Getting to scale.** Any detailed cost estimates at this stage of development are on shaky ground. But there are some indicators. A well-designed effort to estimate first-of-a-kind costs, using a set of 16 industry experts, produced overnight costs for a NuScale-type reactor that ranged from $4,000/KW to $16,300/KW.[89] A 2016 report to the U.K. Parliament developed estimates for "optimism bias" in the anticipated overnight capital costs submitted by SMR vendors ranging from 54 percent to 200 percent (varying also by technology).[90] The uncertainty increases substantially when considering Nth-of-a-kind costs decades into the future.

More generally, nuclear costs are uncertain, as nuclear power construction times and costs have grown, not declined.

Bearing all this in mind, the following is true:

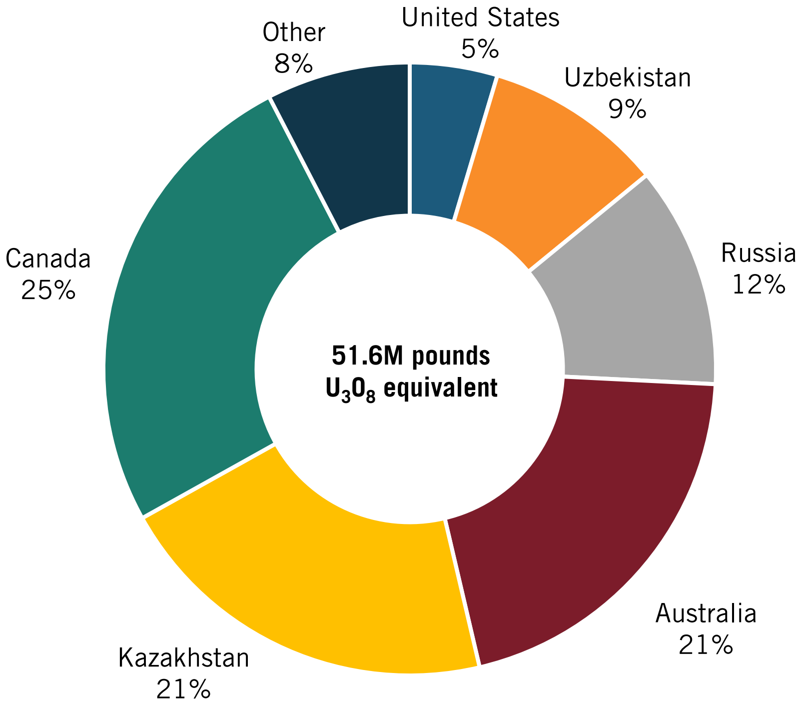
- SMRs could become cheaper than large reactors, but will initially most likely be at least as expensive per MWh.
- Wright's Law suggests that learning curves could eventually bring SMRs down to the region of P3, but this will require substantial scale. The standardization, modularity, and factory production of SMRs open the door to lower costs, but they have yet to be demonstrated.
- Scale will require that specific technologies win out (as the e.g., the ICE did in autos). It also requires that at most a few companies become dominant.
- There will be a tension between the need to get to scale and the need to innovate. MSRs, for example, have some significant advantages but are also more corrosive, while SMRS based on existing PWRtechnology s may get to market faster and hence damage the chances of other technologies reaching scale.
- Overall, initial costs of a first-of-a-kind reactor, plus increases in the cost of materials and the lack of an experienced workforce, mean that SMRs will initially be at best on par with the costs of large reactors. It is still too early to determine how costs will evolve from that point, although production at scale, use of passive safety features, an experienced workforce, and modularity will all tend to reduce costs.[91]

Can SMRs Build a Robust and Cost-Effective Fuel Supply Chain?

There will be challenges both in sourcing uranium and in enriching it so it can be used by SMRs, especially if SMRs do in fact scale.

- **Sourcing.** Russia, Kazakhstan, and Uzbekistan account for 48 percent of total uranium sourcing for the United States (see figure 8). Building a strategic industry on the back of this supply chain seems risky. But finding alternatives will take time—especially given the difficulties of developing domestic uranium resources. TerraPower, for example, has announced that it will delay its Natrium SMR project in Wyoming because it's been forced to switch its supply chain from Russia to new sources in South Africa.[92]
- **Enrichment.** Most planned SMRs will use more highly enriched uranium known as HALEU, which is enriched to between 5 and 20 percent. Centrus—the main U.S. producer—has noted, "A full-scale HALEU cascade, consisting of 120 individual centrifuge machines, with a combined capacity of approximately 6,000 kilograms of HALEU per year, could be brought online within about 42 months of securing the funding to do so."[93] But that's less than 15 percent of the amount DOE says would be needed in 2030.[94] Of course, that demand does not yet exist, and Centrus is expanding.

Figure 8: Sources of uranium for U.S. reactors, 2023[95]



Looking forward to 2050, the fuel supply issue is a potentially formidable problem. DOE estimates that HALEU production will need to ramp up from near zero in 2030 to 520 metric tons annually by 2050. Finding both the uranium and the processing capability at that scale will be a challenge; Russia currently controls 44 percent of global enrichment capacity, and U.S. firms are currently blocked from accessing that capacity by the ADVANCE (Accelerating Deployment of Versatile, Advanced Nuclear for Clean Energy) Act.

China plans to source one-third of uranium domestically, one-third from Chinese-owned foreign mines, and one-third from the open market. However, domestic uranium production uses low-grade ores often in remote mining locations, so Chinese nuclear power companies are ramping up international arrangements to obtain fuel.[96] U.S. companies may be locked out of existing sources.

Costs. While no firm usage data is yet available, it is possible to provide estimates for the cost of SMR fuel compared with that for large reactors. These suggest that SMR fuel, at least for PWR designs, will likely be significantly higher per MWh than for standard large reactors.[97] Of course, other designs (e.g., molten salt) will have significantly cheaper (and more easily acquired) fuel.

The Challenge From China

China and, to a lesser degree, Russia are furthest along in the deployment of SMRs. They are likely to be highly cost competitive with U.S. designs, and of course will benefit from the vast range of supports and subsidies that China bestows on industries it deems strategic. In both cases, national champions or the equivalent have emerged. In China, nuclear power development was controlled by a state-owned entity, but is now largely run through the China National Nuclear Corporation (CNNC), which controls most of the nuclear sector including R&D, engineering design, uranium exploration and mining, enrichment, fuel fabrication, reprocessing, and waste disposal. It also appears to be the major investor in all nuclear plants in China, which are managed or controlled by an array of state entities (the China State Power Corporation, State Nuclear Power Technology Corporation, State Power Investment Corporation, China Power Investment Corporation, and China General Nuclear Power Group).[98]

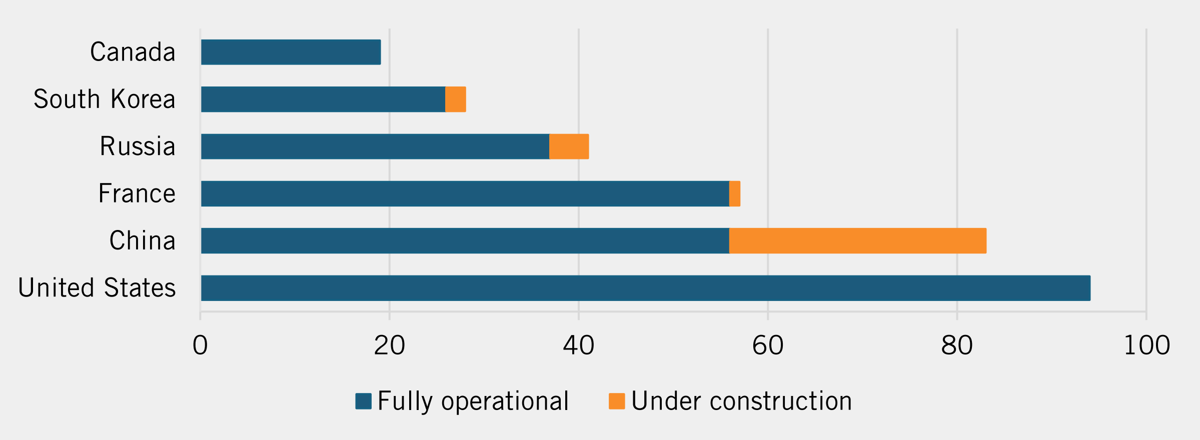
Much of the relevant performance data for Chinese reactors—including the degree of state subsidization—is hidden from outside view.

China also has a deep manufacturing base on which to draw, as well as substantial experience building larger nuclear reactors. Given the current political climate, Chinese reactors are not likely to be deployed in the United States or Europe. But other countries will not be so picky, so Chinese companies are likely to slide down the cost curve more rapidly than are U.S. companies, further extending their advantages.

Box 6: China and Nuclear Power

Although the United States currently has more operating reactors than does China (see figure 9), China intends to build 150 new nuclear reactors between 2020 and 2035, with 27 currently under construction and the average construction timeline for each reactor about seven years, far faster than for most other nations. It has made advanced nuclear power a priority strategic focus and is actively working to deploy all six types of fourth-generation nuclear reactors identified by the Generation IV International Forum.[99]

Figure 9: Nuclear power plants in operation or under construction, May 2024[100]



Advanced nuclear reactors are now reaching deployment: the Shidaowan-1 power plant is the world's first operating fourth-generation nuclear reactor, with two 250 MW high-temperature helium gas-cooled reactors; the Linglong One is a 125 MW SMR, using PWR technology (operational by late 2025).

China is currently also building two prototype floating nuclear reactors (FNNs). The 125 MW and 50 MW designs use PWR technology. Proposed uses include powering military bases, desalination, heating, and supporting sea oil drilling activities.[101] This has obvious implications for regional national security, given China's efforts to project military power in the South China Sea.

National security is also driving deployment. CNNC has already connected a 600 MW fast breeder reactor to the grid, plans to launch another by 2026, and is considering a commercial 1,000 MW fast breeder reactor. Calculations based on Indian plant designs suggest that a 500 MW fast breeder reactor can produce up to 140 kg of weapons-grade plutonium annually—enough for approximately 25–30 warheads.[102]

Demand Side

The door is opening for SMRs because utilities need more clean, firm dispatchable power to meet mandates from regulators, and because large end users such as data centers are also in principle committed to using clean energy. That is also true for industrial users seeking to decarbonize, in the chemicals industry, for example. For these end users, the lack of alternatives makes SMRs more attractive.

This demand is exacerbated by the sudden increase in projected demand for electricity. Electric vehicles (EVs) and other decarbonizing technologies are powering the switch from fossil fuels to electricity—a switch that is, of course, useless from a green perspective if that electricity is itself powered by fossil fuels. Utilities face the need for more capacity, and they are under pressure from regulators to make it as clean as possible.

However, the deregulation of the power sector in many countries creates further risks. For example, nuclear is now much more open to impacts (positive and negative) caused by shifts in the price of competing fuels. Significant increases in gas prices in Europe, for example, have made nuclear much more attractive there. Conversely, the fracking boom and subsequently lower prices in the United States made nuclear less competitive.

The reality is that demand—even new demand—is potentially fickle, especially if it is driven by regulation or political choices. The sudden emergence of big data as an ideal customer for SMRs (see New Markets section) is also potentially unstable. Data centers may find alternative sources of cheaper energy (they are already investing significantly in both gas turbines and solar plus batteries), especially if popular interest in green energy wanes. The projected demand from data centers could also quickly peak if AI training becomes much more efficient (as Deepthink r1 seems to show). There are also timing concerns: SMRs will likely take a decade to become a significant option, so by the time SMRs become fully available, their moment for fueling the AI revolution may have passed.

Even gas plants can be affected by shifts in competing fuel prices. A number of U.S. power plants went bankrupt in the early 2000s as gas became more expensive and those plants became mid-stack suppliers rather than baseline producers.[103]

From the demand-side perspective, SMRs are being developed now for markets that don’t yet exist, and for an environment in which firm clean power will be highly attractive. There are obviously risks that these assumptions are false.

However, there are also some significant opportunities to mitigate these risks. Notably, long-term PPAs are contracts between generating companies and end users or utilities, in which users agree to buy energy for a long period at a fixed price. Typically that price is somewhat higher than current prices, and represents a reasonable deal for both sides: a secure market for the seller, and secure access to power at a fixed price for the buyer.

Risks can also be mitigated by government guarantees of various kinds (e.g., CfD), and by different ways of directly allocating market risks. These are discussed in the policy section ahead.

Taken together, supply-side and demand-side risks dramatically affect pathways for SMRs through the minefield of market failure. These risks can be mitigated, but they are formidable.

Will Demand Materialize?

Despite a further increase in electrification, there may not be increased electricity demand. Over the past four decades, electrification has reached many parts of our lives at scale, yet demand for electricity has grown only 15 percent since 1980, and is significantly down on a per capita basis.[104] That’s because our use of electricity has become much more efficient: appliances are far more energy efficient than their predecessors were; LED bulbs take less energy than incandescent bulbs. So further electrification may not mean that electricity demand will grow.

Still, demand seems to be picking up across the economy, and data centers are potentially a substantial source of new demand for electricity. Data centers seem to be the deep-pocketed patient investors that all start-ups imagine in their dreams.

However, as Michael Barnard has pointed out, there are good reasons to doubt that that demand will be transformative for the electricity sector as a whole. The recent release of DeepSeek’s r1 model, which appears to use 95 percent less energy than competing models has obvious implications, and that model is open source, so those algorithms can spread quickly—although

DeepSeek's performance could rely on piggybacking off ChatGPT and other leading models. Further, ITIF background conversations with Amazon, Meta, and Google strongly suggest that they are planning for massive data center investment that will require very large-scale energy. But Barnard made three other points as well. [105]

1. We have been here before. In the early 2000s, as data centers were deployed for the first time at scale, there was a substantial concern that data centers would raise demand for energy. But that didn't happen
2. In part, that was because optimization (inevitably) followed deployment. Once primary objectives were met (capacity, throughput, etc.) attention could turn, very successfully, to optimizing the software. Optimized software uses fewer cycles, and fewer cycles use less electricity. There was no electricity demand boom in the 2000s.
3. Data centers use a lot of energy to power graphics processing units (GPUs). But that hardware is quickly getting more energy efficient as well. Nvidia's new Blackwell chips will be much more energy efficient: Nvidia claims the Blackwell Grace200 will be 30 times as energy efficient for inference tasks as the Hopper 100.

There are still good reasons for data centers to be looking at nuclear. But the massive boom in related energy demand should be viewed with some caution.[106]

Managing Market Risks

For most supply-side risks, there is little that SMRs companies can do about competing technologies and companies. Instead, they are focused on the one risk they actually control: that the production process will not turn out as advertised. SMRs must shift as much of the production process to the factory as they can. That means both designing for manufacturability—an established branch of industrial design—and developing plans to bring production into the factory as soon as possible. At this early stage, it seems likely that smaller reactors will be more easily manufactured, so interest is growing in microreactors (20 MWe or less).

From a policy perspective, recent supply-side efforts have focused on reshoring the nuclear supply chain, or at least making sure that U.S. reactors are not dependent on Russian uranium. The Prohibited Uranium Imports Act and subsequent Biden executive orders have effectively shut out Russian uranium; the question, though, is whether sufficient new sources will come online soon enough, especially if SMRs get market traction and hence start to impact overall demand. Recent agreements with allies also aim to build a supply chain that excludes Russia.[107] DOE has started to address the problem of enrichment; this requires additional U.S. capacity, and DOE has provided an initial contract to Centrus. There is still uncertainty about whether enrichment can scale up effectively at a pace that matches SMR deployment, but that issue is still some years away. An alternative pathway would open if molten-salt breeder reactors (TS-MSBR) are deployed. TS-MBR technology creates more fissile material than it uses, and can use thorium, a widely available and much cheaper alternative to enriched uranium.[108] Its low pressure also makes safety concerns less of an issue and less expensive to address.

There are also workforce concerns. Constructing reactors is expensive, in part because the concrete, steel, and welds needed are all required to meet much higher standards than those for commercial or residential construction. Those higher standards require a skilled workforce, but the sporadic pace of nuclear deployment in the United States means that each workforce has to be trained from scratch. Any major success in reducing costs will almost certainly require that a trained specialized workforce remains fully employed on nuclear projects. Operations also require trained workers, but this is less difficult to achieve because that workforce does not dissolve once construction is completed; operations are needed for the life of a plant.

Finding customers with deep pockets and long-term needs is the gold standard for addressing demand risk, and SMR companies are clearly having some success there. They are working with utilities, network operators, and large end users to develop offtake agreements that will address the risk that demand won't be there when power eventually starts to flow. The Tennessee Valley Authority, for example, is buying a GE-BWRX 300 MW reactor (it's also supporting the Kairos Hermes reactor at Oak Ridge). Google has an agreement in principle to buy six reactors from Kairos, while Amazon has partnered with Energy Northwest for a series of SMRs (starting with X-Energy reactors) that could eventually provide 960 MW. Amazon is also partnering with Dominion Energy in Virgina on a 300 MW SMR project.

Political Risks

Large reactors can take 10 years or more to build. That period covers at least three U.S. administrations, five national elections, and at least 10 annual budgets plus any number of other financial and administrative crises. There is, in short, ample time for political apple carts to be upset. And that's just at the national level—attitudes toward nuclear have flipped often in U.S. states, as New York's sudden new interest in nuclear demonstrates.

For any industry, this is difficult. For nuclear, it is potentially existential, as the pathway to sustainability is powered by government funding. Developing an effective nuclear power development program requires a stable flow of funds against well-defined milestones.

Those concerns are perhaps more relevant for large reactors than SMRs. Not only are SMRs faster to deploy, shortening the period of political risk, but also they have some hope of eventually reaching financial sustainability, at which point ongoing government funding will become less necessary. And the amounts of funding should also be lower. That said, until SMRs reach scale, they will understandably depend to a considerable extent on government funding.

Nuclear accidents drive a second set of risks. Fukushima occurred in Japan, but the global backlash to nuclear power that it created helped destroy the German nuclear industry (and set the Japanese nuclear industry back a decade). Three Mile Island had similar effects in the United States. Every accident can trigger a turn away from nuclear, and usually tightens the regulatory screw.

Finally, there are political risks related to climate politics. While climate concerns have helped drive the recent nuclear boomlet, the backlash is already here. Nuclear is today a lot more expensive than natural gas in the United States, and it is more expensive than coal in the developing world. If climate-driven policy is rejected, SMRs could find themselves in a very wintry environment.

These political risks can be mitigated mainly by developing a cross-party consensus in support of nuclear policy that is sufficiently robust to withstand a change in administration. That will be challenging, although some countries where national energy security concerns play a big role appear to be developing at least the basis for that consensus (e.g., Poland, and perhaps the

United Kingdom). In the long run, SMRs themselves may help to reduce these risks by becoming sufficiently competitive to avoid dependence on long-term subsidies. That, however, is some way off.

Clearly, the broad political environment has clearly become much less predictable over the past decade. Not even its supporters expected Brexit, and perhaps even fewer that Donald Trump would be on the verge of a second term. The turn against incumbents across the West, and a parallel rejection of experts and their expertise, has simply added to the risks. But more than other carbon-free technologies, nuclear itself has fans across the political spectrum. While the incoming secretary of Energy owns a fracking company and is a strong supporter of fossil fuels (and is a climate skeptic), he is also a board member and investor with Oklo, an SMR company. That said, political risks are hard to mitigate. Nuclear is expensive, and an easy target for political grandstanding. The best solution is clearly to get beyond government funding as quickly as possible.

Regulatory Risks

All nuclear plants are tightly regulated, and that process can be time consuming, expensive, and opaque. It has been very difficult to get new designs approved, it's difficult to get site approvals, alignment between different national regulatory regimes is poor (so designs need to get separately approved), and the balance between safety and progress is, fair to say, heavily tilted toward safety.

All this is challenging, and the advent of SMRs makes it worse.

Regulatory authorities are not yet prepared for a world dominated by SMRs. The regulators understand this: their operating model is of an extremely safety-first culture in which any proposed design changes are examined minutely and in exhaustive detail on the premise that such changes will happen once a decade or so (if that). As noted earlier, SMRs will need to iterate, and it's not clear how that will be regulated. It's also apparent that NRC does not have the funding or the personnel needed to handle the flood of regulatory activity required if SMRs arrive at scale.

Regulation and SMRs

Both Congress and NRC are working to fix the problems with nuclear regulation. Since the mid-2010s, NRC has followed a twin-track strategy to accelerate certification for nuclear reactors, including both design and operations. It has—following direction from Congress—developed a new pathway for certification, known as Part 53. This is now working through the rulemaking process. It has also followed the lead of industry groups and developed new models that work via exemptions from the existing Part 50 and Part 52 processes. Traditional plants using established technology can also use those existing pathways without needed exemptions.

These developments reflect the history of nuclear power regulation in the United States. From 1945 to 1954, nuclear technology in the United States primarily focused on plutonium production reactors for military use at sites such as Hanford and Oak Ridge. As interest in commercial nuclear power grew, the need for safety regulations emerged. The initial regulatory approach (defined in the 1954 Atomic Energy Act) was largely ad hoc, relying on expert panels convened by the new Atomic Energy Commission to evaluate designs and require implementation using conservative operating margins. Construction and operating licenses were separate, borrowing from the 1934 Telecommunications Act covering radio station licensing.

By the end of the 1970s, flexible expert reviews had evolved into much more prescriptive regulations increasingly specific to light-water reactors (LWRs), which had become the dominant design because industry needed more predictability in the face of inconsistent decisions, and sometimes failed projects as reactors were denied operating permits late in the process.

Safety analysis methods also evolved. Initially, DuPont used worst case accident (WCA) analysis in the 1940s—which assumed catastrophic failure. That shifted to maximum credible accident (MCA) analysis, which included the probability of failure in safety calculations. As plants grew larger and more complex, this evolved into the design basis accidents (DBA) approach—a set of regulatory assumptions that were believed to provide a consistent safety envelope for plant operation.

That changed in the 1970s, as the Reactor Safety Study (RSS/WASH 1400) introduced systematic, systems-level safety analysis. This study showed that smaller but more frequent accidents could pose higher risks. Three Mile Island was a turning point. It had become a basic assumption of safety regulation that if the largest potential problems were addressed, smaller ones would be addressed as well. Three Mile Island exploded those assumptions, as a small failure quickly cascaded and led to meltdown. Subsequently, considerable efforts were expended looking at how to evaluate and address risks that were more systematic: not the failure of a single large component, but the impact of multiple smaller failures, for example. The existing checklist approach clearly needed to be supplemented, or possibly replaced.

Regulation evolved further in the 1980s and 1990s. Risk-informed approaches allowed for more intelligent safety assessment, and potentially reduced excessive conservatism in design requirements, eventually leading to technology-inclusive, risk-informed, and performance-based regulation (TIRPB) in the 1990s and early 2000s.

Still, by the mid-late 2010s, more flexibility was clearly needed, especially for new designs. In 2019, Congress passed the Nuclear Energy Innovation and Modernization Act (NEIMA), which directed the Nuclear Regulatory Commission to develop a comprehensive regulatory framework applicable to all reactor technologies, sizes, and operational methods; establish predictable fee structures; and addressed uranium processing regulations. The 2024 ADVANCE Act called on NRC to add staff and reduce licensing application fees (it also introduced prize competitions).

The NEIMA mandate was reflected in the new Part 53 rulemaking now under way. The comment period has now closed, and Part 53 is expected to become operational in 2027. The new framework aims to accommodate emerging technologies such as SMRs and microreactors while maintaining safety standards.[109] Key aspects of the new Part 53 rulemaking include the following:

- A technology-inclusive, risk-informed approach using probabilistic risk assessment. This replaces the highly prescriptive model used to date, and includes a new concept of "defense in depth" using certain design characteristics (e.g., underground location, passive safety designs where failure leads to automated shutdown by design).

- Eight distinct license application types, including early site permits, construction permits, and operating licenses (see box 8). This is designed to split the process into more standardized and transparent milestones, which should improve the bankability of projects.
- Support for efficient licensing of multiple plants using “similar” designs.
- Modified technical requirements addressing fitness for duty, physical protection, and risk metrics, including an alternative to existing requirements.
- Comprehensive waste management requirements (although there is still no national lone-duration repository)

The final draft rule is expected in 2025, with final rule approval anticipated by the end of 2027. This would be a new standard pathway for regulatory approval.

But since NEIMA passed, NRC has demonstrated that Part 50/52 regulation may still be viable, as the existing regulatory exemption process may be flexible enough to work for SMR vendors. The exemption process has been used successfully to license new reactor technologies such as Kairos Power’s reactors and TerraPower’s Natrium reactor, which uses liquid sodium along with molten salt as an energy storage medium.

That is partly because the exemption process has itself been somewhat standardized. In the 2010s, an industry group led by the Southern Company sought to build a new toolkit for assessing nuclear safety, aiming to develop a pathway that satisfied NRC and at the same time worked for different technologies and different-sized reactors.[110] This approach seems to have been remarkably successful: the LMP model has now been formally approved by NRC (although it is not yet itself a formal alternative pathway). Companies can point to the LMP model in their regulatory filings, and NRC will accept that reference.

Box 7: New NRC Mission Statement

In 2025, the NRC issued a new mission statement:

The NRC protects public health and safety and advances the nation’s common defense and security by enabling the safe and secure use and deployment of civilian nuclear energy technologies and radioactive materials through efficient and reliable licensing, oversight, and regulation for the benefit of society and the environment.

The new statement adds a focus on enabling the use of civilian nuclear power, a new mission element.

So developers of new nuclear technologies can now either pursue licensing under Part 50/52 using the exemption process, or wait to use the new Part 53 framework, which offers broader applicability but comes with uncertainties. The NRC’s somewhat surprising flexibility seems to be working for developers, and they may be reluctant to wait for a new process that will start only in 2027 (or later), may be subject to legal challenges, and where the handling of innovative technologies is in practice simply unknown. If the exemption route proves capable of managing innovative designs quickly and efficiently, it may yet become the preferred pathway even if Part 53 rulemaking concludes on schedule.

Box 8: License Types Under the Proposed Part 53 Framework

There are eight types:

- **Early Site Permit:** Allows approval of a site before seeking construction or combined license. This is the initial stage of licensing.
- **Limited Work Authorization (LWA):** Can be requested alongside an early site permit for performing specific construction activities.
- **Standard Design Approval (SDA):** Provides approval for a final standard reactor design that can be referenced in future applications for construction permits, operating licenses, combined licenses, or manufacturing licenses.
- **Standard Design Certification (SDC):** Similar to SDA but goes through a rulemaking process for approving a standard nuclear facility design, and has more finality, as it is a rulemaking and commission approval.[111] More clarity will be needed: for example, when is an SDC required or used as opposed to an SDA?
- **Construction Permit:** Authorizes actual construction of the nuclear plant. Must be obtained before an operating license.
- **Operating License:** Permits operation of the completed facility after construction.
- **Combined License:** Merges construction permit and operating license into a single license. [
- **Manufacturing License (ML):** Authorizes the manufacture of nuclear reactors. NRC is specifically seeking input on provisions for manufacturing and deploying manufactured reactors, including whether Part 53 should allow combined license or operating license holders to reference a manufacturing license.

Remaining Regulatory Problems

The various reform efforts under NEIMA and the ADVANCE Act, and through NRC's own activities, are clearly moving in the right direction. They should make NRC certification more predictable and often shorter, while expanding coverage to a much wider array of technologies.

However, there are still significant problems:

- Design certification takes a lot of time and money—tens of millions of dollars, even though it remains an optional step. Costs also vary widely, and therefore are difficult to predict for small companies with limited resources.
- Design certainty comes at a price: An SDC or SDA certification locks in a design, which may cause problems later when adjustments are needed. Companies face trade-offs between faster approval and design lock-in.
- There seems to be very little attention paid in the sector to the need for iteration. Nuclear deployment has been so slow, and expert analysis has led to a strong focus on the need for design replicability at the cost of design innovation, such that iteration has largely been ignored.[112] Iteration will be crucial for SMRs, and regulation will need to address a range of design changes. A process for identifying and quickly approving noncritical design changes will be needed.

- Fee structures need to better reflect the realities of start-ups; the current 100 percent private sector contribution dates to a period when large reactors were being built by large companies. A range of fees would be an improvement, and this would require congressional action.
- Interconnection will be a problem for SMRs, as it is for other energy technologies. Recent improvements won't be enough to solve the enormous backlog of projects seeking interconnection approval from FERC. It is possible that the long lead times for SMRs will mean that the backlog is not as much of a problem.

Can Regulators Smooth the Path for SMRs?

SMRs face four levels of regulation in the United States (most other countries are broadly similar). First, the design itself must be approved by NRC. This is time consuming (seven years on average), and requires working closely with regulators who are safety-first inclined. Technologies that are genuinely new attract more scrutiny (for understandable reasons: these reactors have not yet been built anywhere!). And most countries require in-country certification, so companies must complete multiple regulatory paths to generate even the capacity for global scale.

Second, the proposed site for a reactor must be approved for both safety and compliance with NEPA. The latter is especially time-consuming in the United States, where nuclear opponents (and concerned locals) have weaponized NEPA to bring countless and long-drawn-out lawsuits. Sites must also, of course, get approval from local authorities (usually counties and\or states in the United States).

Third, NRC must approve an operational and safety plan—which would include both actual safety and operations and evacuation plans and other wider safety measures (e.g., operator training, fuel transportation, and waste management).

Fourth, the new reactor must be approved for interconnection to the grid. Perhaps because reactors take so long to build, the five-year queue waiting for FERC interconnection approval has not been as visible a problem as other regulatory issues, but if SMRs gain traction and dozens of SMR projects seek approval, that will change quickly. And interconnection denial can kill a project, as Amazon's rejected effort to use energy form the Susquehanna nuclear plant shows.

For SMRs to gain traction at scale, a lot of existing regulatory processes will have to be shortened dramatically, and overlaps eliminated.

International Standardization of Licensing and Certification

While the broad pathway for nuclear certification is similar in every country, specific regulatory pathways are defined in national law and are significantly different. These differences present major barriers to scale-up, as SMRs will need to go through certification in every country where they plan to sell products. Not even the EU has a unified certification scheme.

International standardization of licensing as well as harmonization of regulatory requirements has been a goal of several programs, including those of CORDEL (Cooperation in Reactor Design Evaluation and Licensing NEA working group), MDEP (Multinational Design Evaluation Programme), and ERDA (European Reactor Design Approval). CORDEL has looked at international aviation licensing as a model from which good practices can be drawn. IAEA has developed an SMR Regulators' Forum, a working group for member states and stakeholders to discuss their knowledge and experience, but no regulatory legislation or template specifically for SMRs has yet emerged.[113]

The point is that unlike large reactors, which have been largely country specific, SMRs could evolve into a global market. The need for scale also implies that companies that can meet the regulatory requirements of multiple countries and regions will have a significant advantage. In the United States, either DOE or NRC needs to be fully aware of and participating in the development of international standards and certification regimes.

DERISKING SMRS

In general, there are strategies available to share and mitigate the risks related to SMR development and deployment, but so far, no well-defined set of best practices has emerged.

A lot of nuclear policy is about handling and mitigating risks. For example, the Price-Anderson Act established what is essentially a nuclear insurance fund: all nuclear operators are required to participate and to pay up to $137.6 million per reactor in the event of an accident. They must also carry $450 million in direct insurance per reactor. The fund has paid out about $200 million since its inception in 1957, including $71 million for Three Mile Island.

But insurance is far from the only way to mitigate the range of risks related to nuclear power.

In the end, risks are shared between government and end users. The latter are usually rate payers for a utility, but they can be large end users participating directly. No one else can pay for nuclear—operators are, in general, not big enough to assume all the risks involved, and in any event, they will simply pass costs on to ratepayers and end users.

Ideally, as SMRs are successfully deployed, and as their costs fall and deployment timelines become more predictable, risks simply decline. And as that happens, the need for government intervention declines in parallel. We can imagine a future in which government funding shifts to much earlier in the product development curve, focusing on basic and early applied research that is quickly adopted by a flourishing SMR industry. Eventually, even early stage research can be funded by industry, as it mostly is for semiconductors and pharmaceuticals.

But until then, financial risks need to be addressed. Several options focused on different stages of development and deployment have emerged. In general, the earlier in the product development cycle, the higher the justification for government funding.

From a financing perspective, SMRs have two huge advantages over large nuclear reactors: they require much less up-front capital per reactor (because they are smaller), especially once the initial investment in factory manufacturing is completed, and the promise is that they will be completed and delivered in a much shorter period of time, perhaps 2–4 years or less, instead of 7–10 or even more. Lower capital costs and shorter timeframes reduce risk.

These advantages, along with the promise of larger markets—and eventual cost reductions from scaling up—have led to an influx of private sector funding from both investors and end users, such as the large data companies. Despite this, financing remains an enormous challenge for SMRs: they are essentially a new technology that will take at least a decade to reach markets at scale and probably more than that to break even in a context where many energy markets are still regulated and where existing competitors have deep pockets and strong roots. P3 is a long way off.

Market financing is driven by the balance of risk and reward. So left to markets alone, SMRs are not attractive to investors; a lot of government policy in the United States and elsewhere has focused on trying to change that balance at both ends.

Eleven options have emerged for financing nuclear plants, aiming to reallocate costs and hence financial risks:

1. **Government loans.** In the United States, the LPO is a primary financial resource for large energy projects, providing loans and guarantees at below-market rates (using government borrowing power) to help fund construction for projects wherein either private investors will not take the risk or market financing is too expensive. These loans are focused on construction.

   LPO was instituted in 2010 but has been massively upsized in the past few years. In just October and November 2024, it provided direct loans or loan guarantees for $15 billion to Pacific Gas and Electric Company, $6 billion to Rivian for EV manufacturing, approximately $5 billion for the Grain Belt Express, a high-voltage direct-current transmission project, $500 million for a semiconductor plant for EVs, and $445 million for an EV materials project. By the end of 2024 it had provided $69 billion in outstanding loans and $41 billion in loan guarantees, with $11.5 billion going to Vogtle and $1.5 billion for restarting the Palisades plant in Michigan.[114]

   Given the enormous capital needs for SMR deployment at scale, and the long-term risk profile, market-only financing may be very difficult, and expensive, as investor risks must be compensated. Significant nuclear deployment in the United States without LPO support or the equivalent will therefore be challenging.

2. **Tax credits.** U.S. tax policy has been used to reduce operating expenses as well. The IRA offers either ITCs—credits against construction costs for clean energy projects—or PTCs. PTCs offer a subsidy of up to $33/MWh for new clean energy projects, covering the first 10 years of operation.[115] Energy providers can use either, but not both.

3. **Operating subsidies** don’t address construction risks, but they do address longer-term risks that the market for energy will not evolve in ways that make proposed projects sustainable. While this model may offer more certain payment flows than CfDs , these subsidies are paid regardless of market conditions, and could—if construction is cheaper than expected—lead to significant overpayments for developers. Alternatively, PTCs could be insufficient to ensure that a project is sustainable if market prices for energy fall to below even the subsidized price of a new build. That may well happen with hydrogen in the United States. Further, the 10-year subsidy cutoff in the IRA is quite arbitrary; supporters may just hope that political currents 10 years hence will allow for their extension. After all, it’s not as though the cost of an existing project will suddenly fall by $33/MWh 10 years into its operating lifetime. And tax credits are only effective when there is a positive income against which to count them. Failing projects may have no net income. This kind of operating subsidy is somewhat unusual; CfDs appear to be used more widely, and it’s possible that the rate-asset-based model will also be adopted more widely.

4. **Risk tranching.** In financial markets, tranching is a well understood strategy for risk management. For example, while a single mortgage carries a unitary risk (the mortgage will either be paid or it won’t), a bundle of mortgages looks quite different: there is an extremely high likelihood that sufficient mortgages will be paid to cover, for example, 30 percent of the total payments due. It is likely, but not so certain, that the next 50 percent will be paid. The final 20 percent is riskier. Interest rates and prices are tuned accordingly.

For SMRs, the EFI Foundation has suggested a Cost Stabilization Facility using a tranching model to manage construction costs and possible overruns; the idea is to develop an order book for multiple SMR reactors that use a single reactor design. That order book would be collectively owned by a single holding company, which in turn would be owned by project sponsors, and other stakeholders. Construction risks would then be sliced into three tiers: budgeted costs, which would be paid by the project sponsors; costs within a set contingency (e.g., 15 percent over budget), which would be shared between owners and other stakeholders, including vendors, on a negotiated basis; and unexpected costs beyond contingency planning, which would be paid by tapping a government guarantee (in the United States, perhaps through an LPO guarantee).[116]

Tranching could remove tail-end risks, encouraging investors to accelerate SMR development. The downside of course is that government is on the hook should things go badly wrong. And the EFI model adds considerable complexity: projects have to be aggregated into order books, a special holding company has to be agreed on, and shares negotiated between participants and then tiers of financial risk need to be assigned.

5. **Contracts for difference.** The CfD model asks potential energy developers to bid for operating subsidies, with the winner being the company that seeks the lowest subsidy. Essentially, the developer pays the entire cost of construction, while government offers to pay the difference when market prices for energy from a project are lower than the agreed-upon level (the "strike price"). In the United Kingdom, this process is run through auctions in which the government also imposes a maximum amount of subsidy that it is prepared to pay. This has—for example, in the case of a recent auction of wind energy subsidies—led to cases where there are no developers prepared to bid at the level the government is prepared to offer.

   Developers may prefer the CfD structure, which provides more direct contractual certainty and offers a long-term shift of operational risk from the contractor onto the state and hence taxpayers. CfDs have become quite widely used in Europe, and there are multiple subgenres with different ways of determining a strike price and different sources of funding. KEPCO has apparently been somewhat reluctant to bid on Sizewell C because it prefers CfD financing. However, the CfD model has nothing to say about construction and regulatory risks: it is all about operational funding.

6. **End-user funding via PPAs.** PPAs are usually an integral part of the financing package for any large energy project in the United States or Europe. Utilities or sometimes large end users sign agreements that take power (usually for a long time period) from the new energy source. This provides a reliable source of bankable revenue that can be used to help raise financing for the construction—as, for example, Google's 20-year PPA funded development of the Story County II wind farm in Iowa.[117]

7. **Ratepayer pays.** In the United States, ratepayers of Georgia Power and a couple of smaller utilities are on the hook for much of the vastly expanded cost of the Vogtle power station in Georgia.[118] Essentially, in this model, the utility contracts for the reactor and then recoups the costs through charges to ratepayers (although, for Vogtle, the federal government also contributed $3.7 billion through DOE in 1981 and $8.33 billion in LPO loan guarantees in 2010).

An alternative version of ratepayer pays is the rate-asset-based model being deployed in the United Kingdom for the Sizewell C reactor (now estimated to cost £40 billion). It adds a small surcharge to ratepayer bills (approved by an independent regulator—in this case, Ofgen) so that funds are incoming during the construction process itself—the proposed surcharge for Sizewell C should be approximately £1-2/month for each ratepayer during the construction phase.[119] This should reduce the cost of capital by generating revenues earlier, and also places the credit of the regulator (and hence the government) behind a big project without adding any liabilities onto the government's balance sheet.[120]

The rate asset base approach shares risks between a developer and a ratepayer, but it also changes the incentives for developers. If that funding is available without constraint, it can lead developers to overspend, and has been called an "open checkbook" by critics.[121]

This model also means that a regulator must estimate construction costs in advance (including supply chains, construction length, interest rates, and a host of other variables) to calculate an appropriate charge for ratepayers. After all, the increased revenue certainty for investors and developers is generated by early costs imposed on ratepayers.

8. **Vendor financing.** The Paks II project in Hungary is 80 percent financed by Rosatom, the Russian national nuclear contractor. Given that the two countries most likely to provide vendor funding are Russia and China, and that this kind of financing would be extended primarily to allies, this seems to be a fairly limited model. It appears likely that reactors in China are benefitting from complex financing flows between the buyers, vendors, and state entities.
9. **Cooperative financing (Mankala model).** Olkiluoto 3 in Finland is based on the Mankala model whereby several parties join resources to acquire and co-own an asset. Financing lies on the balance sheet of the Mankala company, which does not generate profit or distribute dividends. Instead, shareholders can purchase electricity at cost and cover expenses in proportion to their ownership share. The electricity can in turn be used for self-consumption or sold by the shareholder. More than half of Finland's electricity is generated through Mankala arrangements. The Mankala model stresses the financial contribution of end users; they are also on the hook for construction and operating risks.
10. **Vendor owned and operated.** SMRs are small enough that they potentially offer a wider array of financing arrangements. For example, Last Energy is preparing to deploy its SMRs using a model wherein it takes on all the risk. It owns and operates the reactor, and simply sells the resulting electricity to the utility (or another end user). The company is confident that it can deliver at a competitive price, and that there won't be cost overruns or delays that would affect the price it must charge.
11. **Government equity.** With, for example, the U.K. government now effectively owning a majority share of the Hinkley plant and the Swedish government exploring such options in Swedish nuclear plants, governments around the globe are taking various stakes in nuclear plants.

A recent report from OECD looks in detail at financing for new build reactors across the world, illustrating the wide range of construction financing strategies (see table 2). In some (e.g., Hungary and the Czech Republic) most of the financing is debt, and it is directly funded by a government (the Russian government in the case of Hungary). The Vogtle plant in Georgia was entirely funded by equity, primarily by the utilities that expected to buy the electricity (plus significant federal loan guarantees). And while the Barakah plant in the UAE was 80 percent debt funded, the terms were different than those at other plants; it was apparently a fixed price contract with KEPCO. Debt comes from different sources as well—sometimes government agencies, but often commercial banks (at least ostensibly).

Table 2: Financing arrangements for eight recent nuclear plants[122]

	Debt-to-Equity	Equity Provider(s)	Debt Provider(s)
Olkiluoto 3	75:25	▪ Consortium of electro-intensive companies	▪ Commercial banks
Vogtle 3 and 4	0:100	▪ Georgia Power ▪ OPG ▪ MEAG Power ▪ Dalton Utilities	▪ N/A
Barakah	80:20	▪ ENAC ▪ KEPCO	▪ UAE government ▪ Korean EXIM ▪ U.S. EXIM ▪ Commercial banks
Akkuyu	N/A	▪ Rosatom	▪ Commercial banks
HPC	0:100	▪ EDF Energy ▪ CGN	▪ N/A
Sizewell C	TBD	▪ EDF Energy ▪ U.K. government ▪ Additional, TBD	▪ TBD
Paks II	80:20	▪ Hungarian government	▪ Russian government
Dukovany 5	98:2	▪ CEZ	▪ Czech government

It’s reasonable to conclude that no standard financing structure for risk sharing has emerged. SMRs pose additional challenges because initial funding will include not just construction costs for first-of-a-kind reactors, but also for building the factories that are eventually expected to bring unit costs down substantially.

NUCLEAR R&D IN THE UNITED STATES

Over the past few years, DOE's support of nuclear, which traditionally focused on large reactors, has transitioned toward an approach that is more welcoming and supportive of SMRs. Civilian nuclear R&D is run through the Office of Nuclear Energy (ONE), although nuclear projects close to the market are also funded by OCED and LPO. From the perspective of SMRs, which are still at the developmental stage, DOE offers a range of supports across the development cycle. There are programs for short-, medium-, and long-range development, as well as government-owned infrastructure primarily located at INL and ANL that can be accessed through public-private partnerships. The U.S. Nuclear Reactor Innovation Center (NRIC) at INL provides technical support from proof of concept through commercial demonstration, and access to test reactors and safe environments for reactors using designs that are going critical for the first time. ONE is also working on the nuclear supply chain, supporting the development of domestic capabilities for manufacturing HALEU.

INL, the nation's top laboratory for nuclear research, development, and demonstration (RD&D), works with nuclear researchers to develop, demonstrate, test, and validate next-generation nuclear reactors.[123]

This support is usually provided through Strategic Partnership Projects (SPPs) and Cooperative Research and Development Agreements (CRADAs). SPPs offer partner institutions (including non-DOE federal agencies, universities, and private firms) access to INL's advanced technology equipment, facilities, and research personnel, sometimes on a no-charge basis, otherwise at cost.[124] For example, INL researchers will review the design of NANO Nuclear Energy's new microreactor and provide feedback from an expert panel.[125] CRADAs are cost-sharing partnerships designed to partner the INL with non-federal entities. Under a CRADA, INL and the partner institution work collaboratively, with INL providing personnel, services, and property to the project, but no direct funds.[126]

INL can also serve as a location for new demonstration reactors.[127] BWXT Advanced Technologies, an advanced manufacturing company in Virginia, has partnered with the Department of Defense (DOD) to develop an advanced, transportable reactor that will be piloted at INL.[128]

INL also offers modeling and simulation programs, which are traditionally difficult to produce but essential for nuclear engineering. The Multiphysics Object Oriented Simulation Environment (MOOSE) provides open source and licensed access to 13 simulations describing phenomena in nuclear engineering. Access to this shared resource helps firms reduce the cost of developing models and speeds up reactor development.

DOE has provided substantial support to three SMR projects dating back to the early 2010s (see table 3). However, modest levels of investment were supercharged by funding made available through the Infrastructure Investment and Jobs Act (IIJA), which is the basis for $4.6 billion in awards all focused on building first-of-a-kind reactors in the United States, as a recent GAO report shows.

Table 3: DOE funding for selected SMRs[129]

Awardee	Period	Competition	Purpose	Amount ($M)
NuScale/Carbon Free Power Project	2014–18	Competitive	NuScale design development and certification	$226
	2015–21	Noncompetitive	Site permitting and licensing of the NuScale SMR	$8
	2018	Competitive	Phase 1. NuScale Nuclear Demonstration Readiness Project	$48
	2018–19	Competitive	Phase 2. NuScale Nuclear Demonstration Readiness Project	$43
	2020–24	Noncompetitive	NuScale Nuclear Demonstration Readiness Project completion	$263
	2020–30	Noncompetitive	Commercialization and deployment of the first NuScale SMR in the United States: The Carbon Free Power Project	$1,355
TOTAL				**$1,943**
TerraPower	2020–22	Competitive	Advanced Fuel Qualification Methodology Report for Traveling Wave Reactor	$0.5
	2021–28	Competitive	Natrium™ Demonstration Project	$1,979.0
TOTAL				**$1,979.5**
X-energy	2016–22	Competitive	Xe-100 Pebble Bed: solving critical challenges to enable the Xe-100 Pebble Bed Advance Reactor Concept	$40
	2018–22	Competitive	Design and license application development for high assay low-enriched uranium fuel fabrication facility	$19
	2020–22	Competitive	Xe-100 conceptual design and risk-informed licensing	$3
	2021–27	Competitive	X-energy to deploy first commercial-scale advanced reactor by 2027	$1,232
TOTAL				**$1,294**

Supports are being provided by the ARDP, which was funded through $500 million via annual appropriations and then $2.48 billion in the 2021 IIJA. That was designed to fund ARDP through 2025, and to be further supported through subsequent annual appropriations. While ARDP does not support all U.S. reactor designs, it is supporting 10 of them at various stages of development.

The ARDP itself supports projects that are expected to result in a fully functional advanced nuclear reactor within seven years of the award. The first awards in 2020 went to TerraPower for its Natrium MSR and to X-energy's HGTR. Both included funding for fuel facilities.

Risk Reduction for Future Demonstration Projects (RRFDP), part of ARDP, focuses on projects that are 10–14 years away from full-scale deployment. The following five U.S.-based-teams' projects have received RRFDP funding (DOE's share ranges from approximately 32–80 percent):

- **Hermes Reduced-Scale Test Reactor:**—Kairos's Hermes reduced-scale test reactor, a major is a step toward a commercial-scale Fluoride Salt-Cooled High Temperature Reactor. This is an innovative design that involves TRISO (Tri-structural Isotropic) fuel in pebble form combined with a low-pressure fluoride salt coolant. Funding is $629 million (DOE share is $303 million).
- **eVinci Microreactor:** This Westinghouse heat pipe-cooled microreactor is aimed at producing a nuclear demonstration unit by 2024. Total award value over seven years will be $9.3 million (DOE share is $7.4 million).
- **BWXT Advanced Nuclear Reactor:** This is a commercially viable transportable microreactor using TRISO fuel particles and an improved core design using a silicon carbide matrix. Funding is $106.6 million (DOE share is $85.3 million).
- **Holtec SMR-160 Reactor:** This is an early-stage design for a light water-cooled SMR-160, with $147.5 million (DOE share is $116 million) in funding.
- **Molten Chloride Reactor Experiment:** Developed by Southern Company, this is the world's first critical fast-spectrum salt reactor. Funding is $113 million (DOE share is $90.4 million).

Advanced Reactor Concepts-20 (ARC-20) projects (part of ARDP) support advanced reactor designs at the earliest phases (15 years out or more).[130] The following three projects have been selected, with total DOE funding of $57.2 million:

- **Advanced Reactor Concepts:** This is a conceptual design of a seismically isolated advanced sodium-cooled reactor facility that builds upon the initial pre-conceptual design of a 100 MWe reactor facility. Funding is $34.4 million (DOE share is $27.5 million).
- **General Atomics (San Diego, CA):** This MWe fast modular reactor conceptual design has verifications of key metrics in fuel, safety, and operational performance. Funding is $31.1 million (DOE share is $24.8 million).
- **Boston Atomics:** This is the development of the Modular Integrated Gas-Cooled High Temperature Reactor (MIGHTR) concept from a preconceptual stage to a conceptual stage. Funding is $4.9 million (DOE share is $3.9 million)

Supply chain improvements:

- DOE's recent Nuclear Supply Chain Deep Dive Assessment concludes that the United States needs to develop a robust domestic nuclear fuel supply chain.[131] Between 1980 and 2019, U.S. uranium production fell from 47 million to 0.17 million pounds. And the last U.S. plant for conversion of uranium into fuel closed in 2017, although it has since restarted. While all existing LWR plants use low-enriched uranium (for which there are three U.S.-based suppliers), advanced reactors will almost all use HALEU.
- DOE is deploying a $188 million program for U.S.-based HALEU production. This will be partly focused on down-blending existing government-owned stocks of uranium, but mainly on the ramping up of the American Centrifuge Plant's (Piketon, Ohio) enrichment capabilities, where Centrus has completed a HALEU production demonstration project that enriches uranium up to 19.75 percent, the first such project in United States for 70 years. Centrus claims that annual production can reach approximately 900 kg. Other efforts are underway beyond the Centrus agreements.[132]

NRIC at INL.[133]

- NRIC's mission is to work with industry and national laboratories to bridge the gap between concept, demonstration, and commercialization of advanced nuclear technology (see table 4). It builds or enhances DOE infrastructure to support testing of components and systems. NRIC will have established four new experimental facilities and two large reactor test beds for integrated technology demonstrations and experimentation by 2028, and plans to complete two advanced nuclear technology tests by 2030.

Table 4: 11 NRIC capabilities[134]

Proof of Concept	Proof of Performance	Proof of Operations
R&D for feasibility	Established performance of nuclear technologies	Demonstration platform to address economic/operational feasibility
Materials and fuels	Validation data	Sites for demonstration
Predictive modelling and simulation	Irradiation and transient testing	Licensing support
Experimental capabilities	Irradiated materials characterization	Integrated energy systems support

Key programs and featured resources relevant to SMRs in particular include the following:

- Demonstration of Microreactor Experiments (DOME), which hosts advanced experimental reactors up to 20 megawatt thermal (MWth) using HALEU, providing a safe environment for reactors going critical for the first time
- Laboratory for Operation and Testing in the United States (LOTUS), which is a testbed for microreactor experimental reactors up to 500 KWth using HALEU. It too provides a safe environment for reactors going critical for the first time

- The He-CTF testbed, which allows industry to test and qualify reactor components for gas-cooled reactor designs
- The METL (intermediate-scale facility at Argonne National Laboratory), which provides R-grade sodium to experimental vessels for testing advanced reactor components

DOE also launched the U.S. Industry Opportunities for Advanced Nuclear Technology Development program in 2018, offering funding for applied research at private companies seeking to develop advanced reactors, including SMRs.[135] These projects focus not on building reactors, but rather on ancillary technologies that support reactor deployment, including some help with regulatory preparation.[136]

It's fair to conclude that DOE is providing considerable support for R&D across the nuclear reactor development cycle. ARDP's distinction between short-, medium-, and long-term projects is sensible, and if ongoing funding is provided, should develop into an effective pathway from very early-stage research to commercialization of nuclear reactors. NRIC's efforts are also significant, offering a range of very practical supports (including technical help with licensing, and facilities that support the first test of reactor criticality). However, there are risks that this pathway will become a dead end; all this work is subject to annual appropriations. It is also unclear whether DOE has the interest or the funding to both move beyond the existing 10 projects operating within the ARDP and add companies to the short-term list as they mature, which would require raising the level of support to help reach first-of-a-kind commercial deployment.

Advanced Research Projects Agency–Energy (ARPA-E) runs its own nuclear power research program, typically offering grants of $2 million to $5 million in support of nuclear-related technologies. Currently, there are 61 nuclear projects in its portfolio, of which about one-third involve private companies. ARPA-E aims to fund research that will support the deployment of advanced nuclear reactors, including SMRs.[137]

Note: Outside the programs discussed in this section, DOE also operates its Small Business Innovation Research (SBIR) program, which provides funding to innovative small businesses. DOE SBIR funding continues to be siloed based on the source of funding (despite National Academies recommendations to the contrary), and it is also not clear that this funding is seen as important or even relevant by ONE, which typically works with larger organizations at a much larger scale.

CONCLUSIONS: DEFENDING AND EXPANDING THE INNOVATION AGENDA FOR SMRS

SMRs open a potential pathway for development that large reactors cannot follow. While SMRs and large reactors both offer low emissions, high energy density, relatively small footprints, and a high capacity factor (and we should also expect SMRs to be reliable), only SMRs offer the possibility that they will experience the rapid decline in costs associated with factory production, and that they could eventually become a cost-competitive source of clean energy, with potentially significant implications for other industries as well. There is a possible path to P3.

At a global level, getting to P3 with competing energy sources is mandatory: we know that for the foreseeable future, market-driven economies will not adopt SMRs at scale unless they reach P3.

We also know that developing countries don’t have the resources to pay a significant premium for clean energy, so they won’t buy SMRs at scale either.

Innovation

While scale-up is necessary—we won’t get P3 SMRs without it—it is not sufficient. We need *substantial* innovation on many fronts:

- **A discovery phase, during which many designs and technologies are explored.** This is difficult for nuclear technologies, but necessary. Much of the ARDP is aimed at this phase.
- **A testing, evaluation, and pilot phase, during which promising designs are tried out.** We are entering this phase now.
- **Commercial deployment and then coalescence of the industry around a winning design.** While there may be multiple winning firms, and it’s possible that radically different designs will be needed for microreactors, SMRs, and large SMRs at 300 MW and above, we need to find the ICE equivalent, and it may well not be PWR. Critically, winning designs must show a path to P3.
- **Deployment of winning designs at growing scale.** This may well include the licensing of key technologies outside the leading-edge firms, as some of these firms may not have the capability to get to scale: building lots of reactors is a great deal more difficult than building a lot of PV solar.

Discovery phase. This covers basic and applied R&D. DOE offers grants for basic science (primarily through universities, as well as SBIR funding for private companies). Research partnerships between private companies and National Labs are possible through CRADAs, and outside researchers have access to experts and technology at the Labs as well. Regulatory flexibility will also be needed. Recent reforms at NRC are a good start, but there are still plenty of challenges, including in particular ways for NRC to facilitate iteration, which is a key element of the discovery phase.

Testing, evaluation, and pilot phase. This phase is supported both by funding and by access to Labs’ expertise and technology, notably but not limited to simulation and design software. The focus here is still primarily on the technology; markets are not really part of the equation. Development of multiple regulatory pathways for certification and approval at NRC is promising, but timelines for action are still long. NuScale, X-energy, and TerraPower are all at the point of exiting this phase.

Deployment and coalescence. SMRs have not quite reached this stage, although we may get there in the next two to three years. Commercial deployment is a critical step, and OCED is explicitly designed to support this difficult phase. INL helps here with testing facilities and other supports, some via NRIC. This phase is tightly connected to regulation, from both NRC and EPA (which becomes important for siting and transportation).

There is no office within DOE or the federal government explicitly charged with assessing the P3 potential of technologies. This absence leaves a gaping hole in the foundations of federal strategic plans for clean energy, which has in recent years been filled with an “all of the above approach,” funding via construction grants and generous operations subsidies via tax credits all projects that promise significant emissions reduction.

Scale-up. This is the endgame for SMRs; they must get from first-of-a-kind deployment to NOAK scale. Ideally, markets will determine winners and losers, but the high risks and heavy costs involved at this point in the development cycle mean that government support will be necessary. Currently, that mainly involves support from LPO, but that support is at the moment quite badly designed; under Biden, it was more focused on simply helping to fund clean energy projects than to drive projects toward P3. The Vogtle nuclear plant in Georgia is one example among many in that it is not a demonstration of anything specific, and there is no path or plan for Vogtle technology to reach a scale where its technology reaches P3.

Clean energy has also benefited from PTCs and ITCs that subsidize the production of energy with low or zero emissions. As we can now see, this is a dangerously unstable basis on which to build a clean energy sector. While the credits were designed to run for 10–12 years (and advocates expected they would be extended), they are now on the chopping block.

LPO also rushed to push through new clean energy projects before January 20, 2024, announcing a whole slew of projects ranging from funds to Rivian for EV production to $2.5 billion to WEPCO (a Wisconsin unity) essentially to help reduce electricity costs for its 1.1 million customers.[138]

This undignified scramble reflects a fundamental misunderstanding of the role of LPO. It should be focused entirely on supporting technologies that are ready to scale, on the supply side of the energy sector, and on a path to P3. Demand-side funding is hugely expensive and not sufficiently targeted at P3, although there can be cases in which a short period of targeted subsidy makes sense to help technologies get over the hump and reach scale.

Further, current funding for scale-up fits into either of two relatively narrow boxes: tax credits or loans. Evidence from outside the United States shows that there are other ways to support scale-up and re-risk projects.

Risk and Derisking

Nuclear innovation is a hard nut to crack in large part because it is both very risky (given construction cost disasters and all the other risks previously noted), and it is also highly capital intensive. Smaller reactors help with the latter, but there is still a lot of money on the table at high risk for very long periods of time (full payback can take decades).

Much of the focus to date has unsurprisingly been on getting first-of-a-kind reactors built. They are especially expensive and especially risky. And while various private sector partners have invested heavily (including Bill Gates), the risk/reward ratio for being first makes fully private solutions unlikely.

Government policy should therefore be focused on improving the risk/reward balance, both by reducing financial and nonfinancial risks and by increasing rewards within the context of markets.

Nonfinancial risk mitigation centers around improving the regulatory pathway and reducing technological risk partly through the development and provision of shared capabilities by the government, largely via the National Labs. It seems quite possible that AI applications will enhance these capabilities, perhaps substantially, particularly in modeling and simulation. The expansion of shared test facilities at INL is another important and positive development.

Some companies (e.g., Kairos) have also developed sensible multistage rollout programs, validating technology before moving to scale. This has been difficult in the nuclear sector given the enormous investments required, but SMRs are better placed to implement such a strategy, given lower up-front costs.

A hidden technological risk is that the urgent need to reach commercial revenue will lead companies to lock in on current technology before the sector's discovery phase has been completed. Even though PWR SMRs will likely be cheaper and quicker to build initially, but they may not have a sufficient pathway for cost improvement to reach P3. That, however, is speculative at this point.

The reality of political risk is now looming. The appointment of generally pro-nuclear leaders to several key DOE positions suggests that nuclear will remain a favored technology, but the demand for cuts in all government spending—and the likely rollback of tax credits—means that the existing pathway for deployment in the United States is at least under challenge. It will be especially hard (and important) to defend LPO given the recent obviously political funding rush.

Financial risk. On the supply side, the biggest risk for SMRs is that sufficient projected cost savings from factory production will not manifest. Today, we simply do not know how big a risk this is. And these are, to be clear, normal risks for any emerging technology. Sometimes the technology simply does not reach P3; in other cases—such as the U.S. auto industry—getting to P3 requires the bankruptcy or acquisition of perhaps the majority of manufacturers. That's the necessary creative destruction required to build a new industry. While de-risking is laudable, and sharing the risk, particularly for building the first few iterations, is both necessary and reasonable, the fact is that every SMR company is engaged in a highly risky project. That is unavoidable.

Financial risk mitigation comes in many flavors, and the United States uses only a few of them. The U.S. model has centered on grants for first-of-a-kind development, loans for construction, and tax credits for either construction or production. However, it is a mistake to focus solely on U.S. government policy, as other countries have found different ways to mitigate supply-side and demand-side financial risks.

Supply side. Much recent risk analysis focuses on the problem of construction costs and how to share the risks involved. EFI has developed a tiered risk model, which suggests that buyers and vendors should share most cost overruns and that government should be the insurer of last resort, providing a financial backstop against catastrophic overruns. This has the advantage of reducing the private sector's long-tail risk, especially for first-of-a-kind projects, while leaving the government (and taxpayers) on the hook only for the most catastrophic overruns.

One alternative is to focus on building a strong vertically organized financing coalition that includes the vendor, the construction company, the utility (or energy manager), and eventually large end users. This Finnish model has been used successfully for many energy projects, and to fund and manage nuclear projects there.

In the United Kingdom, the proposed rate-asset-based model simply uses the ratepayers to reduce capital costs by imposing on them some of the construction costs on ratepayers during construction. By creating an immediate stream of revenue, this both reduces the overall cost of debt (which is heavily used to fund large reactor projects everywhere). However, charging ratepayers a fee before construction and delivery of energy would be a challenge in the United States.

Government loans also play a significant role, as they lower the cost of borrowing, which reduces the overall cost of capital substantially. Of course, that implies more government risk, but that can also be mitigated.

Both utilities and large vendors can play a pivotal role in funding SMRs; Rosatom, for example, appears to be bringing highly advantageous financing terms and support in its effort to build an international market for its reactors. The role of the state as a strategic backer of SMRs is likely to grow, as China and Russia make a concerted effort to grow deployment of their national champions in other countries.

Demand-side risks. Again, SMRs are inherently less risky from a demand perspective than are large reactors. They have shorter lead times, so market conditions have less time in which to change adversely. And they cost less.

Still, it is always difficult to overcome the chicken and egg problem as new technologies seek to reach competitive scale against incumbent technologies—which, in the case of energy, are also subsidized. New energy sources are competing not just against other new sources with different technologies, but also against existing energy sources, some of which will have fully amortized their construction costs (aside from having other advantages).

Energy projects have traditionally insured against demand risk through PPAs in which a purchaser guarantees to buy a set amount of energy at a set price for a set period. The recent agreement between Constellation Energy and Microsoft for the revitalization of reactor #3 at Three Mile Island is an example. Microsoft will take 100 percent of the energy from the plant for 20 years at a price that is slightly above current market prices for energy but fixed for the life of the project. Constellation can accept the offer because nuclear operating costs are highly predictable—it would be risky to do the same deal with gas, whose price could spike. And without that PPA, it is unlikely that Constellation would have taken the risk to restart Three Mile Island.

But PPAs are not the only way to mitigate demand risk. Subsidies are another, as they reduce the price of electricity, hopefully to the point that it is competitive. The $30/MWh in PTCs that nuclear projects could receive under the IRA would reduce the cost of nuclear energy by perhaps 20–25 percent. These blunt-force subsidies do have a significant downside for government, though. Because they are paid regardless of the final price, they might be too big (owners would receive more than the amount needed to make their energy competitive) or they might be too small (payable but not enough to make the project competitive). The IRA subsidies are also time limited, and politically exposed.

Alternative forms of support can close the initial gap between the sustainable price of energy from a project and market prices while retaining more flexibility. CfDs provide companies with the exact amount of support needed to close that gap, payable as the difference between project and market prices, for a set period of time. Using an auction approach to CfDs also allows the funder (government) to set a maximum price for the energy, which limits its exposure.

There are also a range of ownership models for reactors, especially for SMRs and microreactors in particular. Both Last Energy and Copenhagen Atomics plan to own and permanently operate their microreactors, selling energy to their customers (presumably through a PPA). Depending on the capital structure and debt load, that model could be both more risky and more profitable.

Regulation

Despite some recent improvements, U.S. regulation of SMRs must still fit somewhat uncomfortably into a model designed for a few large reactors using a single basic technology, rather than a plethora of varied designs deploying across multiple sites. The NRC has adjusted to some degree, leading to a new rulemaking that should suit SMRs better, reducing the time to deployment while retaining key safety regulation features—and to an alternative pathway through NRC exemptions from existing regulation, an approach that has successfully worked for some SMR manufacturers already (e.g., TerraPower). The new pathway should be operational in 2027, but the alternative approach has been so functional that the former may become moot.

These improvements still leave plenty to be done. Notably, there is little visibility into the issue of regulating iteration, a necessity for new designs during the discovery phase. NRC is set up to validate a finished design; indeed, the new pathway doubles down on that conceptual framing. That leaves the question of iteration unexplored: how much change in a design should require review from the NRC, or even recertification? Can the new focus on probabilistic and data-driven assessment harness new modeling capabilities (and even AI) to support iteration analysis?

There are also still problems with fees, which remain a significant challenge for smaller companies. Perhaps Congress can create fee scales that reflect both the size of a reactor and its novelty, with better cost shares for innovative and smaller reactors (larger projects and more established designs should be better able to pay their share). And issues of capacity will become much more important if SMRs do reach some scale; despite recent efforts to expand the workforce, it’s not clear that NRC will have the capacity to manage the necessary throughput of certifications in a timely manner. This, of course, is a growing concern given the current push to downsize government.

NEPA review and transportation issues offer further areas for concern. NEPA reform is of course an issue much wider than the nuclear sector, but recent announcements in the United Kingdom suggest that nuclear needs may play a role in shaping overall policy.[139] Both time limits for litigation under NEPA and the assignment of cases to administrative law judges might significantly shorten average NEPA-related delays.

Finally, interconnection has to be solved. It is not sustainable for the United States to have a five-year queue of energy projects waiting for interconnection approval. Partly, this is a matter of bureaucratic procedures, partly it is the result of numerous speculative projects getting in line in case they get built (especially solar), and partly it is a personnel bottleneck at FERC, where there are not enough engineers and pay is too low to attract them in an increasingly competitive environment.

Regulatory review of SMR transportation has not yet really begun, although NRC has released a white paper on the transportation of fueled reactors. Efforts will ramp up closer to the time when actual SMRs are being built and require transportation. Where that authority might reside by that point is not at all obvious.

POLICY RECOMMENDATIONS

Nuclear power could become a strategic industry in the United States if SMRs become a competitive energy source. To give SMRs the opportunity to become important, government policy needs to focus on helping SMRs reach P3 compared with competing technologies. That requires support across the technology development cycle.

In general, DOE must improve its capacity to undertake P3 analysis at each stage of development. Currently, no single office supports P3 analysis, and DOE is developing no special capabilities for it. This is an enormous gap, and leads to DOE supporting technologies that have no substantial likelihood of reaching P3. Failure here also leads to support for incumbent technologies—such as large reactors using PWR technologies—instead of funding the innovation needed to reach P3.

The P3 analysis function should be removed from the work of technology- and sector-specific offices. P3 assessments should not be in the hands of offices that support specific technologies—the potential conflicts of interest are apparent, and already lead to rosy projections from interested parties within DOE.

Supporting Further Basic and Applied R&D (TRL 1-3)

Government funding will be critical for early stage R&D, as it is for all technologies. However, current approaches could be improved in the following ways:

- **Stabilize or expand budgets for civilian nuclear power.** At a minimum, the administration should stabilize budgets for basic and applied nuclear research both at universities and start-ups and especially at INL, ORNL, PNNL, and ANL, which offer unique resources and capabilities. Ideally, the administration would be expanding these activities. The work done to date on modeling and simulation should be continued and expanded, as should INL efforts in particular to build shared testing facilities and sites for first-of-a-kind criticality. This work should in particular focus on alternatives to PWR, notably molten salt, as these—at a very early stage still—appear to have long-term P3 advantages over PWR.
- **Industry input.** In general, DOE should encourage nuclear industry input into research priorities, and should support collaborative precompetitive research. However, DOE should also insist on the maximum flow of results and technical information to the wider public, conditional on not revealing critical trade secrets. Transparency should be the default, rather than—as it is now—the exception.
- **SBIR for nuclear.** This faces some challenges. Because it is impossible to even design a nuclear reactor with the level of funding SBIR requires, SBIR seems best suited for focusing on component-level improvement—such as NanoNuclear's Annular Linear Induction Pump. Given that ONE controls the topic selection for nuclear SBIR awards, it should ensure that SBIR remains focused on innovation, not just incremental improvement to PWR designs.
- **Addressing the Valley of Death.** DOE is trying to fill the current funding gap that exists toward the end of applied research. This funding—in the $5 million–$25 million range—can prove critical for prototype development, which helps mark readiness for the testing

and evaluation stage. A focus on component development makes sense in the context of the nuclear sector.

Two final notes: ARPA-E may play a more prominent role in this area now that innovation is becoming a much more important part of the nuclear landscape, and it has provided grants for nuclear components in the $5 million range. R&D also matters at other agencies. The U.S. Army continues to explore ideas for mobile nuclear power that could solve energy problems for bases in the United States and abroad, and recently issued a call for microreactor proposals and Navy funds research aimed at improving nuclear powered ships and submarines. The Air Force is also exploring on-base use of microreactors at several bases.[140] NASA continues to work on nuclear for use in space.

Supporting Technology Validation, Further Development, and Testing (TRL 3-6)

Historically, government funding has been scarce for the pilot and demonstration phase of product development, during which designs are constantly being improved, tested, piloted, and often then further improved (excluding DOD, which has an extensive testing and certification system).

However, recent policy innovations have made a huge difference here. DOE funding has supported TerraPower, NuScale, Kairos, and X-energy through this stage of development; NuScale received about $250 million between 2018 and 2024 in the run-up to its first commercial-scale deployment, and X-energy received about $60 million (the boundary between the testing and evaluation phase and commercial deployment is, of course, blurry).

Given that all three companies have transitioned through this stage and are entering the demonstration and deployment stage, this support must be seen as successful. What is not so clear is whether DOE has applied a consistent and appropriate P3 lens to these projects. We don't know these details because DOE has published very little about funded projects. While companies of course need to defend their intellectual property, these projects could not exist without funding from DOE (and hence the taxpayer). It is simply not acceptable that DOE has published no detailed explanation for this funding. Bland statements—little more than corporate public relations in DOE dressing—are no substitute.

DOE is currently also supporting the next cohort of SMRs, providing approximately $1 billion to five companies, mostly for work within the testing and evaluation phase, with Kairos receiving more than $600 million for its Hermes reactor. Again, while these levels of support are likely crucial, very little is known publicly about the assessment and evaluation process at DOE.

- **P3 assessment.** DOE needs to ensure that as projects move through TRL levels, P3 evaluation comes increasingly into focus. While design work, modeling, simulation, and even prototypes will be needed before effective P3 analysis is possible, by the time substantial funding is provided, DOE must have a clear a understanding of the path to P3, and must be able to explain that path publicly to all stakeholders (including Congress and the general public).
- **Transparency.** DOE needs to be much more transparent about its funding decisions. Simply announcing awards and explaining the objectives of funding are not sufficient. A detailed techno-economic analysis that includes P3 pathways should be published for

every funding decision over a certain amount—and certainly for commitments that rise into the hundreds of millions or billions of dollars.

- **TRL 3-6 funding from government is critical.** In general, we strongly support funding for TRL 3-6. Private investment will not be sufficient, especially for nuclear, where risks are high and returns are often a long way off. Building a new industry sector is challenging, and government funding will be needed. And moving through TRL 5-6 is expensive for first-of-a-kind reactors.

Demonstration and Deployment (TRL 7-9)

During the demonstration and deployment phase, costs increase tremendously. Deploying a first-of-a-kind commercial-scale reactor has in the past run to multiple billions of dollars, and even for SMRs, the total cost is likely to be $1 billion or more for a project the size of TerraPower's 345 MW Natrium reactor. DOE has now committed more than $5 billion for first-of-a-kind commercial deployment of the NuScale, TerraPower, and X-energy reactors. This funding has come primarily from OCED.

At this stage, DOE should have two core objectives: 1) supporting first-of-a-kind deployment to demonstrate that the technologies work at commercial scale, and that they have reached the start of a commercial pathway, and 2) ensuring that supported technologies have a feasible path to P3. Given the huge amounts involved, and the level of technology lock-in necessary to activate a first-of-a-kind reactor, finding technologies with a path to P3 is critical. Just getting SMRs operational at commercial scale is not enough, though it is a necessary step.

OCED is an important office; while it has (often at the direction of Congress) supported quixotic projects such as hydrogen hubs, with little to no regard for P3 concerns, the underlying theory is correct: companies will invest when the technological and market risks have been reduced to manageable proportions through demonstration projects. Congress should continue to fund OCED, which can then support innovative demonstration projects, but it should also require that OCED ensure that projects have a viable path to P3. Simply funding technologies because they reduce emissions is not enough, or even necessarily relevant.

On the regulatory side, the NRC has developed more-flexible models for regulating nuclear reactors, although the proposed new rulemaking is not complete and won't be implemented until 2027 or later—and the NRC has not addressed the problem posed by the need to iterate new designs. The NRC also needs to make it a priority to engage with other regulators, working toward the development of shared certification criteria that would simplify international deployment for SMRs.

Regulatory reform also has to address interconnection delays, a problem that affects both the demonstration/deployment stage and scale-up. The current queue should not be tolerated, and both FERC and Congress should consider innovative ways to address it. These could include adding engineers and paying them better from the federal budget; creating a priority lane for companies willing to fund more engineers at FERC (this model has some analogies with pharmaceuticals and FSA); prioritizing projects based on size to reduce the overall amount of energy being delayed; and prioritizing based on grid impact so that applications where the grid is expected to be a rare backup are moved up the queue. The Texas model of simply allowing interconnection with the option to shut off grid access if necessary is also worth exploring. The point here is that drastically shortening the interconnection process should be a national priority, and thinking outside the existing box will be needed.

- **OCED should be retained** as a critical facilitator for expensive new technologies with great potential such as SMRs. It fills a critical derisking function, and should be funded on an ongoing basis.
- **OCED reform** is needed to ensure that its work includes P3 analysis. While pathways to P3 will remain speculative until deployment at scale is reached (and possibly even beyond), this economic analysis must be a foundation piece for OCED funding.
- **Cost-share models should be reviewed.** It may be that some projects require much less cost share (perhaps because of other deep pocketed investors) while others require more (e.g., stand-alone start-ups). A flexible approach would be helpful. In addition, while in-kind cost shares are valid, OCED should be cautious about accepting existing investments (and infrastructure) as cost shares.
- **NRC and innovation.** The NRC will need to find ways to deal with design changes through the demonstration phase and beyond. Recertification will sometimes be needed, but insisting on that for all design adjustments would cripple innovation. However, there is no obvious way to establish which changes impact safety without doing a full-scale safety assessment.
- **Interconnection.** The administration should insist that FERC reduce interconnection delays to a maximum of two years, and should provide the resources and political support that will be needed to make that happen. Interconnection of new energy sources (and big users) has important implications for existing providers and energy users, so FERC will need to be smart.; The status quo is not acceptable, and reform is coming too slowly.

Scale-up

As noted earlier, SMRs face a chicken-and-egg problem: they need to scale up in order to generate economies of scale and lower costs, but they need lower costs in order to attract the orders that drive scale. The Biden IRA was a clumsy effort to solve this for all clean technologies (including nuclear): a combination of construction funding through loans (LPO) and tax credits (ITC) and operational funding through tax credits (PTC). Essentially, this structure was a panic response to an immediate opportunity. Clean energy supporters knew that this was (for them) a once-in-a-political-lifetime chance to supercharge clean energy deployment; it didn’t matter much that many of the resulting policies had no real liftoff capacity or a functional steering system. The result was massive funding commitments without much regard to long-term sustainability (P3).

Those mistakes should not blind us to an important reality: new technologies often do need help to get over the hump of commercial acceptance in order to scale up, and for energy—where rollout is usually very expensive—that can mean large amounts of funding. However, the scale of funding needed means that support needs to be smart, not panicked, such as LPO handing out billions in the last weeks of the Biden administration.

- **Funding and derisking.** LPO is a key tool. Congress and the administration should retain, reform, and even expand LPO, which plays a critical role in helping companies reach scale for new energy technologies and is not replaceable within the U.S. innovation ecology. As a revolving loan facility, it should not be a drain on government resources over the long term.

- **LPO reform** should immediately refocus LPO on helping companies reach P3 through scale-up. That will require stronger capabilities for both assessing pathways to P3 and developing clear milestones and metrics along the way. First-of-a-kind deployment is always hard and risky, but as technologies deploy, risks should recede, and certainty should replace estimates and guesses. Better analysis and expanded information flows should improve DOE's capacity to prioritize between different technologies, and to determine that some technologies will never reach P3 and should be defunded. This process will be challenging, and does carry some risks that government will be forced to pick winners and losers. However, the alternative is failure to prioritize at all.
- **Transparency.** Maximum transparency should be table stakes for acquiring a large DOE investment. Stakeholders, taxpayers, Congress, and the rest of the industry should all benefit from maximum flows of technical and financial information from publicly funded projects at this scale.
- **Scale-up mechanisms.** Congress and the administration should explore alternative mechanisms for supporting technologies as they get to scale, many of which require public-private partnerships. This could include risk tiering (as EFI has recommended); use of more flexible support systems such as CfDs; loans that become due against specific benchmarks; or perhaps even investments that have some upside for the government. Flexible use of U.S. government borrowing power will clearly remain important for reducing capital costs, and loan mechanisms will continue to play a key role.
- **Collaboration.** Government should also actively encourage development of collaborative consortia that include vendors, utilities, and end users. The Finnish model shows that sharing risks across different classes of stakeholders can make nuclear power much more fundable. Antitrust concerns should be waived, if necessary, to allow vertically organized collaborations to flourish.
- **Supply chain.** DOE will need to substantially expand is existing positive steps on the nuclear supply chain. Its HALEU contracts with Centrus are a good first step, but much more will be needed if SMR deployment accelerates. A robust and flexibly and quickly expanding fuel supply chain is an absolutely critical component for any sustainable SMR sector, and there are also international dimensions to consider, especially if SMRs become a global market.
- **Transportation and waste.** No country has yet grappled with the challenges of transportation and waste management for SMRs. They will be different in both scale and type from large reactors. There will be many more SMRs (if all goes well), so many more containers full of reactor fuel and waste will be crisscrossing the country. It's possible that new SMR technologies (e.g., MSRs—see earlier box on Copenhagen Atomics) will substantially reduce waste, but managing waste at a handful of large reactors is very different from managing it at perhaps dozens of smaller ones, especially as one advantage of SMRs is that they could potentially be sited closer to population centers. And again, transportation and waste have important international dimensions.

- **Procurement.** While the federal government has not systematically applied procurement as a tool for nuclear energy, SMRs may open the door to new options. In the United Kingdom, Rolls Royce recently signed an $11 billion contract to provide nuclear power to the Royal Navy, a contract that could fit very well with the company's efforts on both SMRs and microreactors. The U.S. Army and Air Force are currently exploring mobile microreactors, and NASA is looking at nuclear for space. And the General Services Administration recently announced a 10-year agreement with Constellation Energy that will (at least in part) rely on added capacity from Constellation's nuclear fleet to power government buildings in the Washington DC metro area.[141] Just as DOD was a key funder of the semiconductor industry during its early years, there may be a role for procurement in jump-starting SMRs.
- **Regulation.** The NRC will need to accelerate development of regulatory regimes that fit SMRs. This, in particular, means continuing to support iteration as part of innovation, which may require moving away from the core regulatory mindset of the "big reactor" era: that the key step is certifying a standard design that can then be scaled. SMRs will thrive on innovation, and a single "certified" design is unlikely to emerge, at least for more than a decade. Lots of work needs to be done on certifying factory environments, dealing with the possible fueling of reactors within those environments. Changes to the NEPA process may in the end be as important for SMRs as changes at the NRC.
- **International.** As SMRs gain traction, they will inevitably become part of a globally competitive industry. U.S. participation in the development of international standards and certification programs that are at least aligned and perhaps eventually mutually accepted will therefore be important.
- **Nuclear Coordinating Office.** There are a lot of moving parts to SMRs, including an important international dimension, different kinds of support across different stages of development, and the involvement of multiple agencies. Currently, there is effectively no strategic coordinating body across the nuclear life cycle. ONE largely focuses on R&D; OCED (which may soon be dismantled) funds demonstration projects at commercial scale; LPO has the most available funding and is focused downstream of OCED. There is no obvious coordination structure between these three, or with the DOE Office of Policy, or across agencies. While offices without budgets tend to be toothless, a coordinating body (probably located within DOE) would be a good start, and could be strengthened as SMR deployment gathers pace. Some central coordinating body must be established, whether at DOE or OSTP or elsewhere.

In the end, SMRs will become important when they reach P3 with competing technologies; they could become a globally strategic industry within the next two decades. However, SMRs are also reaching a critical juncture, as they are on the cusp of commercial deployment, after which they will face the challenge of scale-up. That challenge will be formidable, as this paper demonstrates, and success will depend on a wide range of positive U.S. government actions, including some existing programs that need reform and relaunch.

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