DEEP DIVE

Nuclear Power

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Executive summary

- **What is nuclear power?** Nuclear energy is released from the core of an atom and can be harnessed for electricity generation or heat. Nuclear power accounts for around 10 percent of the global electricity supply. Recently, there has been increased focus on advanced nuclear fission reactors that are designed to be safer and cheaper than traditional large light-water reactors.
- **How could nuclear power reduce greenhouse gas emissions?** Nuclear power can reduce greenhouse gas (GHG) emissions if it replaces or avoids carbon-emitting energy sources. We think the most promising and large-scale GHG reduction opportunity comes from nuclear power's ability to complement renewable energy sources by providing a steady source of electricity regardless of seasonal or environmental factors. As a dispatchable power source, nuclear power can also provide reliable energy, short-term flexibility, and enough capacity to meet high demand when needed. Additionally, some types of advanced nuclear reactors have use cases that can help decarbonize hard-to-abate sectors.
- **Theory of change:** US nonprofits have supported advanced nuclear reactor research, development, and deployment (RD&D) through domestic- and export-focused policy advocacy, community engagement, and licensing reform. These inputs can help derisk nuclear projects, establish a more predictable path for licensing, increase federal funding and support, and decrease community opposition to nuclear projects. We think these factors influence whether companies can profitably scale advanced nuclear reactors. A successful deployment model in the US and reduced costs could have international spillover effects, such as through technology transfer, exports, and leasing.
- **What is nuclear power's cost-effectiveness?** We developed a highly subjective rough-guess cost-effectiveness analysis (CEA) to estimate the costs and effects of nonprofits' efforts on increasing advanced nuclear reactor deployment. We have low confidence in this CEA and do not think it should be taken literally, but generally view it as a slight positive input to our overall assessment of nuclear power.
- **Is there room for more funding?** We think nonprofit advocacy for nuclear power is relatively neglected when contextualized against the greater environmental movement and has room for more funding.
- **Are there major co-benefits or potential risks?** Nuclear power is the least land-intensive source of electricity production. Also, per unit of electricity generated, nuclear power is safer than fossil fuels and as safe as wind and solar. Potential risks include nuclear waste disposal, environmental and procedural justice concerns, and potential safety and nuclear proliferation risks.
- **Key uncertainties and open questions:** The future cost-competitiveness of advanced nuclear reactors is uncertain, and nuclear power may not be a large part of a future carbon-free energy mix. We think there are also some open questions about where to best direct philanthropic funds to support advanced nuclear reactors (e.g., innovation in the US versus other countries).
- **Bottom line / next steps:** Although there is substantial uncertainty on advanced nuclear reactors' future costs, we see value in supporting nuclear power as a way to diversify energy portfolios

given the mix of advantages and disadvantages that different sources of electricity production provide. We also think advanced nuclear reactors have value propositions outside the electrical grid, such as heat and hydrogen production for decarbonizing heavy industry. Our theory of change rests on supporting an ecosystem of nonprofits working on policies supporting advanced nuclear reactor innovation in the US, given that the US is important for designing and demonstrating these technologies before they are exported elsewhere.

What is nuclear power?

Nuclear energy is released from the nucleus, or core, of an atom. It can be harnessed to produce electricity and heat. Nuclear fission reactions split atoms into smaller nuclei and release energy that can be used to heat water into steam and turn a turbine to produce electricity.[1] Currently, nuclear power accounts for around 20% of electricity generation in advanced economies and 10% globally.[2]

In this report, we refer to both traditional large-scale light-water reactors and advanced nuclear reactors, which can be smaller, safer, and cheaper to build.[3] We also focus on nuclear fission and not nuclear fusion because we think it will probably take at least decades before nuclear fusion reactors can generate electricity at large scales.

How could nuclear power reduce greenhouse gas emissions?

Nuclear power plants could reduce greenhouse gas (GHG) emissions if they replace or avoid carbon-emitting energy sources such as coal-fired or natural gas power plants.[4] We think the most promising and large-scale GHG reduction opportunity comes from nuclear power's ability to complement renewables because, unlike wind and solar, nuclear power can produce steady electricity regardless of seasonal or environmental factors.[5] As a dispatchable power source, nuclear power can also provide reliable energy, short-term flexibility, and enough capacity to meet high demand when needed.[6] Some

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[1] "Nuclear energy comes from splitting atoms in a reactor to heat water into steam, turn a turbine and generate electricity." NEI, n.d.

[2] "Nuclear power accounts for about 10% of electricity generation globally, rising to almost 20% in advanced economies." IEA, 2022.

[3] "Nuclear energy is generated by splitting uranium atoms in a controlled operation called fission. Traditionally, nuclear power is generated using light water nuclear reactors to heat water and create steam to drive a turbine; however, several new reactor technologies are in development. These advanced nuclear reactors extend beyond traditional reactors, offering the opportunity of safer, cheaper, and more efficient generation of emissions-free electricity, as well as heat for industrial processes." Resources for the Future, 2021.

[4] Nuclear produces 3 tCO_2e per GWh of electricity, compared to 820 for coal and 490 for natural gas. Our World in Data, 2022.

[5] "Nuclear power plants contribute to electricity security in multiple ways. Nuclear plants help to keep power grids stable. To a certain extent, they can adjust their operations to follow demand and supply shifts. As the share of variable renewables like wind and solar photovoltaics (PV) rises, the need for such services will increase. Nuclear plants can help to limit the impacts from seasonal fluctuations in output from renewables and bolster energy security by reducing dependence on imported fuels." IEA, 2019.

[6] "Nuclear and other dispatchable power sources complement renewables by providing critical services to electricity systems. The predominance of wind and solar in the power mix and the end of unabated fossil generation must be complemented by a diverse mix of dispatchable generation to provide stability, short-term flexibility and adequate capacity during peak demand

types of advanced nuclear reactors could play a role in decarbonizing sectors that are hard to abate due to financial and technological barriers. For example, the high heat produced from some advanced nuclear reactors can be used to create synthetic fuels such as hydrogen, which is important in the industrial, power, and transportation sectors for reducing carbon emissions.[7] However, we note there are technical, economic, and regulatory challenges to scaling nuclear reactor deployment for these novel applications.[8] Additional opportunities for advanced nuclear reactors include coal-to-nuclear transitions, where former coal-fired power plants host advanced nuclear power plants, and off-grid electricity and district heating.[9]

What is nuclear power's role in an energy portfolio?

We think nuclear power can play a valuable role in the grid by operating throughout the day and across all seasons, which would complement an expansion in renewables. Within the US, system-level decarbonization modeling has indicated that the US needs significantly more clean, firm capacity to reach net-zero emissions and nuclear power is one of only a few viable options that can provide such power at large scales.[10] In addition, we think nuclear power could play a role in meeting the projected increase in demand for electricity from the growth of the AI industry.[11] We think it's valuable to support multiple technologies that can provide clean, carbon-free electricity because they each have different value propositions, such as cost and impacts on land use (**Figure 1**).

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periods. For example, in an analysis of a carbon neutral power system in China, nuclear would provide only 10% of total electricity produced in 2060, but supply almost half the required inertia, a key component of system flexibility." [IEA, 2022.]

[7] Producing synthetic fuels: " For example, they produce large amounts of heat that can be leveraged for useful purposes: either nuclear electricity or nuclear heat can be used to desalinate water or produce synthetic fuels1 like hydrogen, ammonia, and gaseous and liquid hydrocarbons." [National Academies of Sciences, Engineering, and Medicine, 2023.] Usefulness of hydrogen: "Hydrogen provides perhaps the most credible non-electric revenue stream for nuclear reactors, because it is likely that hydrogen will have value across the industrial, power, and transportation sectors for deep decarbonization." [National Academies of Sciences, Engineering, and Medicine, 2023.]

[8] "However, employing nuclear power for these novel applications raises serious technical, economic, and regulatory challenges that must be resolved for any expanded deployment to be realized." [National Academies of Sciences, Engineering, and Medicine, 2023.]

[9] Coal-to-nuclear: "Repurposing existing fossil generation sites (e.g., coal plants) with new nuclear generation to benefit from existing transmission infrastructure, cooling capability, and possibly portions of the existing plant outside the nuclear island (e.g., turbine-generators)." [National Academies of Sciences, Engineering, and Medicine, 2023]. Off-grid: "Combining off-grid electricity and district heating," ibid.

[10] "System level decarbonization modeling, regardless of renewables deployment, suggests that the U.S. would need significantly more clean, firm capacity to reach net-zero (Figure 3). There are only a few options for clean, firm power, and nuclear power is one of the most viable options proven at large scale, with ~100 GW3 of nuclear reactors currently operating across the U.S., beginning in the 1950s." [Kozeracki et al, 2023.]

[11] Increased demand: "Data center power demands are growing rapidly. Connection requests for hyperscale facilities of 300-1000MW or larger with lead times of 1-3 years are stretching the capacity of local grids to deliver and supply power at that pace. A significant factor today and in the medium-term (2030+) is expanding power demand of AI applications." [DOE, 2024]. Role of nuclear: "**T**he power needs of future data centers are unclear both in terms of magnitude and temporal shape. For a large, flat load, characteristic of many data centers today, technologies such as nuclear or gas with CCS may be preferred. If data center computational activities increasingly have flexible or fluctuating requirements, other generation and storage technologies may be preferred." [DOE, 2024.]

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

Figure 1: Value propositions of different power sources (Source: US Department of Energy)[12]

We think nuclear power's small footprint could be especially meaningful in the future because renewables' large footprint may become more of a concern as their deployment scales.[13] Several system-level decarbonization models have indicated that significant new nuclear power would be required in the US by 2050 if limitations from transmission buildout and land use curb a buildout in renewables (**Figure 2**).[14]

At the same, nuclear power has major drawbacks that could make it less competitive relative to other options. Crucially, traditional large light-water reactors (LWRs) require intensive regulatory approval and have had high capital costs, cost overruns, and long construction periods.[15] Given these constraints, nuclear power projects have had trouble competing against cheaper and faster-to-install alternatives, such as natural gas or renewables.[16] Additionally, we think emerging technologies such as advanced geothermal systems and long-duration energy storage could play a similar role in the grid as nuclear

[12] Figure 5: Select elements of nuclear's value proposition as compared to other power sources. Kozeracki et al, 2023.
[13] "First, we see that there are massive differences between sources. At the bottom of the chart we find nuclear energy. It is the most land-efficient source: per unit of electricity it needs 50-times less land compared to coal; and 18 to 27-times less than on-ground solar PV." Ritchie, 2022.
[14] "Multiple system level decarbonization modeling exercises over the last two years have concluded that, especially with estimates for renewables buildout that account for limitations from transmission expansion and land use, significant new nuclear power would be required by 2050." Kozeracki et al, 2023.
[15] "With large up-front costs and long lead times for projects": IEA, accessed 2022. Regulatory costs may be more difficult to quantify. We haven't identified an objective source for this, but anecdotally note that the "center-right" American Action Forum estimates: "The average nuclear power plant must comply with a regulatory burden of at least $8.6 million annually." Batkins, 2016.
[16] "With large up-front costs, long lead times and an often-poor record of on-time delivery, nuclear power projects have trouble in some jurisdictions competing against faster-to-install alternatives, such as natural gas or modern renewables." IEA, accessed 2022.

power and become more cost-competitive in the future.[17] Ultimately, it's unclear to us how these emerging technologies will compare against advanced nuclear reactors in the future.

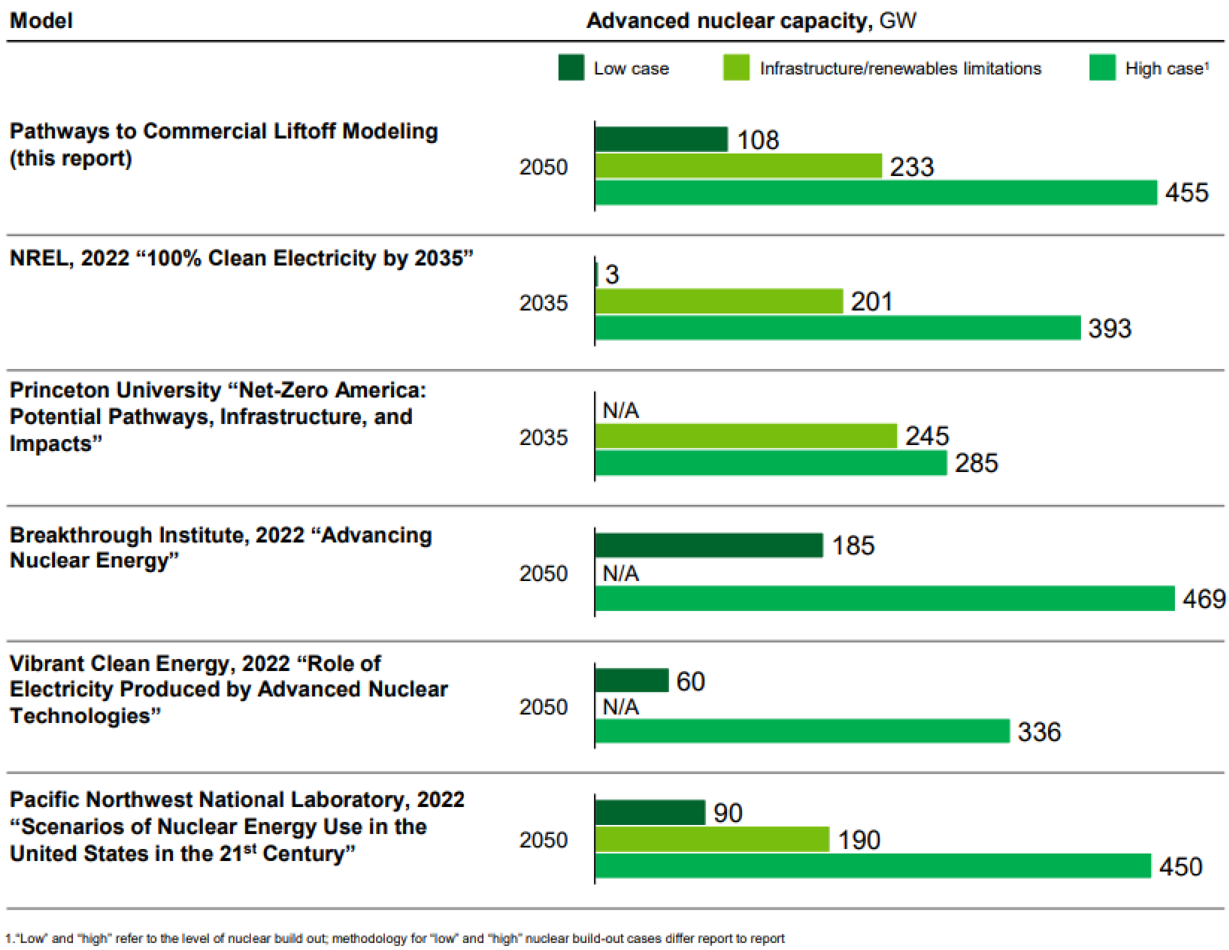

Figure 2: New nuclear capacity in a net-zero grid, based on various modeling efforts (Source: US Department of Energy)[18]

We are cautiously optimistic about nuclear power's future because our understanding is that there have been systemic efforts to make nuclear power cheaper, such as a shift in focus from traditional nuclear reactors to advanced nuclear reactors, including small modular reactors (SMRs) that are designed to be

[17] Geothermal: We think advances in enhanced geothermal systems (ESGs) could potentially expand where geothermal power plants are deployed and that EGS may become more cost-competitive than small modular reactors in the future. For more information, see our [geothermal energy deep dive report](). Long-duration energy storage: Battery technologies have also become substantially cheaper over time and there are ongoing efforts to commercialize LDEs. "Since 1991, prices have fallen by around 97%. Prices fall by an average of 19% for every doubling of capacity. Even more promising is that this rate of reduction does not yet appear to be slowing down." Ritchie, 2021. "Funded by the Bipartisan Infrastructure Law, the LDES portfolio received $505 million to help advance LDES systems toward widespread commercial deployment." OCED, n.d.

[18] See Figure 4: New nuclear capacity in a net-zero grid, based on various modeling efforts. Kozeracki et al, 2023.

smaller and lower cost to build with advanced safety features like passive cooling systems.[19] Although advanced nuclear reactors are unlikely to reach the demonstration state until the late 2020s or 2030s, we think they could help with decarbonization in the long term as electricity demand grows.[20] We also believe it is worth it to work on nuclear power now because waiting to deploy nuclear reactors at scale could lead to missed decarbonization goals, supply chain issues, and higher costs in the future.[21]

How do we maintain or increase nuclear power?

Overview

Keeping traditional nuclear power plants open would help maintain nuclear power, while scaling up LWRs and supporting advanced nuclear reactors can increase nuclear power. Of the three, we believe supporting advanced nuclear reactors to be the most promising in terms of scale, feasibility, and funding need.

Keeping traditional nuclear power plants open

The number of traditional nuclear power plants has decreased in the US since the 1990s, dropping from 112 in 1990 to 93 in 2021.[22] As of September 2024, our take is that keeping nuclear reactors open in the US is important, but we have not prioritized it because it may be well-covered under recently passed bills. For example, the Infrastructure Investment and Jobs Act (IIJA) includes the Civil Nuclear Credit Program (CNC), a $6 billion USD investment that can support continued operations. Nuclear plants at risk of

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[19] SMRs: "Because of their size, small modular reactors (SMRs) could solve some of the major challenges of traditional nuclear power, making plants quicker and cheaper to build and safer to operate." Crownhart, 2023. Passive systems: "To achieve the higher safety standards in terms of reduction of risk, passive systems could play an important role by eliminating the requirements of operators or external inputs for their operation. However, it may be difficult or impossible to incorporate passive systems extensively in large size reactors, but could be well fit into small and medium sized reactors." Nayak & Sinha, 2007.

[20] "Because demonstrations of new and advanced nuclear designs are not expected until the late 2020s or early 2030s, it may be difficult for new nuclear technologies to contribute significantly until the next few decades. Nonetheless, there is a potential longer-term role for advanced reactors. Electricity demand will grow, the costs and benefits of various technologies may change, capital stock will turn over and need to be replaced (providing the opportunity for technology substitutions), and decarbonization of buildings, industry, and transportation will continue to be targets for decades to come (Figure 1-2). While there is urgency in focusing on short-term solutions for decarbonization, advanced reactors could play an important role in coming decades." National Academies of Sciences, Engineering, and Medicine, 2023.

[21] "Waiting until the mid-2030s to deploy at scale could lead to missing decarbonization targets and/or significant supply chain overbuild. Committing to rapidly scaling the nuclear industrial base will increase capital efficiency and enable nearer-term decarbonization. If deployment at scale begins in 2030 and throughput is ramped up to 13 GW per year over the next 15 years, 200+ GW of new nuclear capacity can be achieved by 2050; however, a five-year delay in scaling the industrial base would require 20+ GW per year of throughput to achieve the same target. Delivering projects at that rate and scaling a supply chain to 20+ GW could come at significantly higher capital costs, both overall and for the marginal unit (Figure 22)." Kozeracki et al, 2023.

[22] "Number of nuclear power reactors in the United States from 1957 to 2021. 1990: 112, 2021: 93." Statista, 2022.

closing also benefit from production tax credits in the Inflation Reduction Act (IRA) and can apply for future funding rounds from the CNC.[23]

We think there are probably opportunities to keep nuclear reactors open in other countries. For example, some countries—such as Belgium, Germany, and South Korea—that had committed to phasing out nuclear power have delayed closures to address energy crises or reduce emissions.[24] Due to capacity constraints, we have yet to investigate in depth philanthropic opportunities for preventing nuclear reactor closures in non-US countries.

Scaling up traditional nuclear power plants in the US

Traditional nuclear reactor construction in the US has faced significant cost run-ups and delays.[25] For example, Georgia Power's Vogtle Units 3 and 4 came online seven years later than expected and at a cost of $35 billion, more than double their original estimate.[26] [27] Cost overruns and delays in the US have been partly associated with increased regulations after nuclear disasters. For example, after the Three Mile Island accident, the overnight construction cost and construction time of nuclear reactors escalated to

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[23] "As Diablo Canyon highlights the limits and difficulty of navigating the Civil Nuclear Credit, the industry has praised the production tax credit included in the Inflation Reduction Act. The credit offers $3 per megawatt-hour (MWh) of electricity produced and sold, which can increase to $15 per MWh if certain wage standards are met, according to the bill… Some nuclear plants in limited situations—such as those struggling to operate in high-cost, high-price regions—may not see a benefit from the tax credit and choose to apply for future rounds of the CNC program." Moore, 2022.

[24] Belgium: "The Belgian federal government postponed a planned phaseout of nuclear power Friday, citing "a chaotic geopolitical environment" as the war in Ukraine disrupts energy markets across the European Union." Guillot, 2022. Germany: "Germany is to temporarily halt the phasing-out of two nuclear power plants in an effort to shore up energy security after Russia cut supplies of gas to Europe's largest economy." Connolly, 2022. South Korea: "President Yoon Suk-yeol, who took office in May, has vowed to reverse former President Moon Jae-in's policy of phasing out nuclear power, a policy which was brought in after he assumed office in 2017, and followed the 2011 Fukushima Daiichi accident in Japan." World Nuclear News, 2022.

[25] "Nuclear power plants provide roughly half of the low-carbon electricity in the US. However, projections of nuclear plant costs have repeatedly failed to predict the cost overruns observed since the 1960s. We study the mechanisms that have contributed to the rise in nuclear construction costs over the past 5 decades to understand the divergence between expected and realized costs. We find that nth-of-a-kind plants in the US have been more expensive than first-of-a-kind plants, with "soft" factors external to reactor hardware contributing over half of the cost increase between 1976 and 1987. Costs of the reactor containment building more than doubled, primarily due to declining on-site labor productivity. Productivity in recent US plants is up to 13 times lower than industry expectations. A prospective analysis of the containment building suggests that improved materials and automation could increase the resilience of nuclear construction costs to variable conditions." Eash-Gates et al, 2020.

[26] "Yet it's no secret that the Vogtle expansion was behind schedule and over budget. The new reactors came online seven years late at a cost of $35 billion — more than double the initial $14 billion estimate." Bright, 2024.

[27] New cost: "A nuclear power plant being built in Georgia is now projected to cost its owners more than $30 billion." Original costs and delays: "When approved in 2012, the third and fourth reactors were estimated to cost $14 billion, with the first electricity being generated in 2016. Now the third reactor is set to begin operation in March 2023, and the fourth reactor is set to begin operation in December 2023." Amy, 2022.

meet new safety procedures and requirements.[28] Additional factors impacting cost and scale-up include utility deregulation, which made large plants less favorable; construction management issues; and opposition to nuclear power.[29]

We think it's possible that the cost of building traditional nuclear reactors in the US could go down if they are built as fleets but we are not optimistic about this. For example, costs in France may have been stable over time because of construction efficiencies (e.g., using the same few nuclear reactor designs repeatedly) and a less adversarial regulatory process than in the US.[30] South Korea had similar efficiencies, benefited from importing other countries' designs, and had a single utility to oversee construction.[31] Recently, there has been interest in building fleets of nuclear power plants in the US using existing, licensed technologies as a way to potentially drive down costs.[32] However, we are not optimistic about philanthropic opportunities for scaling traditional nuclear power plants in the US primarily because we are unsure of the extent to which large, traditional reactors can get on a steep learning curve and decrease in price. Unlike solar panels, which are mass-produced products, traditional light-water reactors are both customized and complex, which slows their rate of improvement.[33] Additionally, while construction at nuclear plants can be made more efficient, delays during construction–which significantly contribute to cost overruns–will still remain.[34] We have deprioritized this intervention primarily due to

[28] "When the full cost experience of US nuclear power is shown with construction duration experience, we observe distinctive trends that change after the Three Mile Island accident. As shown in Fig. 3 in blue, reactors that received their operating licenses before the TMI accident experience mild cost escalation. But for reactors that were under construction during Three Mile Island and eventually completed afterwards, shown in red, median costs are 2.8 times higher than pre-TMI costs and median durations are 2.2 times higher than pre-TMI durations. Post-TMI, overnight costs rise with construction duration, even though OCC excludes the costs of interest during construction. This suggests that other duration-related issues such as licensing, regulatory delays, or back-fit requirements are a significant contributor to the rising OCC trend." Lovering, Yip, and Nordhaus, 2016.

[29] Utility deregulation: "The wave of utility deregulation started in the 1970s disfavored large, expensive plants." Plumer, 2016. Project management: "The recent experience of nuclear construction projects in the United States and Europe has demonstrated repeated failures of construction management practices in terms of their ability to deliver products on time and within budget." Buongiorno et al. 2018. Opposition to nuclear power: It seems likely that advocacy against nuclear power (e.g., lawsuits, demonstrations) has played a role in delays and increased costs.

[30] "How did France pull this off? It helped that the country had only one utility (EDF) and one builder (Areva) working closely together. They settled on a few standard reactor designs and built them over and over again, often putting multiple reactors on a single site. That allowed them to standardize their processes and get better at finding efficiencies… France's regulatory process was also less adversarial than America's — and, for better or worse, doesn't allow legal intervention by outside groups once construction gets underway. After the Soviet Union's Chernobyl disaster in 1986, the government tweaked safety rules, leading to some delays. But costs didn't skyrocket like they did in the US after Three Mile Island." Plumer, 2016.

[31] "South Korea had an advantage in that it didn't start entirely from scratch. The country imported proven US, French, and Canadian designs in the 1970s and learned from other countries' experiences before developing its own domestic reactors in 1989. It developed stable regulations, had a single utility overseeing construction, and built reactors in pairs at single sites." Plumer, 2016.

[32] "In order to meet that long-shot goal, the U.S nuclear industry will have to radically change the way it operates. The new startup has a plan to try to achieve that. Instead of the first-of-a-kind construction process that has paralyzed the nuclear supply chain and workforce for the last 30 years, The Nuclear Company's fleet-deployment model counts on using proven, licensed technology to construct a series of reactors across the U.S." Wesoff, 2024.

[33] See Figure 1. Schematic Characterization of Different Energy Technologies Based on Their Design Complexity and Need for Customization. Malhotra and Schmidt, 2020.

[34] "While on-site construction efficiencies can be improved, the deployment of large amounts of construction and craft labor will inevitably be a drag on costs. In this regard, the nuclear industry is similar to, but worse than, the construction industry at large, as illustrated by Figure 18." Clean Air Task Force, 2023.

feasibility concerns. Due to capacity constraints, we have yet to investigate in depth philanthropic opportunities for scaling up traditional nuclear power plants outside the US.

Innovating and supporting advanced nuclear reactors

What are advanced nuclear reactors?

Advanced nuclear reactors include designs that are meant to be cheaper, more flexible, more efficient, and easier to deploy than traditional nuclear reactors. SMRs can be mass-customized and constructed in factories, which could enable "learning by doing" and drive down costs.[35] Many advanced nuclear reactors also include passive safety measures, which can help prevent loss of coolant accidents.[36] Some advanced nuclear reactors are designed to be more efficient than traditional nuclear reactors, requiring less fuel to produce electricity and generating less waste.[37] However, waste remains an issue because disposal standards and regulations need to be updated to account for non-light water reactor technologies.[38] Advanced nuclear reactors are still under development and are not expected to be demonstrated until the late 2020s or early 2030s.[39] They face economic challenges such as high development and

[35] Small modular reactors: "While traditional reactors are constructed on site, many small advanced nuclear reactors can be constructed in a factory setting and transported to a site for quick installation. For some reactor types, factory construction would allow for large numbers of reactors to be manufactured and deployed much more quickly than traditional reactors, which may be essential to reaching low-carbon generation targets." Resources for the Future, 2021. Learning by doing: "At Nth-of-a-kind (NOAK) costs, new nuclear is expected to play a critical role in a deeply decarbonized system. While first-of-a-kind (FOAK) reactors may be expensive, repeat deployments within a design are expected to drive substantial cost reductions. Eliminating rework, experience, and cross-site standardization are expected to drive the majority of FOAK to NOAK cost reductions. The nuclear industry, working together with customers and offtakers, can accelerate the learning curve by down-selecting and standardizing reactor designs, minimizing time between projects, and siting multiple units at the same location." Kozeracki et al, 2024.

[36] "In many cases, they can also take advantage of passive safety measures, such as pressure relief valves, rather than relying on active safety features that require a backup power supply or human intervention to work. These passive safety measures allow reactors to withstand a broader set of accident conditions without causing damage." Resources for the Future, 2021.

[37] "Some advanced reactors use fuel much more efficiently than traditional reactors, converting up to 95 percent of the energy in the fuel to usable electricity (traditional nuclear reactors convert less than 5 percent). Therefore, they have the potential to provide energy using much less fuel… The increased energy efficiency of many advanced reactors also results in a smaller amount of nuclear waste." Resources for the Future, 2021.

[38] "As the U.S. Nuclear Regulatory Commission (NRC) staff prepares for regulatory interactions and potential license applications for non-light water reactor (non-LWR) technologies, a need to develop an understanding of potential challenges associated with regulating the long-term storage, transportation, and disposal of advanced reactor fuel (ARF) types has been identified. For example, revisions may be needed to guidance documents and rules in Title 10 of the Code of Federal Regulations (10 CFR) Part 71 and 10 CFR Part 72. Potential ARF types that may be subject to NRC regulation in the future include metal fuels (i.e., uranium alloys such as U-Pu, U-Fs, U-Zr, U-Mo, U- Pu-Zr, often with Na between the fuel and cladding), uranium fuels for high-temperature gas-cooled reactors (HTGR) and molten salt reactors." Hall, He, & Pan, 2019. For more information on technical gaps related to storing, transporting, and disposing advanced reactor fuels and spent waste see: Matteo et al, 2023.

[39] "Because demonstrations of new and advanced nuclear designs are not expected until the late 2020s or early 2030s, it may be difficult for new nuclear technologies to contribute significantly until the next few decades." National Academies of Sciences, Engineering, and Medicine, 2023.

construction costs for first-of-a-kind reactors, and high operating costs.[40] Although SMRs are less customized than traditional nuclear reactors, they remain complex, which can present barriers to scaling up.[41]

Giving Green's take on advanced nuclear reactor innovation and deployment in the US

We think supporting research, development, demonstration, and deployment (RDD&D) of advanced nuclear reactors in the US could lower costs and help derisk nuclear power projects. We think if companies reach a tipping point where they can profitably scale advanced nuclear, this would most likely increase production and deployment. Importantly, RDD&D could have global implications if a proven model for advanced nuclear reactor deployment is developed in the US and applied elsewhere. Additionally, cost reductions from accelerated progress could have international spillover effects by exporting and leasing technologies.

We focus on the US because it is a major innovation site, and other countries could adopt its technological advances and deployment model; additionally, it is our understanding that the US government is currently keen to make the US a global leader in commercial nuclear energy again, creating a chance to push for regulatory reforms and more support for domestic nuclear.[42] For example, licensing by the Nuclear Regulatory Commission (NRC), a US government agency meant to ensure the safe use of radioactive material, is viewed as an international gold standard.[43] Therefore, we believe progress in licensing advanced nuclear reactors in the US could help other countries. Indeed, all of the experts we spoke to claimed that focusing philanthropic efforts on the US makes sense even with global deployment in mind.

Of the different methods for increasing nuclear power, we find advocacy for advanced nuclear reactors to be the most promising in terms of scale, feasibility, and funding need. However, these technologies are still in the early stages of development. Therefore, our impression is that their success is not guaranteed and relies on financial de-risking, technological progress, cost-competitiveness relative to other sources of electricity production, a supportive political environment, and community buy-in. Additionally,

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[40] "Generally, the greatest inhibitors are substantial costs associated with the development and construction of first-of-a-kind reactors. These costs are inflated by risk premiums - uncertainty due to lack of mature deployment makes first-of-a-kind generators financially risky investments. Although some projections suggest that capital costs will be lower for mature advanced reactors than for traditional ones, it is also possible that there will be substantial capital costs associated with long and complex initial construction phases, creating a significant hurdle for adoption. Finally, even once advanced reactors are built again, they may still be relatively expensive to operate." Resources for the Future, 2021.

[41] See Figure 1. Schematic Characterization of Different Energy Technologies Based on Their Design Complexity and Need for Customization. Malhotra and Schmidt, 2020.

[42] "America has lost its competitive global position as the world leader in nuclear energy to state-owned enterprises, notably Russia and China, with other competitor nations also aggressively moving to surpass the United States (U.S.). The Strategy to Restore American Nuclear Energy Leadership is designed to restore America's competitive nuclear advantages. It is in the U.S. national security interest to preserve and grow the assets and investments of the entire U.S. nuclear enterprise. We can do so by addressing domestic and international security interests, expanding nuclear generation, minimizing commercial fleet fiscal vulnerabilities, assuring defense needs for uranium, and leveling the playing field against state-owned enterprises." DOE, 2020.

[43] "The NRC is viewed internationally as the leader in nuclear safety licensing and regulation, the NRC has long been considered the gold standard for nuclear regulation." congress.gov, 2023.

successful export of US technologies requires competing against state-owned or state-financed vendors in the international energy market.[44]

Philanthropic sub-strategies

After interviewing representatives from various nonprofits, speaking with funders and nuclear power experts, reviewing organizations' websites, and reading papers, we identified several broader sub-strategies that NGOs supporting advanced nuclear reactors generally employ. We describe these sub-strategies below in **Table 1**:

Table 1: Descriptions of philanthropic sub-strategies

Strategy	**Example activities**
Domestic-focused policy research, advocacy, and thought leadership	Writing policy recommendations and advocating for increased federal funding and support for advanced nuclear reactor RD&D, establishing demonstration sites, and developing a domestic supply chain for enriched fuels.
Export-focused and international financing-based policy advocacy	Writing policy recommendations that unlock financing for US nuclear export projects, advocating for more nuclear expertise in existing international financing institutions, establishing a multilateral international financing institution for nuclear
Community engagement	Engaging with communities and community leaders to address concerns, build a social license to operate, and increase demand
Domestic licensing reform	Engaging with congressional oversight committees, providing technical and regulatory analysis, convening stakeholders, supporting other groups working on licensing reform

We assessed these strategies qualitatively in terms of scale, feasibility, and funding need in **Table 2**. We recognize that our list is not exhaustive and that there is inevitable overlap between sub-strategies.

[44] "Although it is not anticipated that significant modifications of export regulations are required to accommodate advanced reactor designs, efforts to increase international harmonization could greatly improve options for export financing. For U.S. vendors to better compete with state-owned or state-financed vendors in the dynamic international energy market, a technically and economically viable product must be established that could then be supported by a robust and reliable source of export credit financing. Most U.S. advanced reactor vendors will not be ready for international commercial deployment until successful demonstrations are completed in the United States and thus will be unlikely to tap export-import bank (EXIM) financing before a new authorization cycle is necessary" National Academies of Sciences, Engineering, and Medicine, 2023.

Table 2: Giving Green's assessment of philanthropic sub-strategies

Strategy	Scale	Feasibility	Funding Need	Notes
Domestic-focused policy research, advocacy, and thought leadership	High	Medium	Medium	**Scale:** Our impression is that scale is high because policy is high-leverage and could address multiple major barriers to deploying reactors in the US. For example, government incentives, such as economic incentives that value externalities like reduced emissions, are probably needed to help new nuclear technologies enter the market.[45] **Feasibility:** We think feasibility is medium because, while there is bipartisan support in Congress for nuclear, we do not think additional legislation will guarantee commercial viability and reduced emissions.[46] Recently passed legislation will need to be continually assessed to determine whether they are adequate.[47] We have also heard from several sources that while Congress has been supportive of nuclear, it is possible that resources for implementing nuclear policies and programs may change with different presidential administrations (e.g., reduced coordination across relevant agencies). A promising policy intervention is incentivizing private industry to finance nuclear power plants, similar to Google's deal with Kairos Power.[48] **Funding need:** We think funding need is medium because while the nuclear power industry has a strong lobbying presence, there are relatively few nonprofits working in this space compared to the environmental movement at large.[49] We believe the few nuclear policy nonprofits that exist are able to fill gaps industry cannot address.

[45] "There likely will be a need for government assistance in developing the finance structures and market incentives to help these emerging nuclear technologies make entry into the market. Some have argued that the federal government should refrain from establishing policies that influence the market. However, some targeted economic incentives may be necessary because the market does not always properly value certain important externalities such as climate change, system costs, and low emissions of other pollutants. As the advanced reactor technologies move beyond demonstrations, incentives may be necessary to enable advanced reactors to become an integral part of a carbon-free energy system in the United States. Such commercial incentives have allowed the penetration of renewables, and the same model should be followed for other low-carbon technologies, including advanced reactors." National Academies of Sciences, Engineering, and Medicine, 2023.

[46] "Expanding nuclear power has broad bipartisan support, with Democrats seeing it as critical to decarbonizing the power sector to fight climate change and Republicans viewing it as a way to ensure reliable electricity supply and create jobs." Reuters, 2024.

[47] "Continued evaluation of the recently passed incentives will need assessment to determine their adequacy. The scale of these incentives needs to be sufficient not only to encourage nuclear projects but also the vendors and the supporting supply chains." National Academies of Sciences, Engineering, and Medicine, 2023.

[48] "Google has signed a deal to use small nuclear reactors to generate the vast amounts of energy needed to power its artificial intelligence (AI) data centres. The company says the agreement with Kairos Power will see it start using the first reactor this decade and bring more online by 2035." da Silva, 2024.

[49] The ADVANCE Act of 2023, which had multiple wins for nuclear, included 36 unique organizations registered to lobby on this bill. In comparison, the Geothermal Energy Optimization Act only had five unique organizations registered to lobby on this bill. Nuclear: OpenSecrets, n.d. Geothermal: OpenSecrets, n.d.

Strategy	Scale	Feasibility	Funding Need	Notes
Export-focused and international financing-based policy advocacy	High	Medium	Medium	**Scale:** We think scale is high both because policy is high leverage and because most demand for new reactors is likely to come from outside the US.[50] **Feasibility:** We have assessed policies under this strategy as either medium or low feasibility. For example, we think efforts to unlock more funding from the U.S. International Development Finance Corporation and the Export–Import Bank of the United States are timely because they will need to be reauthorized before or in FY2025 and FY2026, respectively.[51] At the same time, we think efforts to unlock funding for nuclear projects from the World Bank are challenging because Germany, which opposes nuclear power, has outsized influence at the World Bank.[52] **Funding need:** We believe funding need for export-focused policy advocacy is similar to that for domestic policy advocacy because companies are interested in building an international market for their products.
Community engagement	Medium	Medium	High	**Scale:** We rated community engagement as medium because, while having a social license to operate is necessary for operating advanced nuclear reactors in communities, we think meaningful community engagement would likely need to occur at a local level.[53] We think the time-intensiveness of building relationships with local stakeholders reduces scalability.

[50] "Expectations are that increased demand for new reactors will come from both existing and emerging nuclear power countries in Africa, the Middle East, and Asia, a development of importance in global efforts to address climate change" National Academies of Sciences, Engineering, and Medicine, 2023.

[51] DFC: "Since the Corporation's current authorization is set to expire in October 2025, DFC will require reauthorization from Congress in or before FY 2025." DFC, n.d. EXIM Bank: "In 2019, Congress extended the Bank's general statutory authority for seven years, through December 31, 2026 (P.L. 116-94, Div. I, Title IV)." CRS, 2024.

[52] "To be sure, the World Bank's job is not easy. It faces a structural problem in that, the more funds a country adds into the bank, the larger that country's voting share becomes. This has given a handful of developed countries majority control over where funds are spent and in what ways, letting nuclear-opposing countries such as Germany block any serious consideration of nuclear power project financing." Lloyd, 2023.

[53] Need for a social license to operate: "Public opposition to nuclear power ranks among the most salient challenges impeding the construction of new nuclear power plants (NPPs); it has persisted despite decades of research into underlying attitudes toward the technology and has proven to be a difficult task for the industry to address. Like achieving cost control and ensuring high levels of regulatory quality, overcoming the social acceptance challenge is a necessary but insufficient condition if new reactors are to play an expanded role in decarbonizing the global energy system." National Academies of Sciences, Engineering, and Medicine, 2023. Importance of working at a local level: "The siting approach will have to be adjusted for a particular place, time, and culture. The nuclear industry should follow the best practices, including (1) a participatory process of site selection; (2) the right for communities to veto or opt out (within agreed-upon limits); (3) some form of compensation granted for affected communities; (4) partial funding for affected communities to conduct independent technical analyses; (5) efforts to develop a partnership to pursue the project between the implementer and local community; and (6) an overriding commitment to honesty. Following these practices will require additional time and financial resources to be allotted to successfully site and construct new nuclear power facilities, and the industry should account for these costs in their plans." Ibid.

Strategy	Scale	Feasibility	Funding Need	Notes
Community engagement (cont.)				**Feasibility:** We rated community engagement's feasibility as medium because, while community engagement can increase the likelihood of a project being built, it does not guarantee it will happen.[54] **Funding need:** We are under the impression that communities are more likely to trust nonprofits than industry interests. At the same time, we think this strategy has been neglected by most nonprofits working on nuclear policy advocacy. We are optimistic about this strategy's ability to absorb funds because we think increased funding can increase the number of places where people engage with the local community.
Licensing reform	Medium	Medium	Medium	**Scale:** NRC regulations are tailored to LWRs and may not be well-suited for many new reactor designs.[55] We think it is important to reform NRC licensing such that it is more efficient and better-suited for new designs, which can reduce costs and financial uncertainty for investors. At the same time, while safety regulations have contributed to increases in nuclear reactor construction costs, this is not the only driver of cost increases.[56] We think licensing reform has lower leverage than policy advocacy, which can address multiple cost drivers and barriers to nuclear reactor deployment simultaneously. **Feasibility:** We think licensing reform is feasible given nuclear's bipartisan support and the licensing wins included in the passed

[54] "The industry should be willing to fully engage with a community, hear its concerns and needs, and be ready to address them, including adjusting plans. While this would raise the likelihood of successful deployment, it is not a guarantee of success." National Academies of Sciences, Engineering, and Medicine, 2023.

[55] "The fundamental design of light water reactors dates from the early days of reactor operation, although there have been significant enhancements to improve operations and safety over the years. The NRC requires compliance with detailed regulations that are tailored to light water reactors (LWRs). The existing regulatory requirements may be inappropriate or inapplicable to non-LWR designs and some of the advanced designs present new regulatory issues. As a result, significant modification or adjustment of regulatory requirements is required to accommodate some of the advanced reactors." National Academies of Sciences, Engineering, and Medicine, 2023.

[56] "Our results also provide a starting point for quantifying the effect of safety regulations. While safety-related considerations likely had an influence on many of the high-level mechanisms studied here, the mechanism most directly related to compliance with regulations is PIS, which contributed approximately 30% to the observed cost increase between 1976–2017. The mechanism representing R&D activities typically addresses multiple objectives at once, and it is thus more difficult to strictly separate this into safety- and non-safety-related activities, and the same holds for productivity slowdowns reflected in "WDD." However, despite these difficulties, it is relevant to note that direct interference to address safety contributed significantly to cost increases observed (roughly 30%) but was not the only driver of cost escalation." Eash-Gates et al, 2020.

Strategy	Scale	Feasibility	Funding Need	Notes
Licensing reform (cont.)				ADVANCE Act and NEIMA.[57] We have rated feasibility as medium because, although we think further licensing reform wins are likely, they do not guarantee commercial viability. **Funding need:** We are under the impression that this is an area in which there is already a fair amount of private-sector funding because companies want to ensure that their designs can be licensed efficiently. Although we think nonprofits can and have made important contributions to licensing reform, we are unsure how much of this would have been covered by industry in the absence of these nonprofits.

Theory of change for advanced nuclear reactor deployment in the US

Overview

Our impression is that successful advanced nuclear reactor deployment in the US requires an acceptable policy environment, commercial viability, an acceptable regulatory environment, and feasible implementation (e.g., community acceptance) (**Figure 2**).[58] US policy advocacy and community engagement can improve these interrelated conditions.[59] For example, increased federal funding for RDD&D in the US can lead to cost reductions and increased adoption in the US. Community engagement could also increase demand and companies' likelihood of profitably scaling advanced nuclear power. A US-based model could also have global implications through technological diffusion. We note that this theory of change is not stepwise, and the perceived future success of "downstream" nodes might

[57] ADVANCE Act: "It also requires the Nuclear Regulatory Commission (NRC) to (1) develop a process that enables timely licensing of nuclear production facilities or utilization facilities at brownfield sites, and (2) establish an initiative to enhance preparedness and coordination with respect to the qualification and licensing of advanced nuclear fuel. NRC may hire specialized staff without regard to civil service laws to address its critical licensing or regulatory oversight needs." congress.gov, n.d. NEIMA: "This bill revises the budget and fee structure of the Nuclear Regulatory Commission (NRC) and requires the NRC to develop new processes for licensing nuclear reactors, including staged licensing of advanced nuclear reactors." congress.gov, n.d.

[58] "Even with significant government support, a credible and commercially viable nuclear power technology requires:

- Developing a business case that shows a competitive advantage over alternatives. For example, a nuclear plant to provide high-temperature heat would have to outperform natural gas with carbon capture and storage or solar-to-heat systems.
- Convincing investors to finance and build the needed supply chains and factories. A current example is the need for high-assay low-enriched uranium (HALEU) desired by many advanced reactor vendors.
- Completing regulatory approvals in a timely manner for products that are new to the regulator.
- Attaining community acceptance for deploying nuclear reactors, both in traditional ways and in first-of-a-kind deployment scenarios (e.g., microreactors as part of a distributed network of electric vehicle charging stations)." National Academies of Sciences, Engineering, and Medicine, 2023.

[59] We group legislative advocacy, policy research and education, and licensing reform under US policy advocacy.

influence upstream nodes. For example, commercial viability is most likely impacted by community buy-in.

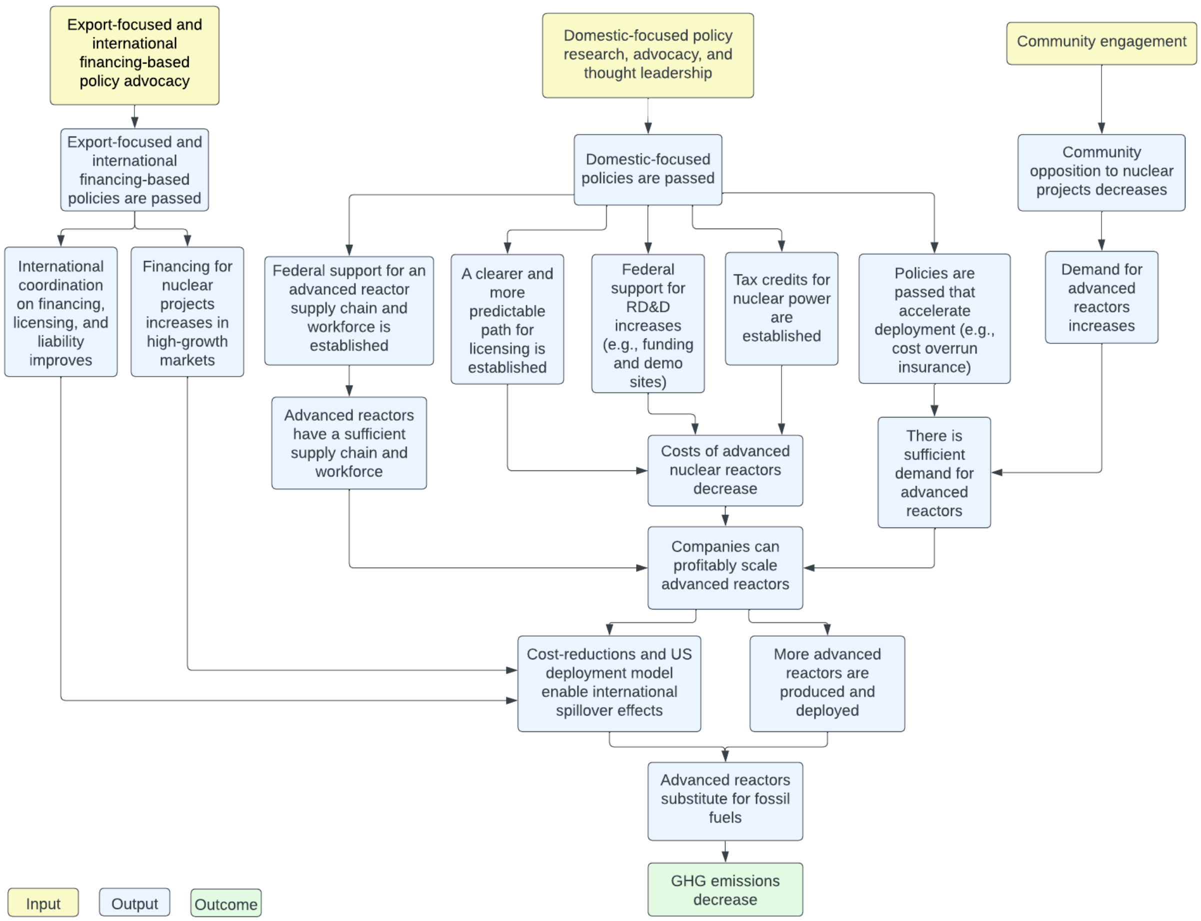

Figure 2: Theory of change for the influence of RDD&D policy advocacy on emissions reductions.

Examining the assumptions behind nuclear power's theory of change

Below, we discuss and evaluate the assumptions related to the theory of change for advanced nuclear technologies. We rank whether we have **low**, **medium**, or **high** certainty about each assumption.[60] Importantly, a number of the stages of the theory of change are not amenable to easy measurement or quantification, or are expected to occur in the future but have yet to happen. We assess whether the best evidence, primary or secondary, for each assumption suggests whether it will plausibly hold.

[60] We describe our certainty as low/medium/high to increase readability and avoid false precision. Since these terms can be interpreted differently, we use rough heuristics to define them as percentage likelihoods the assumption is, on average, correct. Low = 0-70%, medium = 70-90%, high = 90-100%.

1. **There is an acceptable policy environment for advanced nuclear reactors in the US (high certainty).**

Our impression is that there is an acceptable policy environment for advanced nuclear reactors in the US. For example, legislators have demonstrated bipartisan support for nuclear technologies in the US with passed measures such as the Nuclear Energy Innovation Capabilities Act (2018), the Nuclear Energy Innovation and Modernization Act (NEIMA) (2019), and the Nuclear Energy Leadership Act, which was included in the National Defense Authorization Act for Fiscal Year 2021.[61] In addition, IIJA and IRA included tax credits for nuclear technologies.[62] More recently, the ADVANCE Act was passed in 2024 and is intended to spur nuclear power development.[63] Also, more than half of the US states have nuclear power in their plans to reduce carbon emissions from electricity generation.[64] Further signs of support include the lifted ban on nuclear power in West Virginia and the Diablo Canyon Power Plant's extended life.[65] Despite an overall friendly policy environment, our understanding is that progress on regulation has been slow.[66]

2. **Advanced nuclear reactors can become commercially viable (medium certainty).**

Driving down advanced nuclear reactors' costs

We think economics might be the largest challenge to commercializing advanced nuclear reactors. Our take is that advanced nuclear reactors' high costs may be reduced through increased production and deployment, but we are unsure how quickly costs will drop. In particular, mass-customized and factory-fabricated advanced nuclear reactors can take advantage of efficiency gains from "learning by doing" and economies of scale. However, because advanced nuclear reactors require customization and are complex, we do not believe they necessarily analogize to solar and wind technologies, which have

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[61] Inclusion in National Defense Authorization Act: "U.S. Senator Lisa Murkowski, R-Alaska, today thanked her colleagues for supporting the inclusion of S. 903, her Nuclear Energy Leadership Act (NELA), in S. 4049, the National Defense Authorization Act (NDAA) for Fiscal Year 2021. The Senate today passed the NDAA bill, with NELA incorporated by amendment, by a vote of 86 to 14." Senate Committee on Energy & Natural Resources, 2020.

[62] Infrastructure Investment and Jobs Act: "The newly enacted Bipartisan Infrastructure Law created the Civil Nuclear Credit Program (CNC), allowing owners or operators of commercial U.S. reactors to apply for certification and competitively bid on credits to help support their continued operations." DOE, 2022. Inflation Reduction Act: "One real IRA game changer for nuclear energy is a production tax credit to help preserve the existing fleet of nuclear plants... IRA also includes several tax incentives for clean energy technologies, including advanced reactors." "DOE, 2022.

[63] "Today, the president signed into law the Accelerating Deployment of Versatile, Advanced Nuclear for Clean Energy (ADVANCE) Act, bipartisan legislation to provide a major boost to the future of nuclear energy in America." Senate Committee on Environment & Public Works, 2024.

[64] "More than half of all states include nuclear power in their plans to reduce carbon emissions from electricity generation, according to an Associated Press survey." Benshoff, 2022.

[65] West Virginia: "West Virginia Gov. Jim Justice on Tuesday signed a bill eliminating the state's ban on nuclear power plants but cautioned against jumping in to diversify the coal-dependent state's energy offerings." Associated Press, 2022.
Diablo Canyon: "The Diablo Canyon plant - the state's largest single source of electricity - had been slated to shutter by 2025. The last-minute proposal passed by the state legislature early Thursday could keep it open five years longer, in part by giving the plant's owner, Pacific Gas and Electric (PG&E), a $1.4 billion forgivable loan." Rott, 2022.

[66] "Despite the accomplishments of past legislation and regulation, the regulatory process is slow; it cannot respond to rapid changes in technology and changing customer expectations. Greater informal collaborations are needed to expedite and improve critical decision-making in areas of particular concern." National Academies of Sciences, Engineering, and Medicine, 2023.

decreased sharply in price over time. We think advanced nuclear reactors may decrease in price more slowly because projects are more likely to be context-specific and their production will likely be limited to a few countries with high technical capabilities. We think some interventions focused on enabling spillover effects and learning by doing, such as enhanced coordination on RD&D and harmonized licensing across multiple countries, could help drive down costs but may be challenging to implement.[67]

Competitiveness with other sources of electricity production

Recent studies have found that many new nuclear deployments can occur when certain conditions are met:

- Nuclear costs are substantially lower than recently experienced in the United States (~$2,000–$4,000/kW).
- There is highly constrained growth of renewable energy and transmission due to issues like supply chain or land availability, which can make nuclear energy competitive at higher costs (~$5,500/kW, depending on assumptions)
- There are limitations to the availability of other technologies that can provide capacity (e.g., no biofuels, hydrogen, CCS, or long-duration energy storage), assuming $4,000-$6,000/kW nuclear costs.[68]

In comparison, recent nuclear construction projects in the US have had overnight capital costs over $10,000 per kilowatt.[69] The US Department of Energy (DOE)'s *Pathways to Commercial Liftoff: Advanced Nuclear* report estimates that new nuclear projects could reach an overnight capital cost of $3,600 per kW

[67] "Ongoing efforts by national-level policymakers and the private sector to scale up and mass-customize Type 3 technologies need to be complemented with top-down international measures to enable learning-by-using and to maximize inter-project and inter-context spillovers.38–40 Ideally, such measures would include (1) enhanced coordination in RD&D activities across projects and firms to facilitate inter-project spillovers for highly complex technologies, (2) support for characterization of user preferences and physical environments to facilitate inter-context spillovers for customized technologies, and (3) support for learning by doing through harmonization of regulations across multiple countries for technologies that need extensive customization to suit different regulatory environments." Malhotra and Schmidt, 2020.

[68] "The EPRI study is consistent with many recent studies that show significant growth for new nuclear to meet grid needs when certain conditions are met:

- Nuclear costs are substantially lower than those experienced recently in the United States (~$2,000–$4,000/kW). In this case, nuclear is competitive regardless of other factors such as decarbonization policies, timing of advanced nuclear's commercial availability, and assumptions about renewable energy (RE) and natural gas competitiveness (EPRI 2018, 2022; Cole 2021b; Larson et al. 2021; IEA 2022).
- Highly constrained growth of RE and transmission owing to issues such as supply chain or land availability, which in turn increases overall system cost, enabling nuclear energy to be competitive at higher costs (e.g., ~$5,500/kW, depending on assumptions). These conditions also assume commercial availability starting in 2035 (or sooner) and stringent decarbonization policies (Larson et al. 2021; Denholm et al. 2022).
- Limitations on availability of other technologies that provide capacity (e.g., no biofuels, hydrogen, CCS, or long-duration energy storage) assuming decarbonization policies and $4,000–$6,000/kW nuclear costs (Brown and Botterud 2021)." National Academies of Sciences, Engineering, and Medicine, 2023.

[69] "While the estimated first of a kind (FOAK) cost of a well-executed nuclear construction project is ~$6,200 per kW, recent nuclear construction projects in the U.S. have had overnight capital costs over $10,000 per kW." Kozeracki et al, 2023.

after ten to twenty deployments, depending on learning rate.[70] Key drivers of cost reduction include improved pre-project planning, learning by doing, standardization, build time reduction, supply chain development, modularization, and reductions in other cost categories.[71] Coal-to-nuclear transitions, where coal-fired power plants are replaced by nuclear reactors, could also reduce overnight construction costs by reusing infrastructure from the coal facility.[72] At the same time, we think advanced nuclear reactors could offer value propositions outside of electricity production, such as providing high heat for industrial processes, which could help improve their ability to commercialize. Additionally, tech companies have also been interested in powering data centers with nuclear power, although this could have mixed effects on total power sector emissions.[73]

We are cautiously optimistic about advanced nuclear reactors' ability to compete with other sources of electricity production, and we acknowledge the uncertainty on how quickly advanced nuclear reactors can reduce costs, given its dependence on technological progress and political conditions.[74] At the same time, we think it is too early to rule out advanced nuclear reactor technologies because there could be value in maintaining flexibility and having multiple technologies available for decarbonization.[75] We agree with the National Academies of Sciences, Engineering, and Medicine's recommendation: the US DOE should continue supporting developers in designing smaller plants and microreactors, because when they are deployed in certain contexts, this could help control cost and schedule overruns, generate

[70] "Delivering FOAK projects without cost overrun would require investment in extensive upfront planning to ensure the lessons learned from recent nuclear project overruns are incorporated. Subsequent nuclear projects would be expected to come down the cost curve to ~$3,600 per kW after 10-20 deployments depending on learning rate; this cost reduction would largely be driven by workforce learnings and industrial base scale-up." Kozeracki et al, 2023.

[71] See Figure 15: Categorizations for how advanced nuclear costs could decrease from FOAK to NOAK deployments. Kozeracki et al, 2023.

[72] "Based on the nuclear technology choices and sizes evaluated to replace a large coal plant of 1,200 MWe generation capacity at the case study site, nuclear overnight costs of capital could decrease by 15% to 35% when compared to a greenfield construction project, through the reuse of infrastructure from the coal facility." Hansen et al, 2022.

[73] Tech companies: "The first such announcement came in March, when Amazon Web Services agreed to spend $650 million to buy an existing 960 megawatt data center campus that's already hooked up to Talen Energy's 2.5 gigawatt Susquehanna nuclear power plant in northeastern Pennsylvania. Several similar proposals are in the works, with nuclear power plant owners Constellation Energy, Vistra, Dominion Energy, and Public Service Enterprise Group eyeing prospects, according to company statements and analyst reports." St John, 2024. Emissions: "But these claims face mounting scrutiny from energy analysts and climate advocates, who fear that a rush to divert existing zero-carbon nuclear energy to power-hungry data centers could end up raising ratepayer bills, reducing grid reliability, and increasing power sector emissions overall." St John, 2024.

[74] We have not closely compared advanced nuclear reactors to early-stage renewables that can provide uninterruptible electricity, such as advanced geothermal.

[75] "Broadly, studies show that while nuclear capital costs are an important driver for nuclear's deployment, there remain situations in which nuclear generation can be competitive. For example, a more uncertainty-oriented approach would incorporate aspects of "real options" that value the future trajectory of technology options and ensure that options are not prematurely eliminated from consideration. While the approach may ultimately not yield decisions to deploy nuclear as a low-carbon alternative, it would properly reflect the value that is inherent in maintaining flexibility in grid expansion decision making (Caunhye et al. 2022). Balanced approaches to decarbonization that incorporate a wide variety of technologies can also spread risk across multiple supply chains and limit challenges in integration (IEA 2021; Brick and Thernstrom 2016)." National Academies of Sciences, Engineering, and Medicine, 2023.

demand and a larger number of signed contracts for advanced nuclear reactors, and lead to greater potential for rapid learning.[76]

3. An acceptable regulatory environment exists for advanced nuclear reactors (medium certainty).

Licensing impacts how long it takes for reactors to reach the market. According to nuclear advocates, if the licensing procedure for advanced nuclear technologies is too long, this can threaten their long-term deployment and reduce customer interest.[77]

NEIMA directed NRC to create a new licensing framework for advanced nuclear reactors that is more efficient than the existing framework designed for traditional nuclear reactors.[78] According to experts we have spoken to, ambiguities in the licensing framework need to be clarified, and the window of opportunity for modifying the framework is closing because rulemaking is set to be finalized by 2024.[79] Companies can still license their projects with existing procedures instead of going through this drafted framework, but there may still be major pitfalls and uncertainty over regulation. Overall, we think an acceptable regulatory environment can exist for advanced nuclear reactors because, while NRC can improve its licensing process, there are still pathways to getting licensed.

4. Implementing advanced nuclear reactors at scale in the US is feasible (medium certainty).

Our take is that implementing advanced nuclear reactors at scale in the US is feasible but not guaranteed. According to the DOE, an essential first step for catalyzing scale-up in the US is a "committed orderbook of at least 5-10 deployments of a single reactor design."[80] However, there has been a stalemate between vendors and customers due to perceived financial risks.[81] As of January 2023, there are no committed orders or signed contracts for new nuclear reactors in the US.[82] In June 2024, the DOE

[76] "Recommendation 4-1: The Department of Energy should continue to support developers in their efforts to design smaller plants and microreactors. This may be an early and low-risk path for nuclear deployments in certain selected applications where reduced scale may enable better control of cost and schedule overruns, potentially creating demand-pull, a larger number of orders, and greater potential for rapid learning." National Academies of Sciences, Engineering, and Medicine, 2023.

[77] "Unnecessarily long licensing reviews can raise significant barriers to investment, reduce customer interest in advanced reactors, and threaten their successful long-term deployment." Gilbert, White, & Greenwald, 2021.

[78] "This bill revises the budget and fee structure of the Nuclear Regulatory Commission (NRC) and requires the NRC to develop new processes for licensing nuclear reactors, including staged licensing of advanced nuclear reactors." S.512 - Nuclear Energy Innovation and Modernization Act, 2019.

[79] "On November 2, 2020, the staff provided a response to SRM-SECY-20-0032 outlining a schedule for preparing a rulemaking package that conforms to the Commission's direction to achieve publication of the final rule by October 2024 and to inform the Commission of key uncertainties impacting publication of the final rule by that date." NRC, 2022.

[80] "A committed orderbook of at least 5–10 deployments of a single reactor design is the first essential step for catalyzing commercial liftoff in the U.S." Kozeracki et al, 2023.

[81] "However, the nuclear industry today is at a commercial stalemate between potential customers and investments in the nuclear industrial base needed for deployment—putting decarbonization goals at risk. Utilities and other potential customers recognize the need for nuclear power, but perceived risks of uncontrolled cost overrun and project abandonment have limited committed orders for new reactors." Kozeracki et al, 2023.

[82] "As of January 2023, there are no committed orders, e.g., signed contracts, for new nuclear reactors in the U.S." Kozeracki et al, 2023.

announced it would fund up to $900 million to support US deployments of SMRs, which is intended to address the commercial stalemate.[83] We believe it is too early to tell whether this funding will resolve the commercial stalemate.

Additional challenges that advanced nuclear reactors face include having a sufficient supply chain and workforce and a predictable licensing pathway. Our impression is that provisions in the IIJA and IRA (e.g., investments in a domestic supply chain for enriched fuels) address some supply chain concerns and the ADVANCE Act addresses some licensing concerns.[84]

5. Advanced nuclear reactors scaled in the US will increase the likelihood of global adoption (medium certainty).

We think international markets will play a large role in whether advanced nuclear reactor technologies take off. For example, in the future, 75% of new electricity demand is expected to come from outside of high-income countries.[85] As part of that new electricity demand, we think it is likely that most new demand for nuclear power will come from outside the US.[86] Indeed, in 2022, emerging markets and developing economies accounted for about 60% of new nuclear power capacity additions.[87] Additionally, although US reactor vendors are currently focused on successfully demonstrating their reactors in the US, many have plans to market their reactors internationally and may depend on international sales to justify whether they establish manufacturing infrastructure.[88]

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[83] "As part of President Biden's Investing in America agenda, the U.S. Department of Energy (DOE) issued a Notice of Intent (NOI) to fund up to $900 million to support the initial U.S. deployments of Generation III+ (Gen III+) Small Modular Reactor (SMR) technologies. This funding—made possible in part by President Biden's Bipartisan Infrastructure Law—will help strengthen America's domestic nuclear industry and spur follow-on reactor projects, which are vital to achieving our nation's ambitious clean energy and climate goals and meeting the growing demand for clean, reliable power." DOE, 2024.

[84] Supply chain: "Finally, IRA invests $700 million to support the development of a domestic supply chain for high-assay low-enriched uranium, commonly referred to as HALEU. This higher enriched fuel is urgently needed to support the deployment of advanced reactors, including DOE's two demonstration projects with TerraPower and X-energy. Establishing a U.S. HALEU supply can also play a role in eliminating our current dependence on Russia for 20% of the enrichment and conversion services needed for our nuclear fuel supply." Office of Nuclear Energy, 2022. Licensing: "The ADVANCE Act builds on the successes of previous legislation to develop a modernized approach to licensing new reactor technologies. Many of the advanced reactors under development use different coolants than what is currently used in our commercial light-water reactors—making the regulatory process more of a challenge. The ADVANCE Act directs the U.S. Nuclear Regulatory Commission (NRC) to reduce certain licensing application fees and authorizes increased staffing for NRC reviews to expedite the process." Office of Nuclear Energy, 2024.

[85] New demand: "Around 75% of new demand will come outside of High Income countries, down 12% from the previous year's figure." Ahn et al, 2022. "In the coming decades, the majority of increased energy demand is projected to occur in developing and nuclear newcomer countries (Ford and Abdulla 2021)." National Academies of Sciences, Engineering, and Medicine, 2023.

[86] "Expectations are that increased demand for new reactors will come from both existing and emerging nuclear power countries in Africa, the Middle East, and Asia, a development of importance in global efforts to address climate change (Ford and Abdulla 2021; IAEA 2021)." National Academies of Sciences, Engineering, and Medicine, 2023.

[87] "In 2022, nuclear power capacity increased by about 1.5 GW globally (a 0.3% increase year-on-year), as nuclear power capacity additions outpaced more than 6 GW of retirements. Emerging market and developing economies (EMDEs) accounted for around 60% of new capacity additions, while more than half of retirements were in advanced economies such as Belgium, the United Kingdom and the United States." IEA, n.d.

[88] "Although U.S. reactor vendors are currently focused on successful completion of demonstration projects in the United States, many have plans to market their reactors internationally and may depend on significant international sales to justify the establishment of a manufacturing infrastructure." National Academies of Sciences, Engineering, and Medicine, 2023.

However, numerous barriers stand in the way of commercializing US designs in global markets, such as “a complicated set of rules to market and sell nuclear products internationally, increased competition among nations, and potential expansion of nuclear reactors into newcomer countries that may lack effective government, industry, and societal frameworks to support the facilities.”[89] Additional barriers include those related to regulatory oversight capabilities and financing mechanisms that provide advantages to non-US vendors.[90] Notably, build-own-operate models are increasingly popular among countries starting nuclear programs, and state-owned or state-financed vendors provide these more easily than US vendors.[91]

We are unsure whether the US is the best site for investing in nuclear innovation. According to a 2023 report by the National Academies of Sciences, Engineering, and Medicine, Russia and China play leading roles in international nuclear development and deployment and only 10 out of the 55 nuclear reactors under construction are US designs.[92] Russia has been successful in marketing its designs due to its attractive financial terms, including taking back spent fuel, while China is ramping up its domestic nuclear

[89] “However, a number of potential barriers exist for U.S. vendors in global markets, such as a complicated set of rules to market and sell nuclear products internationally, increased competition among nations, and potential expansion of nuclear reactors into newcomer countries that may lack effective government, industry, and societal frameworks to support the facilities.”National Academies of Sciences, Engineering, and Medicine, 2023.

[90] “These potential barriers (some of which U.S. vendors have little control over) include development of regulatory oversight capabilities, financing mechanisms that provide market advantages to non-U.S. vendors, management of the fuel cycle, expanded transportation networks for nuclear materials, and education and outreach to local communities that may house reactors.” National Academies of Sciences, Engineering, and Medicine, 2023.

[91] Build-own-operate: “The BOT/BOO arrangements are becoming more popular among countries that lack the funds to construct nuclear power plants, as one of the attractive features of such arrangement is that the contractor also arranges the financing, which is part of the BOT/ BOO arrangement, hence delivers the whole package. Generally, multiple investors, financiers, vendors, etc., form a consortia to BOO/BOT a project for large-scale infrastructure projects, which is important for risk diversification.” Barkatullah & Ahmad, 2017. State-owned or state-financed vendors: “Finding 10-4: For U.S. vendors to better compete with state-owned or state-financed vendors in the dynamic international energy market, a technically and economically viable product must be established that could then be supported by a robust and reliable source of export credit financing. Non-U.S. vendors have more options for financing the export and deployment of advanced reactors than U.S. vendors. This imbalance will eventually reduce the competitiveness of the U.S. advanced reactors in the international marketplace, which could limit the opportunities to build successful partnerships that the United States has used effectively to promote U.S. national security and global nuclear safety, security, and safeguards. Exploring non-standard financial mechanisms and ownership models, such as Build Own Operate (BOO) or Build Own Operate Transfer (BOOT), could be useful in non-Organisation for Economic Co-operation and Development (OECD) markets.” National Academies of Sciences, Engineering, and Medicine, 2023

[92]Russia and China: “Russia and China are playing a leading role in international nuclear development and deployment.” National Academies of Sciences, Engineering, and Medicine, 2023. Current construction: “As a result, while a few international reactors currently being deployed have their origins in U.S. companies, only ten of the 55 reactors (~4 percent) are being built using U.S. designs—two in the United States and eight reactors in China (i.e., Westinghouse’s AP1000s).” National Academies of Sciences, Engineering, and Medicine, 2023.

power capacity and has made civil nuclear cooperation a part of its Belt & Road Initiative.[93] Although Russia has faced sanctions for invading Ukraine, which have impacted its nuclear industry, this may only have limited impact on its work developing nuclear power in some potential high-growth markets.[94]

There are some policy interventions that could help improve the competitiveness of US designs, such as financing packages for US exporters.[95] Also, while Russia and China lead in hard memoranda of understanding (i.e., agreements with explicit terms related to nuclear power exports and related services) for building new power plants abroad, the US still has a considerable number of soft agreements (i.e., agreements without explicit terms that are intended to be supportive of nuclear power deployment).[96] Other conditions may limit Russia and China's abilities to expand nuclear power internationally, such as the various challenges China has faced in finding a market for its nuclear technologies.[97]

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[93] Russia: "The Russian success in marketing arises in part from its willingness to provide very favorable financial terms, thereby advancing a foreign policy objective of having an important role in the customer country's critical energy infrastructure for the life of the plant (as long as 100 years). In pursuit of this objective, it also offers favorable terms on fuel supply and even the take-back of spent fuel, alleviating the customer country's obligation to develop disposal capability." National Academies of Sciences, Engineering, and Medicine, 2023. China's domestic market: "In the past 10 years, more than 34 gigawatts (GW) of nuclear power capacity were added in China, bringing the country's number of operating nuclear reactors to 55 with a total net capacity of 53.2 GW as of April 2024. An additional 23 reactors are under construction in China. The United States has the largest nuclear fleet, with 94 reactors, but it took nearly 40 years to add the same nuclear power capacity as China added in 10 years." Johnson and Russo, 2024. Belt & Road Initiative: "China not only has the most expansive current plans for domestic nuclear power reactor construction, but it has also made civil nuclear cooperation an integral part of its Belt & Road Initiative." National Academies of Sciences, Engineering, and Medicine, 2023.

[94] "Of course, recent events in Ukraine and the resulting sanctions will certainly impact the recent dominance of Russia in the existing nuclear reactor market overall, although it might not have much effect on potential high-growth markets in Africa, the Middle East, and Southeast Asia." National Academies of Sciences, Engineering, and Medicine, 2023.

[95] "Recommendation 10-2: International nuclear projects by U.S. exporters are likely to require a financing package that reflects a blending of federal grants, loans, and loan guarantees along with various forms of private equity and debt financing. The Executive Branch should work with the private sector to build an effective and competitive financing package for U.S. exporters." National Academies of Sciences, Engineering, and Medicine, 2023.

[96] MOUs: "Hard MOUs: Agreements that include terms or contractual concurrence on nuclear plant construction, export of hardware or reactor components, or services necessary or relevant to the operation of nuclear power facilities—including fuel supply, recycling, waste management, and decommissioning. Soft MOUs: Agreements that do not contain explicit terms on actual exports of nuclear reactors and related services, but are intended to be supportive of nuclear energy deployment and civil nuclear development. These MOUs may include agreements on knowledge-sharing, training, institution of regulatory frameworks, etc. Agreements exclusively focused on uranium supply were not included in this category." Ahn et al, 2023. Russia and China MOUs: ""The data is consistent with assessments from the last several years that Russia is by far the world's leading exporter in nuclear power plants in terms of reactors planned and under construction—Russia has hard MOUs with 45 different countries. In comparison, the United States only has 12 such agreements... Even though its emergence as a global nuclear supplier has been relatively recent, even China leads the US on hard agreements with 13." Ahn et al, 2023. US: "The US has a considerable number of soft agreements (48), a significant portion of which are with countries that are either ready or potentially ready for nuclear power by 2030 based on assessments made in the Third Way-Energy for Growth Hub global advanced nuclear market map. Twenty-nine countries that have concluded supportive agreements with the US are viable near-term markets." Ahn et al, 2023.

[97] Russia: "Of course, recent events in Ukraine and the resulting sanctions will certainly impact the recent dominance of Russia in the existing nuclear reactor market overall, although it might not have much effect on potential high-growth markets in Africa, the Middle East, and Southeast Asia." National Academies of Sciences, Engineering, and Medicine, 2023. China: "Nevertheless, China's nuclear technologies still face the challenge of finding a market, as China's nuclear exports may only have minor advantages over those of other suppliers in relation to construction time and overnight costs while falling short in terms of financial and business innovations to attract potential buyers." Li, Liu, and Yu, 2023.

What is the cost-effectiveness of donating to nonprofits that support advanced nuclear reactors?

As a rough plausibility check, we developed a cost-effectiveness analysis (CEA) to estimate the costs and impacts of US policy efforts and community engagement on deploying advanced nuclear reactors. We assumed these activities change the probability of advanced nuclear reactors being on an ambitious or low build-out track. We think this CEA may underestimate the impact of advanced nuclear reactors on emissions because our model only focuses on US deployment. We think efforts focused on US deployment would likely have international spillover effects, such as through exports and leasing.

This CEA includes highly subjective guess parameters and should not be taken literally. In particular, we estimated the change in the likelihood that advanced nuclear reactors would move from a low to an ambitious build-out scenario due to advocacy efforts, the change in that probability that could be attributed to nonprofits, and the number of years that advocacy moves an ambitious build-out scenario forward compared to the counterfactual. We have low confidence in the ability of our CEA to estimate the cost-effectiveness of NGOs' US policy advocacy and community engagement but view it as a slight positive input into our overall assessment of supporting advanced nuclear reactors.[98] See below for a high-level explanation and the model for additional notes and citations.

- **Costs:** We estimated how much the six leading nonprofits advocating for US-focused advanced nuclear reactor policies and community engagement spend each year on these activities. We assumed their work between 2022 and 2030 would influence whether advanced nuclear reactors are in an ambitious or low buildout scenario. Therefore, we multiplied the total annual budget by the time spent on advocacy and arrived at a total cost of about $160M.
- **Avoided GHG:** Using the US Department of Energy's *Pathways to Commercial Liftoff: Advanced Nuclear* report, we estimated new nuclear capacity from 2025 to 2050 under ambitious and low build-out scenarios. We calculated the difference in output between the two scenarios to estimate the additional electricity generated by nuclear power under the ambitious build-out case. We assumed that a percentage of this extra electricity would have been generated by natural gas instead of nuclear power under the counterfactual. We estimated avoided emissions by multiplying that percentage by the difference in output and natural gas's emission factor, with some additional math based on the percentage we think would have been from natural gas with or without carbon capture and storage.
- **Effectiveness:** We assumed that policy advocacy and community engagement increase the likelihood of being in an ambitious buildout scenario by some small percentage (5 to 30 percent) and that a fraction of this work can be attributed to nonprofits. We further assumed that these activities advance progress that would have also eventually been achieved in the absence of these

[98] We describe our confidence as low/medium/high to increase readability and avoid false precision. Since these terms can be interpreted differently, we use rough heuristics to define them as percentage likelihoods our takeaway (i.e., [not] plausibly within the range of cost-effectiveness we would consider recommending) is correct. Low = 0-70%, medium = 70-90%, high = 90-100%.

nonprofits (one to ten years). We estimated effectiveness by multiplying the change in probability by the percent change attributable to nonprofit advocacy, the number of years advanced, and the annualized amount of avoided GHGs.

- **Results:** Our best guess is that donations to nonprofits working on US nuclear policy efforts and community engagement avoid 1 tCO_2e for around $3.68 (range: $0.60 to $321.71). We also developed a Guesstimate version of this CEA, allowing us to assign ranges of values and probability distributions for each input, and found similar results. Our model does not include benefits that would likely come from international spillover, which would increase overall cost-effectiveness. We have low confidence in the ability of our CEA to estimate cost-effectiveness but view it as a slight positive input into our overall assessment.

Is there room for more funding?

Philanthropy's role in supporting nuclear power

We think nonprofits can play a role in nuclear power advocacy that industry, which we believe to be well-funded, cannot perform. For example, nonprofit organizations that are not funded by industry interests can play a role in building trust with communities and can write policy proposals that do not have profit motives in mind.[99]

Our impression is that nuclear power is relatively neglected in philanthropy because many mainstream environmental organizations do not work on nuclear power. For example, there has been resistance to nuclear technologies from major environmental organizations—such as the Sierra Club, Greenpeace, and Friends of the Earth—and some environmental justice groups, including the Climate Justice Alliance.[100] Our understanding is that there are also relatively few funders of nuclear-power-focused organizations.

Are there major co-benefits or potential risks?

Nuclear power's co-benefits include lower land intensity compared to other energy systems and improved safety over fossil fuels. Its potential risks include its production of radioactive waste, its effect on the local environment, environmental justice concerns, and risks related to safety and nuclear proliferation.

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[99] For example, in mid-2024, we heard that proposed cost overrun insurance policies that groups in the nuclear industry have put forth may incentivize companies to spend more instead of less. A nonprofit organization we spoke to said it was working on an alternative to this policy and that it had the freedom to do so because it did not receive industry funding.

[100] Sierra Club: "The Sierra Club remains unequivocally opposed to nuclear energy." Sierra Club, n.d. Greenpeace: "Greenpeace got its start protesting nuclear weapons testing back in 1971. We've been fighting against nuclear weapons and nuclear power ever since." Greenpeace, n.d. Friends of the Earth: "For 40 years, Friends of the Earth has been a leading voice in the U.S. opposing nuclear reactors." Friends of the Earth, n.d. Climate Justice Alliance: "This flawed bill is deeply tainted by the inclusion of proposals that are not only unacceptable to the Environmental Justice (EJ) community, but dangerous to the climate and the planet. Of particular concern is the focus on and investment in nuclear energy, as well as the promotion of risky, unproven carbon removal schemes." Climate Justice Alliance, 2020.

Co-benefits

- **Less land-intensive than other energy systems:** Nuclear power is the least land-intensive energy system.[101] Our understanding is that its reduced land intensity may pose fewer risks related to increased land use, such as trade-offs for food production, urban development, and conservation.
- **Improved safety over fossil fuels:** Compared to energy derived from fossil fuels, nuclear has led to fewer deaths per unit of electricity and is as safe as wind and solar.[102]

Potential risks

- **Nuclear waste and hazardous materials:** After generating electricity, nuclear reactors produce high-level radioactive waste from spent fuel, which must be safely recycled or stored.[103] High-level waste is hazardous because it can produce fatal radiation doses with brief direct exposure.[104] Some advanced nuclear reactors also use coolants that pose safety concerns related to reactivity, toxicity, or corrosiveness.[105] Since 2010, there has been an impasse in the US over where to store spent nuclear fuel; this has led to the federal government paying billions of dollars in damages to utilities for failing to dispose of this waste.[106] The US DOE established a Consent-Based Siting Consortia to help address this impasse, but this work is still in its early stages.[107]

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[101] "At the bottom of the chart we find nuclear energy. It is the most land-efficient source: per unit of electricity it needs 50-times less land compared to coal; and 18 to 27-times less than on-ground solar PV." Ritchie, 2022.

[102] "Nuclear energy, for example, results in 99.9% fewer deaths than brown coal; 99.8% fewer than coal; 99.7% fewer than oil; and 97.6% fewer than gas. Wind and solar are just as safe." Our World in Data, 2022.

[103] Explanation of spent fuel: "Once the uranium is enriched, it can be used effectively as nuclear fuel in power plants for three to five years, after which it is still radioactive and has to be disposed of….The operation of nuclear power plants produces waste with varying levels of radioactivity." IAEA, 2022. High-level waste: "High-level radioactive waste primarily is uranium fuel that has been used in a nuclear power reactor and is "spent," or no longer efficient in producing electricity." US NRC, 2024.

[104] "High-level wastes are hazardous because they produce fatal radiation doses during short periods of direct exposure. For example, 10 years after removal from a reactor, the surface dose rate for a typical spent fuel assembly exceeds 10,000 rem/hour – far greater than the fatal whole-body dose for humans of about 500 rem received all at once. If isotopes from these high-level wastes get into groundwater or rivers, they may enter food chains. The dose produced through this indirect exposure would be much smaller than a direct-exposure dose, but a much larger population could be exposed." US NRC, 2024.

[105] "While some advanced reactor coolants and moderators may have the advantages described above, some also have chemical properties that pose safety concerns. Examples include reactivity, toxicity, or corrosiveness of the primary coolant in the case of sodium, lead, and molten salts, respectively." Arostegui and Holt, 2019.

[106] "The nation has over 85,000 metric tons of spent nuclear fuel from commercial nuclear power plants. DOE is responsible for disposing of this high-level waste in a permanent geologic repository but has yet to build such a facility because policymakers have been at an impasse over what to do with this spent fuel since 2010. As a result, the amount of spent nuclear fuel stored at nuclear power plants across the country continues to grow by about 2,000 metric tons a year. Meanwhile, the federal government has paid billions of dollars in damages to utilities for failing to dispose of this waste and may potentially have to pay tens of billions of dollars more in coming decades." GAO, n.d.

[107] "The Consent-Based Siting Consortia support the U.S. Department of Energy's efforts to facilitate inclusive community engagement and elicit public feedback on consent-based siting, management of spent nuclear fuel, and federal consolidated interim storage." Office of Nuclear Energy, n.d.

- **Effects on local ecology:** Traditional nuclear power plants require 30 to 80 percent more cooling water than other power plants with similar outputs.[108] They can generate thermal pollution if they discharge heated water into the environment, such as lakes and oceans. Changes in water temperature impact dissolved oxygen concentrations and local ecology. We think some types of advanced nuclear reactors will also cause thermal pollution, but we are uncertain about its extent.
- **Environmental and procedural justice concerns**: In the US, historical nuclear power plants' employment, climate, and safety benefits have disproportionately gone to whiter and wealthier communities while adverse effects, such as contamination related to mining, have mostly impacted marginalized communities.[109] We are uncertain of the extent to which these inequities will impact future nuclear projects.
- **Safety risks:** According to the Congressional Research Service, safety risks are generally low for existing traditional nuclear reactors in the US.[110] However, nuclear reactors still pose safety risks; incidents at Fukushima (2011) and Chernobyl (1986) have led to direct deaths, cancer deaths, and/or deaths from evacuation.[111] We think it is likely that, compared to the counterfactual, increasing the number of nuclear reactors in the world would increase the risk of meltdowns by increasing opportunities for errors.[112] However, advanced nuclear reactors often incorporate passive safety features (e.g., cooling the core when there is a loss of electricity) and inherent safety features (e.g., higher boiling points for coolants) that could reduce that risk.[113]

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[108] "The cooling water discharge from nuclear power plants (NPPs) is among the greatest local sources of thermal pollution due to the high levels of energy produced per plant. In addition, nuclear power plants require 30–100% more cooling water than other types of plant with a comparable power output." Kirillin, Shatwell, and Kasprzak 2013

[109] Distribution of risk: "Advanced nuclear advocates often tout the benefits of nuclear projects to local communities: zero-emissions electricity with plenty of high-paying jobs and tax revenue. But our analysis finds an inequitable spread in the benefits and risks of historical nuclear power projects in the United States. The benefits from hosting a nuclear power plant tend to go to whiter and wealthier communities, whereas the riskier activities like uranium mining and milling have been concentrated in poorer communities, less educated communities and communities of color." Schroer, 2022. Risks of uranium mining: "Despite evidence in Europe, from as early as 1932, that uranium mining posed occupational risks, health and safety protections for U.S. uranium miners were minimal until 1962, after U.S. Public Health Service studies concluded a correlation between radon levels in uranium mines and rates of cancer… Community contamination from legacy uranium mines exacerbates existing inequities in under-resourced communities that lack access to reliable income, food, and medical care." Gould, 2022.

[110] "For existing nuclear power plants in the United States, security and proliferation risks are generally considered to be low, given the current fuel cycle and safeguards regimes in place." Arostegui and Holt, 2019.

[111] Chernobyl: "Combined, the confirmed death toll from Chernobyl is less than 100. We still do not know the true death toll of the disaster. My best approximation is that the true death toll is in the range of 300 to 500 based on the available evidence." Ritchie, 2017. Fukushima: "Despite it being such a large event, so far, only one death has been attributed to the disaster. This includes both the direct impact of the accident itself and the radiation exposure that followed. However, it's estimated that several thousand died indirectly from the stress and disruption of evacuation." Ibid.

[112] For this to be true, the likelihood of a nuclear meltdown per nuclear plant would have to decrease at a rate slower than an increase in nuclear power plants. We haven't investigated this, but think this is a plausible scenario.

[113] "Advanced nuclear reactors tend to incorporate passive and inherent safety systems as opposed to active systems. Passive systems refer primarily to two types of safety features: (1) the ability of these reactors to self-regulate the rate at which fission occurs through negative feedback mechanisms that naturally reduce power output when certain system parameters (such as temperature) are exceeded, and (2) the ability to provide sufficient cooling of the core in the event of a loss of electricity or other active safety systems… The chemical properties of various advanced coolants, fuels, and moderators may also contribute inherent safety advantages. Examples include higher boiling points for coolants, higher heat capacities for fuels and moderators, and higher retention of radioactive fission products for some coolants." Holt, 2019.

- **Potential increased risk of nuclear proliferation:** Nuclear proliferation refers to the spread of nuclear materials and weapons by countries not recognized as Nuclear Weapon States (e.g., the US is a Nuclear Weapon State).[114] Whether advanced nuclear reactors increase or decrease that small risk depends on technical and policy choices and how people implement them.[115] For example, advanced nuclear reactors are often designed to make fuel and waste less accessible, but some produce concentrated wastes that could make it easier to create weapons-grade nuclear material.[116] We think it is likely that making nuclear materials more commonplace could increase proliferation risks by increasing opportunities for bad actors (e.g., theft along the supply chain, targets for sabotage). However, the increase in the likelihood of proliferation is highly dependent on (a) where nuclear expands, (b) technological development, and (c) the efficacy of nonproliferation oversight. We will continue to monitor this, but we think advanced nuclear is in an early enough stage that it would be preemptive and overly cautious to not support further development at this point because of future uncertain effects on proliferation.
- **Threats to nuclear facilities:** Nuclear facilities can be targets of terrorist attacks, which can lead to significant casualties, economic damage, and land contamination.[117] Advanced nuclear reactors, which use more automation and wireless controls than traditional light-water reactors, may face enhanced cybersecurity threats.[118] We think increasing the number of nuclear reactors in the world likely increases the risk of a successful terrorist attack by increasing opportunities for attack. We think risks of physical attacks are low given the safeguards in place: most nuclear-energy facilities are difficult to destroy from the outside, while guards and other barriers protect facilities from the inside.[119] NRC also requires facilities to develop a cybersecurity plan, but we are unsure

[114] "Nuclear proliferation is not a risk in the United States simply because it already possesses nuclear weapons and is designated as a nuclear-weapon state under the Nuclear Non-Proliferation Treaty." Lyman, 2021.
[115] "The variety of advanced nuclear power plant designs have the potential to further reduce this relatively low risk, or to increase the risks, depending on the technical and policy choices and how they are implemented." Holt, 2019.
[116] "The effect of reactor advancements on the risk of proliferation is ambiguous. Some sources state that advanced reactors produce less waste than what could traditionally be used to make nuclear weapons. In addition, advanced reactors are often designed to make fuel and waste less accessible than in traditional reactors. However, advanced reactors also often produce concentrated plutonium waste that may pose a higher proliferation risk than traditional reactors. As proliferation risks are generally perceived to be low for traditional reactors, slight differences due to advancements may not pose significant benefits or drawbacks." Resources for the Future, 2021.
[117] "A successful attack on a nuclear power reactor, for example, could destroy the facility itself, worth hundreds of millions to billions of dollars; produce tens to hundreds or even thousands of early fatalities and tens of thousands of delayed cancer deaths; and severely contaminate hundreds to thousands of square miles of land, requiring removal of much of it from habitation, commerce, and agriculture for periods ranging from months to many decades." National Academies of Sciences, Engineering, and Medicine, 2007.
[118] "Advanced reactor vendors face significantly different challenges than the designers of the existing LWR fleet. Increased use of automation, wireless sensors and controls, and digital management of a complex operations and supply chain may create opportunities for reducing human error in such systems. They also mean that the threat spectrum may be significantly enhanced in some respects for the new design." National Academies of Sciences, Engineering, and Medicine, 2023.
[119] "Obstacles are in place to prevent successful attacks on civil nuclear-energy facilities. First, multiple security barriers would need to be breached in order to generate a large release of radioactivity. Second, guard forces and other entry barriers complicate the task of terrorists seeking to penetrate a facility in order to try to blow it up or otherwise create a containment-breaching event from within. In addition, the "hard target" characteristics of most nuclear-energy facilities make them challenging to destroy from the outside with the types of weapons terrorists are most likely to have at their disposal, namely rocket launchers, mortars, light aircraft packed with explosives, and hijacked airliners used as cruise missiles." National Academies of Sciences, Engineering, and Medicine, 2007.

how quickly vendors can adjust their plans as cybersecurity threats evolve and become more sophisticated.[120]

Key uncertainties and open questions

- **The viability of advanced nuclear reactors:** Advanced nuclear reactors' future depends on technological progress and political conditions. High capital costs, risk premiums for first-of-a-kind generators, potentially high operating costs, and local resistance to nuclear projects are barriers to advanced nuclear reactor development and deployment.[121] We do not anticipate that every nuclear project will succeed; for example, NuScale Power canceled a commercial small modular reactor project in 2024 due to a lack of subscribers.[122] We think canceled projects could chill investor interest in nuclear power, but we are unsure of the extent to which this will occur. Ultimately, nuclear power may not be a large part of a future carbon-free electricity mix.
- **Cost of expanding renewables and battery storage in the future:** We think it is important to support nuclear power and other sources of clean firm power because relying entirely on renewables is more expensive and challenging to implement than a diversified energy portfolio. However, the costs of renewables and battery storage have substantially decreased over time.[123] We think we could have overrated the importance of supporting nascent technologies that provide clean firm power if there is a massive build-out of transmission in the US and batteries become cheap enough to store significant amounts of renewable energy for long periods.
- **Uncertainty around focusing on the US:** We are unsure whether focusing on advanced nuclear reactors solely in the US is the best use of philanthropic funds if we are most interested in expanding this technology globally. Other high-innovation countries working on advanced nuclear reactors include Canada, China, France, India, Japan, the United Kingdom, and South Korea.[124]

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[120] "Each advanced reactor vendor is required to develop a cybersecurity plan and maintain a cybersecurity program as part of security protocols." National Academies of Sciences, Engineering, and Medicine, 2023.

[121] "Generally, the greatest inhibitors are substantial costs associated with the development and construction of first-of-a-kind reactors. These costs are inflated by risk premiums - uncertainty due to lack of mature deployment makes first-of-a-kind generators financially risky investments. Although some projections suggest that capital costs will be lower for mature advanced reactors than for traditional ones, it is also possible that there will be substantial capital costs associated with long and complex initial construction phases, creating a significant hurdle for adoption. Finally, even once advanced reactors are built again, they may still be relatively expensive to operate." Resources for the Future, 2021.

[122] "NuScale and the Utah Associated Municipal Power Systems (UAMPS), a group of local electric utilities that had agreed to purchase power from the project, mutually decided to terminate what was known as the Carbon Free Power Project (CFPP), according to a news release… but substantial cost overruns and delays from its originally scheduled 2026 operational date spooked utilities that are members of the UAMPS, leading several to withdraw from a 2019 agreement to buy 200 MW from the reactors once completed. The project previously was the subject of intense discussion among UAMPS members. Oregon-based NuScale said in the Wednesday release that the reason it could no longer advance toward deployment was because it lacked enough subscribers." Bright, 2023.

[123] Solar and wind: The cost of solar photovoltaics decreased from $378 per MWh in 2010 to $68 per MWh in 2019. Offshore wind decreased from $162 to $115 per MWh over the same time period. Roser, 2020. Batteries: "Since 1991, prices have fallen by around 97%. Prices fall by an average of 19% for every doubling of capacity. Even more promising is that this rate of reduction does not yet appear to be slowing down." Ritchie, 2021.

[124] High-innovation countries: We defined high-innovation countries as ones that have high research research output, as measured by Nature Index. Nature, accessed 2022. Global advanced nuclear projects: We used Third Way's map of advanced nuclear projects to determine which countries are working on advanced nuclear technologies. Ahn and Allen, 2022.

Experts we spoke with have unanimously agreed that the most likely path to global deployment of advanced nuclear reactors goes through the US due to its innovation experience and gold-standard licensing process. However, most of these experts focus primarily on US advanced nuclear efforts themselves.

- **Rate of technological diffusion:** It is unclear how quickly advanced nuclear technologies will diffuse from the US to other countries, partly because this will rely on geopolitical factors that are difficult to predict.
- **Likelihood of increased proliferation:** Our impression is that expanded nuclear power could slightly increase the possibility of nuclear proliferation because it increases the availability of nuclear fuel, which, under some circumstances, could be refined into weapons-grade material by bad actors. Still, the magnitude of this increase is highly conditional on uncertain circumstances and could be close to zero. Our take is that this risk is low overall, so we still recommend nuclear power to reduce emissions.
- **The neglectedness of donating to nuclear power advocacy:** The US government has historically given more funding for nuclear power innovation compared to different types of renewables.[125] This continues to be true in the present day; the DOE's RD&D's FY2023 budget for nuclear energy was about $1.3 billion, compared to $318 million for solar, $132 million for wind energy, and $118 million for geothermal.[126] Given this history of RD&D funding, the number of policy wins nuclear power has had under IIJA and IRA, and the nuclear industry's strong lobbying presence, we think other impact areas could be more neglected and that a dollar donated to those impact areas could go further in reducing GHG emissions. We try to address this uncertainty by supporting a variety of impact areas with our Giving Green Fund.

Bottom line / next steps

We think nuclear power has some advantages that can complement an expansion in renewables. We have been most optimistic about advanced nuclear reactors because of their potential for being cheaper, faster, and easier to operate than traditional large light-water reactors. Although we are uncertain about the extent to which advanced nuclear reactors can reduce costs and become cost-competitive with other sources of electricity production, we think it is too early to rule out advanced nuclear reactors because they can play a role in providing clean firm power and diversifying energy portfolios. They also have value outside of electricity production (e.g., heating, hydrogen production), which can be important for decarbonizing heavy industry. Our theory of change rests on supporting an ecosystem of nonprofits working on policies supporting advanced nuclear reactor innovation in the US given that the US is important for designing and demonstrating these technologies before they are exported elsewhere.

[125] See Figure 1, Fiscal Year R&D Funding of DOE Energy Technologies, Clark, 2018.

[126] See Table 2: DOE Energy RD&D programs summary, FY 2021 enacted through FY 2024 request ($millions), Chong, 2023.

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