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THE GLOBAL FUTURE OF NUCLEAR ENERGY

by Matt Bowen

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The Global Energy Center promotes energy security by working alongside government, industry, civil society, and public stakeholders to devise pragmatic solutions to the geopolitical, sustainability, and economic challenges of the changing global energy landscape.

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Cover: An artist's rendering of what a NuScale Power small modular reactor plant might look like.
Source: Idaho National Laboratory

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Executive Summary

Energy supply is an integral and essential part of modern society. Given nuclear energy's low-carbon nature, and its ability to be called upon when needed, it could play a larger global role as part of efforts to address growing energy demands while reducing the risks of climate change and air pollution. Russia's unprovoked invasion of Ukraine has also highlighted energy security as a national imperative, which is an additional goal that nuclear power could help countries to achieve.

Preserving the existing fleet of reactors is a common element of analyses illustrating how countries can reach deep decarbonization of their electricity supply systems while maintaining affordability and reliability. New advanced nuclear power plants could also play a role in achieving deep decarbonization by mid-century, and private companies have been developing new reactors with greater inherent safety than previous generations. Beyond power generation, these advanced reactors could also potentially supply high-temperature process heat to replace fossil fuels currently used for applications such as district heating, desalination, hydrogen production, and more.

Public support will be crucial to nuclear power's future. Accidents at older-generation reactors, cost overruns at newer reactors deployed in the West, and relatively small progress made in high-level nuclear waste disposal have all weighed on the public's opinion of nuclear power to varying degrees. Correspondingly, developing designs with greater inherent safety is necessary, though whether the entities involved in managing reactor construction are successful at keeping projects at reasonable costs and schedules may be the greatest determinant of nuclear energy's future. Nuclear power's future would also benefit from national governments putting renewed emphasis on spent nuclear fuel disposition given the stalled nature of some nations' programs.

Nuclear power plants are a source of well-paying jobs, but they rely on having access to a pipeline of trained students as their existing workforces age and retire. The lack or paucity of new reactor builds in some regions of the world—for example, the United States—raises questions over whether an adequate workforce currently exists to support a substantial new build program. By contrast, Russia's and China's significant domestic build programs in recent decades, as well as their reactor exports, demonstrate to students in their respective countries that the nuclear sector has growth potential.

How national regulators approach licensing advanced reactors will play some role in determining future reactor deployment levels. Especially for commercial reactor types that have never been deployed before, or for reactor missions (i.e., process heat) that haven't been licensed in the past by a given regulator, how national bodies approach this challenge will impact nuclear energy's future. Cooperation among national regulators to share learning experiences—as a given advanced reactor design is licensed in multiple countries at the same time or in subsequent deployments—could help enable a larger deployment in the same amount of time. The cooperation between the US Nuclear Regulatory Commission and the Canadian Nuclear Safety Commission on the licensing of the GE-Hitachi BWRX-300 is one example of the type of cooperation that could be mirrored in other bilateral activities.

There are a number of actions that national governments in NATO countries and Japan and South Korea could pursue to overcome the challenges discussed in this report related to energy demand, energy security, and associated environmental and public health risks.

- National governments should support advanced reactor demonstration efforts in the 2020s to increase the likelihood that new options will be available in the 2030s.

- National governments should conduct research and development (R&D) into topics that relate to extending the lifetime of the existing fleet of reactors, including the effects of material aging and irradiation, as well as advanced nuclear fuels, which could increase operating safety margins.

- National governments should conduct research, development, and demonstration (RD&D) into fuel cycle topics, such as the production of uranium from seawater; high-assay low-enriched uranium fuel; and disposal technologies, such as boreholes. Borehole disposal might prove to be economical and perhaps more socially acceptable in some areas of the world, making international R&D collaboration on this front potentially fruitful.

- National governments should explain to the public in documents from their environmental, energy, and regulatory agencies the benefits to society from avoiding carbon dioxide and air pollution, and in particular how firm, low-carbon power can simultaneously help meet reliability, affordability, and emissions goals. In addition, it would be helpful to explain how nuclear power offers some nations greater energy security at a time when energy relationships have seen great disruption.

- National governments should pursue technology-neutral approaches to addressing climate change, whether the policy focuses on restricting carbon dioxide and air pollution release or adding financial penalties for their emission. For example, the US Inflation Reduction Act (IRA) of 2022 added a technology-neutral tax credit that renewable, nuclear, and fossil energy (equipped with carbon capture and sequestration technology) could all qualify for.

- National governments should provide support for student education (e.g., PhD programs in nuclear engineering) in related fields. The Nuclear Energy University Program in the United States could serve as one model for other countries to draw upon.

- To increase efficiencies, regulatory bodies in countries looking to deploy small modular reactors should look for opportunities to collaborate with other regulatory entities in countries that are similarly considering SMR deployment. The actions described in Section 5 involving collaboration between US and Canadian regulators could serve as a template to help increase the efficiency of licensing advanced reactors in multiple countries.

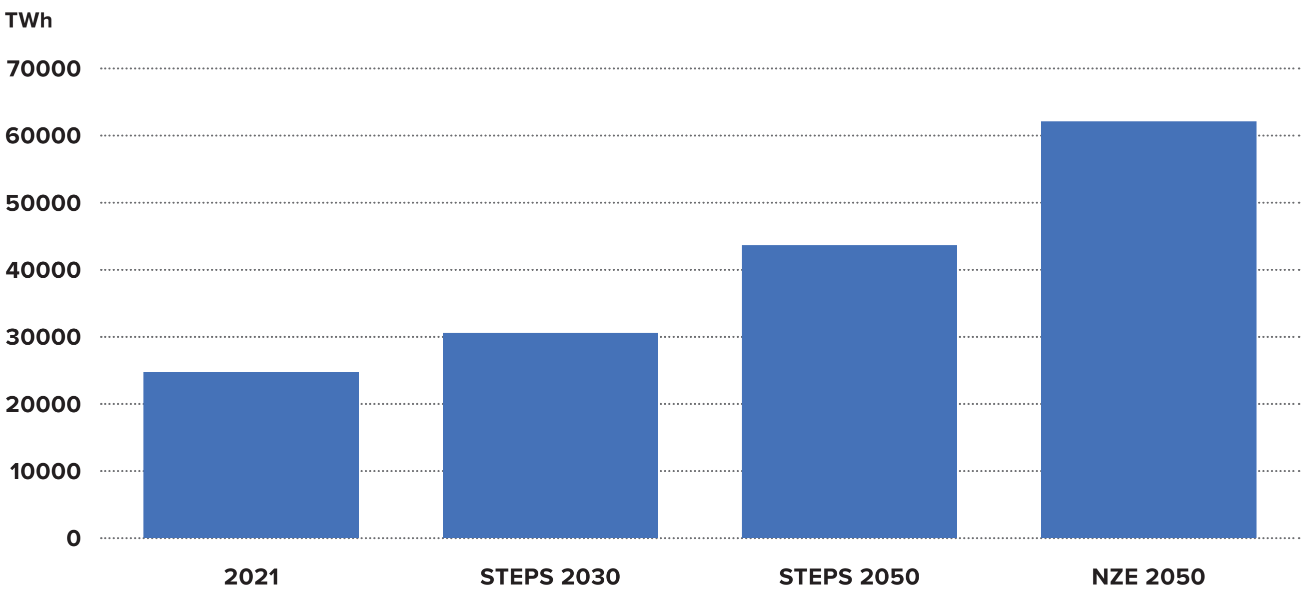
I. Global Energy and Environmental Challenges

Energy supply is an integral and essential part of modern society. Despite the potential for energy efficiency to limit the growth of overall world energy consumption, it is not expected to reduce it. According to energy system modeling, the world has a variety of avenues to reduce the risks of accumulating greenhouse gases in the atmosphere and the public health impacts of air pollution from fossil fuels. In the end, however, there are only three basic categories of energy sources available to address these energy and environmental challenges: renewable, fossil, and nuclear—the last of which is the subject of this report. Nuclear can provide other benefits as well, such as energy security, resiliency against extreme weather, and reduced land usage for energy purposes, among others.

A. World energy demand

In recent decades, global energy demand has risen, and that growth is expected to continue in the coming decades.[1] The world's increasing population is a driver behind that growth. A recent study by the United Nations suggests that the global population could grow from approximately eight billion today to around 8.5 billion people in 2030 and 9.7 billion in 2050.[2] The International Energy Agency (IEA) estimates that total world energy consumption will grow 10 percent between 2021 and 2030, and grow 24 percent between 2021 and 2050.[3] Global electricity demand in those two periods is estimated to grow by 24 percent and 77 percent, respectively. On the other hand, it is possible that electricity growth

Figure 1. Global Electricity Demand



NOTE: Stated Policies Scenario (STEPS) is the trajectory implied by today's policy settings; Net Zero Emissions by 2050 (NZE) maps out a way to achieve 1.5 degrees Celsius stabilization in the rise in global average temperatures, alongside universal access to modern energy by 2030. TWh = terawatt-hours.

SOURCE: INTERNATIONAL ENERGY AGENCY, *WORLD ENERGY OUTLOOK 2022*, 2022, HTTPS://WWW.IEA.ORG/REPORTS/WORLD-ENERGY-OUTLOOK-2022, TABLE 6.1.

1 BP, *BP Statistical Review of World Energy,* 71st edition, 2022, https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2022-full-report.pdf, 10.

2 United Nations Department of Economic and Social Affairs, Population Division, "World Population Prospects 2022: Summary of Results," UN DESA/POP/2022/TR/NO. 3, 2022, https://www.un.org/development/desa/pd/sites/www.un.org.development.desa.pd/files/wpp2022_summary_of_results.pdf.

3 International Energy Agency, *World Energy Outlook 2022,* 2022, https://www.iea.org/reports/world-energy-outlook-2022, Tables 5.1 and 6.1.

could be even greater: The IEA also estimates that an intensive decarbonization effort could cause electricity demand to grow by 150 percent out to 2050 compared with demand in 2021.[4] These possibilities for global electricity demand growth are illustrated in Figure 1.

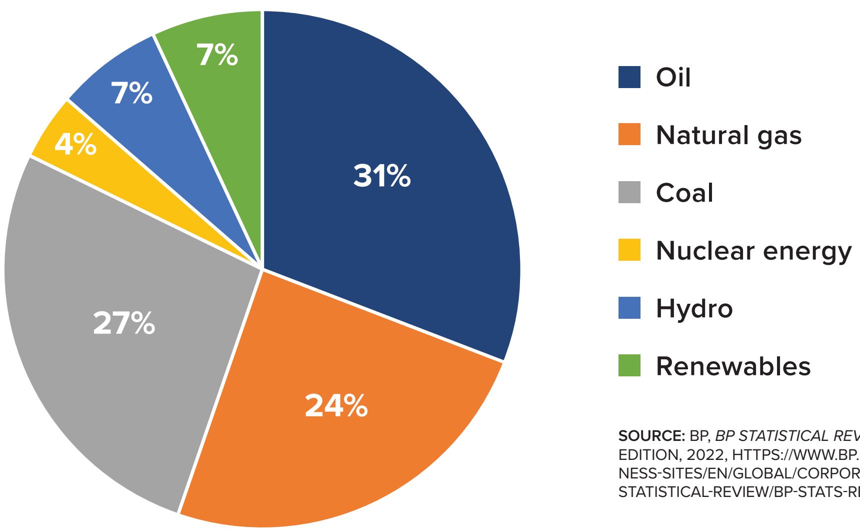
While wealthier nations (such as those of the Organisation for Economic Co-operation and Development) may see relatively small increases in overall aggregate energy demand, hundreds of millions of people in other nations still lack access to electricity. Projections assert that the developing world will need much more overall energy in the coming decades as nations try to raise quality-of-life metrics.[5]

Russia's unprovoked invasion of Ukraine in 2022 sparked a global energy crisis, disrupted energy relationships, and in the process put a spotlight on energy security. The stark illustration of countries deciding not to supply energy to (or buy energy from) other countries for geopolitical reasons heightened national governments' attention to the security of their energy supplies, as well as to strengthening cooperation with other like-minded countries.

B. Climate change and public health concerns

Despite the yearly conferences on climate change and media coverage of low-carbon technologies such as solar and wind, world energy supply remains more than 80 percent fossil energy as of 2021, as shown in Figure 1. The burning of fossil fuels is the largest contributor to the emission of greenhouse gases and despite the risks entailed with higher concentrations of greenhouse gases in the Earth's atmosphere, the world is continuing to drive forward on an unsustainable path. Instead of dramatic emissions reductions, global carbon emissions rose in 2021 from 2019 levels as the world economy recovered from the COVID-19 pandemic.

Figure 2. World Energy Supply by Fuel in 2021



SOURCE: BP, *BP STATISTICAL REVIEW OF WORLD ENERGY*, 71ST EDITION, 2022, HTTPS://WWW.BP.COM/CONTENT/DAM/BP/BUSINESS-SITES/EN/GLOBAL/CORPORATE/PDFS/ENERGY-ECONOMICS/STATISTICAL-REVIEW/BP-STATS-REVIEW-2022-FULL-REPORT.PDF.

4 Ibid., Table 6.1 on page 281.

5 Jason Bordoff, "The Developing World Needs Energy—and Lots of It," *Foreign Policy*, October 29, 2021, https://foreignpolicy.com/2021/10/29/cop26-climate-summit-developing-countries-energy-glasgow/.

In addition to carbon dioxide emissions, the burning of fossil fuels negatively impacts human health by producing air pollution, including fine particulate matter, which is a leading environmental health factor. Studies have estimated that, for example, the burning of fossil fuels led to one million deaths in 2017, with the burning of coal responsible for over half of those deaths.[6]

C. Modeling of deep decarbonization scenarios

To address both the increasing energy demands of a growing population and the developing world while reducing risks posed by greenhouse gas emissions and pollution, models very generally show large deployments of low-carbon energy infrastructure by mid-century. The IEA, for example, published a study in 2021 on how the world might reach net zero emissions by 2050.[7] In it, the IEA estimates a large growth in renewable, nuclear, and fossil energy (the last equipped with carbon capture utilization and sequestration [CCUS] technology) by mid-century.

To take two instances, the IEA projects that, as part of reaching net-zero emissions to mitigate risks posed by climate change, solar capacity would grow twenty-fold by 2050 and wind power would increase eleven-fold in the same period. Fossil energy would decrease from about 80 percent of world energy supply today to around one-fifth by 2050 in the same IEA scenario; the fossil fuels still being used in 2050 were in goods such as plastics (where the carbon is embodied in the product), in facilities using CCUS, and in sectors where it is difficult to find a low-emission alternative.

Relevant to the subject of this report, the IEA projects nuclear energy deployment to approximately double by 2050. The reasons why nuclear power may play an important role in a deeply decarbonized world energy supply are several, but one basic feature that is valuable in an era of rising variable renewable energy use is that nuclear reactors can be called upon at any time during the year to produce energy (also known as "firm capacity"). Studies have shown that the availability of low-carbon firm capacity helps mitigate the costs associated with achieving deep decarbonization while maintaining power grid reliability.[8] For example, in the United States, studies have estimated that to reach decarbonization of the energy sector, 500 to 1,000 gigawatts (GW) of low-carbon firm power capacity may be needed (as compared with just over 100 GW of low-carbon firm power capacity today, which is mostly nuclear plants).[9]

D. Looking forward

After the Russian invasion of Ukraine in 2022, commodity prices spiked and competition for liquefied natural gas intensified. This left countries such as Japan exposed to high costs and supply insecurity, which has factored into their decisions to additionally restart idled nuclear reactors.[10] A majority of Japanese respondents to a poll in February 2023 supported restarting idled reactors and indicated that rising energy costs had factored into their reasoning.[11] As of March 2023, only ten of Japan's thirty-three operable reactors were online,[12] though energy costs, shifting public opinion, and recent policy changes may lead to more restarts.[13]

Lifetime extensions for existing reactors, new advanced reactor deployments, and non-electricity missions for nuclear power are described in Section 2. Social and political developments related to nuclear power's future are explored in Section 3, and Section 4 focuses on workforce challenges facing the nuclear sector. Section 5 discusses the potential benefits to international regulatory harmonization, and, finally, Section 6 provides policy recommendations for national governments.

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6 E.E. McDuffie, R.V. Martin, J.V. Spadaro, et al., "Source Sector and Fuel Contributions to Ambient PM2.5 and Attributable Mortality across Multiple Spatial Scales," *Nat Commun* 12, no. 3594 (2021), https://doi.org/10.1038/s41467-021-23853-y https://www.nature.com/articles/s41467-021-23853-y.

7 International Energy Agency, *Net Zero by 2050,* May 2021, https://www.iea.org/reports/net-zero-by-2050.

8 Nestor A. Sepulveda, Jesse D. Jenkins, Fernando J. de Sisternes, and Richard K. Lester, "The Role of Firm Low-Carbon Electricity Resources in Deep Decarbonization of Electric Power Generation," *Joule* 2, no. 11 (2018): 2403–2420, https://doi.org/10.1016/j.joule.2018.08.006.

9 Eric Larson, Chris Greig, Jesse Jenkins, Erin Mayfield, Andrew Pascale, Chuan Zhang, Joshua Drossman, et al., "Net-Zero America: Potential Pathways, Infrastructure, and Impacts," Final Report Summary, Princeton University, October 29, 2021, https://netzeroamerica.princeton.edu/.

10 Jacob Dick, "Japan Plans Nuclear Restart in Response to LNG Prices, Supply Volatility," *Natural Gas Intelligence,* August 24, 2022, https://www.naturalgasintel.com/japan-plans-nuclear-restart-in-response-to-lng-prices-supply-volatility/.

11 "Poll Finds Record Support for Japanese Reactor Restarts," *World Nuclear News,* February 21, 2023, https://www.world-nuclear-news.org/Articles/Poll-finds-record-support-for-Japanese-reactor-res.

12 Shoko Oda, "Nuclear Power Revival Reaches Japan, Home of the Last Meltdown," *Japan Times,* March 6, 2023, https://www.japantimes.co.jp/news/2023/03/06/national/nuclear-power-revival/.

13 "Cabinet Approves Change in Japanese Nuclear Policy," *World Nuclear News,* February 10, 2023, https://www.world-nuclear-news.org/Articles/Cabinet-approves-change-in-Japanese-nuclear-policy.

II. Nuclear Energy's Role in a Decarbonized Future

While the IEA's Net Zero Emissions by 2050 scenario sees nuclear power doubling by 2050, reactor deployment remains uncertain, especially given the lack of clarity over whether national governments will actually pursue deep decarbonization policies. As of June 2023, 410 nuclear power reactors were in operation providing 368,610 megawatts electric (MWe) of total net installed capacity.[14] As Table 1 shows, 7,360 MWe of nuclear energy capacity was connected to electrical grids in 2022, while 3,286 MWe of reactors were permanently shut down, and construction began on reactors representing 9,313 MWe.

Table 1. Reactor Connections, Permanent Shutdowns, and Construction Starts in 2022

Action	Country	Site	Power (MWe)
New connections to the grid	China	Fuqing-6	1,000
	China	Hongyanhe-6	1,061
	Finland	Olkiluoto-3	1,600
	Pakistan	Kanupp-3	1,014
	Republic of Korea	Shin-Hanul-1	1,340
	United Arab Emirates	Barakah-3	1,345
Permanent shutdowns	Belgium	Doel-3	1,006
	United Kingdom	Hinkley Point B-1	485
	United Kingdom	Hinkley Point B-2	495
	United Kingdom	Hunterston B-2	495
	United States	Palisades	805
Construction starts	China	Haiyang-3	1,161
	China	Sanmen-3	1,163
	China	Tianwan-8	1,171
	China	Xudabu-4	1,200
	China	Lufeng-5	1116
	Egypt	El Dabaa-1	1,194
	Egypt	El Dabaa-2	1,194
	Turkey	Akkuyu-4	1,114

SOURCE: INTERNATIONAL ATOMIC ENERGY AGENCY, "POWER REACTOR INFORMATION SYSTEM," HTTPS://PRIS.IAEA.ORG/PRIS/.

14 International Atomic Energy Agency, "Power Reactor Information System," June 2, 2023.

A. The existing fleet

Preserving the existing fleet of reactors is "low-hanging fruit" to keeping costs down in deep decarbonization studies as the capital costs for these plants have already been paid off, leaving only the ongoing operations, maintenance, and fuel costs. Research has indicated that getting to zero emissions will be easier and happen faster if existing nuclear plants stay on the electrical grid longer.[15] Indeed, the IEA has assessed that for advanced economies, lifetime extensions for existing reactors are one of the most cost-effective sources of low-carbon electricity.[16]

For that reason, the United States has invested billions of dollars into preserving the existing fleet. Congressional laws such as the Bipartisan Infrastructure Law and the Inflation Reduction Act provide financial assistance to US nuclear plants that are struggling economically. The first law created a new Civil Nuclear Credit Program at the US Department of Energy (DOE), which conditionally selected Diablo Canyon in California in November 2022 to receive funding of $1.1 billion.[17]

At the end of 2022, Germany similarly decided to temporarily extend the operations of its last three nuclear power reactors amid an energy crisis,[18] though only until April 2023. Other countries are also weighing whether to retire their existing fleets of reactors. In the Republic of Korea, the new Yoon Suk-yeol administration has brought a national policy reversal there to support nuclear power, including lifetime extensions for existing plants.[19]

A general view shows the Neckarwestheim nuclear power plant, as Germany shuts down its last nuclear power plants in Neckarwestheim, Germany, April 15, 2023. REUTERS/Heiko Becker

15 John Larsen, Ben King, Hannah Kolus, and Whitney Herndon, "Pathways to Build Back Better: Investing in 100% Clean Electricity," Rhodium Group, March 23, 2021, https://rhg.com/research/build-back-better-clean-electricity/.

16 International Energy Agency, *Net Zero by 2050,* 115.

17 US Department of Energy, "Civil Nuclear Credit First Award Cycle," https://www.energy.gov/gdo/civil-nuclear-credit-first-award-cycle, accessed June 2, 2023.

18 "Germany Extends Nuclear Power amid Energy Crisis," BBC, October 18, 2022, https://www.bbc.com/news/world-europe-63294697.

19 Lee Kyung-min, "President-Elect to Extend Lifespan of 10 Nuclear Reactors," *Korea Times,* April 6, 2022, https://www.koreatimes.co.kr/www/tech/2022/04/419_326867.html.

B. Advanced reactors under development

In terms of potential new reactors, a wide variety of advanced designs are under development. Many of them are small (i.e., less than 300 MWe in output) compared with the current generation of gigawatt-class light water reactors, and many companies plan to use modular construction techniques in building them.[20] This has given birth to the term "small modular reactor," or "SMR."

Some of these advanced reactors use water as their coolant, which is used in all operating reactors in the United States and in most of the world's reactors. These light water–cooled SMRs—such as NuScale's VOYGR or GE-Hitachi's BWRX-300—have advanced safety cases, where, for example, the coolant may circulate naturally during operation as well as after the reactor has been shut down. In the latter case, the power plant would then not require access to electricity from the electrical grid or even from generators or batteries on-site to keep the fuel cool.

Other advanced reactor developers are pursuing designs using different coolants, such as liquid metals, helium, and molten salts. These designs also use different fuels and could reach higher output temperatures than light water reactors and potentially carry out new process heat missions.

At a much smaller scale, various companies have been developing reactors with outputs less than 20 MWth, or "micro-reactors." These facilities could operate in remote areas of the world where a large reactor would be infeasible. While micro-reactors are likely to have higher overnight costs than larger reactors, in some remote areas of the world their competition would be expensive diesel generation.

Finally, a variety of companies are trying to commercialize power plant designs that make use of nuclear fusion, which involves the joining of lighter elements to produce heavier ones. While it has never been successfully commercialized, fusion would present a number of appealing technical characteristics as compared with fission: no high-level nuclear waste production, better nonproliferation attributes, and an even greater inherent safety case. For these reasons, and others, it is possible that if commercialized, fusion might prove acceptable to a wider cross-section of the world population than fission has, to date.[21]

This new generation of advanced nuclear energy sources could come with several advancements that would increase their deployment potential. The generally greater focus on inherent safety to the reactor—i.e., relying on materials that tolerate a wider range of off-normal conditions for a longer period without the need for operator intervention—could generate greater public acceptance than the older generation of reactors. An ability to do faster ramping up and down of power output to balance electrical grids in response to changing solar and wind outputs could be more valuable in an era of rising variable renewable energy usage. Micro-reactors and even some of the smaller advanced reactors could be sited in remote areas or perhaps closer to population centers, given the smaller amount of material on-site and the greater emphasis on inherent safety.

C. Electricity and process heat

In the IEA Net Zero by 2050 study, electricity accounts for almost half of world energy consumption in 2050. This makes it the largest market for advanced reactor developers, which overwhelmingly plan for their first commercial plant to produce electricity.

Although electricity has been the principal mission of today's operating reactors, a few of them have been used for cogeneration (producing electricity and district heating, desalination, or industrial process heat). District heating reactors are located primarily in Eastern Europe and in Russia.[22] China has even been investigating and using the new US AP1000s for district heating and desalination purposes.[23]

While there are additional process heat applications that are possible, hydrogen production is one avenue that has received increased attention in recent years. Hydrogen has the potential to be a "Swiss army knife" of decarbonization efforts, as it can help replace fossil fuels in industrial processes such as making plastic, steel, or liquid transportation fuels.[24] If it can be made in a low-carbon manner at a reasonable cost, this could greatly aid world efforts to address climate change. For this reason, the US Department of Energy is supporting initiatives at US utilities to demonstrate hydro-

20 For a discussion of how modular construction techniques could help bring nuclear power plant costs down, see Massachusetts Institute of Technology, *The Future of Nuclear Energy in a Carbon-Constrained World,* 2018, https://energy.mit.edu/research/future-nuclear-energy-carbon-constrained-world/, 43-46.

21 Matt Bowen, "Could Fusion Overcome Public Opposition to Nuclear Power?" *Foreign Policy,* January 21, 2023, https://foreignpolicy.com/2023/01/21/nuclear-fusion-energy-waste-nonproliferation-public-opposition/.

22 International Atomic Energy Agency, *Guidance on Nuclear Energy Cogeneration,* 2019, https://www-pub.iaea.org/MTCD/Publications/PDF/P1862_web.pdf.

23 Sonal Patel, "How an AP1000 Plant Is Changing the Nuclear Power Paradigm through District Heating, Desalination," *Power,* November 1, 2021, https://www.powermag.com/how-an-ap1000-plant-is-changing-the-nuclear-power-paradigm-through-district-heating-desalination/.

24 Bill Gates, "To Cut Emissions, Use This Swiss Army Knife," *GatesNotes,* June 21, 2022, https://www.gatesnotes.com/Clean-Hydrogen.

gen production at US nuclear power plants.[25] That assistance has already led to the Nine Mile Point Nuclear Station in New York, which is beginning to produce hydrogen from nuclear power.[26]

TerraPower is developing a sodium-cooled fast reactor that incorporates a molten salt storage capability. The reactor will run at 100 percent power all day, every day, but when power demand drops, the heat produced by the reactor core will be stored in molten salt tanks. That stored heat can later be turned into electricity if demand from the grid grows or generation from wind and solar resources fall. In that case, the stored heat can be used to produce up to 150 percent of the reactor's nominal power.[27]

In summary, the different applications and varied deployment environments likely require a range of nuclear power plants, from traditional light water reactors that remain in demand today to small modular reactors, micro-reactors, and, possibly one day, fusion. Outside of the power sector, there remain difficult-to-decarbonize areas of the world economy that will need some form of zero-carbon heat to replace the fossil fuels currently used.[28]

25 "4 Nuclear Power Plants Gearing Up for Clean Hydrogen Production," US Department of Energy, November 9, 2022, https://www.energy.gov/ne/articles/4-nuclear-power-plants-gearing-clean-hydrogen-production.

26 "Nine Mile Point Begins Clean Hydrogen Production," US Department of Energy, March 7, 2023, https://www.energy.gov/ne/articles/nine-mile-point-begins-clean-hydrogen-production.

27 "Exploring the Natrium Technology's Energy Storage System," TerraPower, November 4, 2020, https://www.terrapower.com/exploring-the-natrium-energy-storage-system/.

28 S. Julio Friedmann, Zhiyuan Fan, and Ke Tang, *Low-Carbon Heat Solutions for Heavy Industry: Sources, Options, and Costs Today*, Center on Global Energy Policy, Columbia University, October 2019, https://www.energypolicy.columbia.edu/publications/low-carbon-heat-solutions-heavy-industry-sources-options-and-costs-today.

III. Social and Political Environment

Rising worldwide support for action on climate change has led to an international agreement in the form of the Paris accord, and at the national level, declared targets of reaching net zero emissions. Though these targets and goals represent some level of societal emphasis, there is still the risk that if either cost or reliability becomes an issue during the energy transition at some point, climate ambitions will be dropped.

Like many countries, while the United States has climate ambitions, it does not have a legally binding policy that forces economy-wide emissions (or even emissions from one sector) to zero or near zero by 2050. Instead, actions in the United States have been limited to those such as providing tax incentives for low-carbon sources of energy; individual states enacting clean energy standards forcing their power grids to decarbonize by roughly mid-century; and utility voluntary commitments to the same effect.

There have been a couple of signs indicating growing support for nuclear power. In 2022, for example, the European Union's list of officially approved "green" investments included nuclear energy.[29] In the United States, recent legislation, such as the bipartisan infrastructure law and the Inflation Reduction Act included measures to both preserve the existing fleet of US reactors and incentivize the development of advanced reactors. One IRA provision in particular—a technology-neutral investment credit—may point in the direction of future climate policy. The tax credit would make low-carbon technologies such as renewable, nuclear, and fossil energy (the last equipped with carbon capture and sequestration) eligible for the same subsidy, as opposed to differing incentives made available to each technology separately, as has been the practice in the past.

Taking a technology-neutral approach to decarbonization to address climate change would give industry the greatest amount of flexibility in how to reduce greenhouse gas emissions. Correspondingly, it would provide the world with the best chance of achieving much lower emissions by mid-century at affordable costs and without sacrificing reliability. Such an approach would also support nuclear energy development and deployment as opposed to one premised solely on one energy source, such as renewables.

For public support to continue to grow for nuclear energy, existing plants need to continue operating safely. In addition, striving toward greater inherent safety in advanced development—and communicating that inherent safety case—will also be important. However, focusing attention on at least two other specific areas would be helpful toward building a more supportive social and political environment for nuclear energy.

A. Improved management of reactor construction in NATO countries

Reactor construction in NATO countries has a checkered past. After a history of construction overruns in the United States, the most recent new builds—Westinghouse AP1000s—have followed a similar pattern. The two reactors, which have now been under construction for over a decade in Georgia, are taking more than twice as long as projected to begin commercial operations and will cost more than double the original estimate. Separately, the two AP1000s that were ordered in South Carolina were canceled in 2017 after $9 billion in expenditures.

In Europe, recent experience has not been better. The first French European Pressurized Reactor (EPR) began construction in Finland in 2005, but only achieved commercial operations in 2023—well over a decade past its expected start date.

These recent experiences with the AP1000 and EPR have damaged the perception of nuclear power as a constructable, affordable decarbonization option. At a recent roundtable discussion hosted by Columbia University's Center on Global Energy Policy, SIPA, members of the finance community pointed to these schedule and cost overruns as perhaps the greatest impediment to investment in nuclear power in the United States.[30] To the extent that the small modular reactors under development can achieve substantially better con-

29 "European Parliament Backs Nuclear and Gas in EU Taxonomy," *World Nuclear News,* July 6, 2022, https://www.world-nuclear-news.org/Articles/European-Parliament-backs-nuclear-and-gas-in-EU-ta.

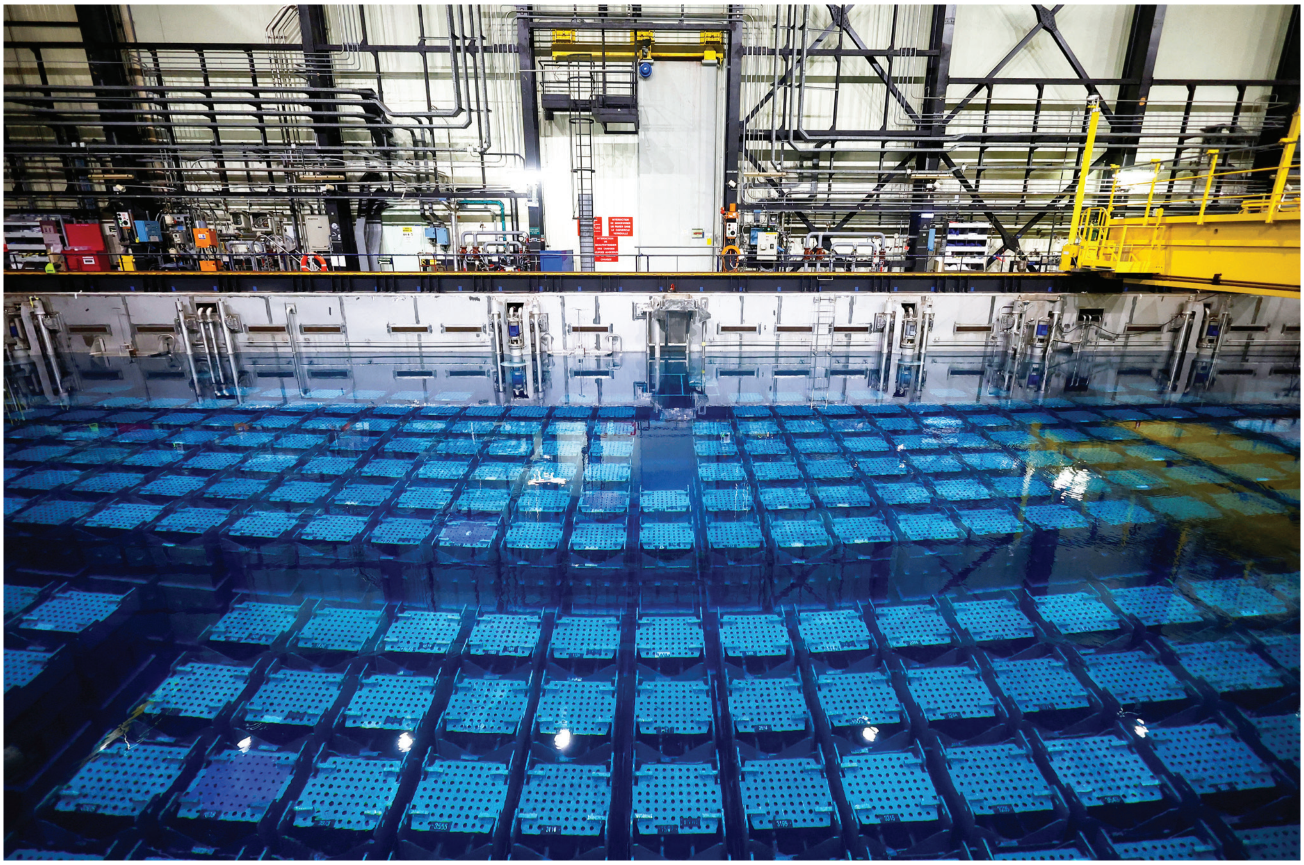
30 Matt Bowen and Kat Guanio, *Climate Finance Taxonomies and Nuclear Energy: Roundtable Report,* Center on Global Energy Policy, Columbia University, January 11, 2023, https://www.energypolicy.columbia.edu/publications/climate-finance-taxonomies-and-nuclear-energy-roundtable-report/.

struction records than the AP1000 and EPR and ultimately produce a product that can confidently be built in a known (and shorter) time period, this would assuredly add public and financial support for more new builds.

A 2023 US Department of Energy report *Pathways to Commercial Liftoff: Advanced Nuclear* estimates that a well-managed first-of-a-kind reactor project could cost $6,200 per kilowatt.[31] The same report assesses that subsequent nuclear projects could be expected to come down a cost curve to about $3,600 per kilowatt after ten to twenty deployments depending upon the learning rate. With the right development approach, DOE estimates that 200 GW of new nuclear is achievable in the United States by 2050.

B. Progress in spent nuclear fuel management

Some countries have been making progress in their management of commercial spent nuclear fuel. Finland, for example, has been building a deep geologic repository at Onkalo and is expected to begin disposal operations for commercial spent nuclear fuel in 2024, which would constitute the first such achievement in the world.[32] In January 2023, Andra, the French radioactive waste management agency, applied for a construction license to build a deep geologic repository for France's high-level nuclear waste.[33] Canada's Nuclear Waste Management Organization is selecting a site for its deep geologic repository and is expected to make that decision in 2024.[34]



Used nuclear fuel is seen in a storage pool at the Orano nuclear waste reprocessing plant in La Hague, near Cherbourg, France, January 17, 2023. REUTERS/Stephane Mahe

31 US Department of Energy, *Pathways to Commercial Liftoff: Advanced Nuclear,* 2023, https://liftoff.energy.gov/wp-content/uploads/2023/05/20230320-Liftoff-Advanced-Nuclear-vPUB-0329-Update.pdf

32 "Drilling of First Test Deposition Holes Completed at Onkalo Used Fuel Storage," *Nuclear Engineering International,* February 24, 2023, https://www.neimagazine.com/news/newsdrilling-of-first-test-deposition-holes-completed-at-onkalo-used-fuel-storage-10622637.

33 "Application Lodged for Construction of French Repository," *World Nuclear News,* January 18, 2023, https://www.world-nuclear-news.org/Articles/Application-lodged-for-construction-of-French-repo.

34 "One-Year Delay in Canadian Repository Site Selection," *World Nuclear News,* August 15, 2022, https://www.world-nuclear-news.org/Articles/One-year-delay-in-Canadian-repository-site-selecti.

In other countries, however, spent fuel management programs are not obviously making progress. In the United States, Congress has not allocated appropriations to move the Yucca Mountain project forward since 2010. Some states still have laws that prohibit new nuclear builds until and unless progress is made.[35] The Blue Ribbon Commission on America's Nuclear Future (BRC) recommended a number of policy changes in 2012, but Congress has not acted on any of them. One recommendation of the BRC, however, may be gaining some momentum. The American Nuclear Society has supported having the US Environmental Protection Agency (EPA) issue new standards for future high-level nuclear waste repositories, and in 2023 produced draft recommendations for how the EPA should go about doing this.[36] This is an early and necessary step as part of conducting a search for a deep geologic repository for long-lived nuclear waste from commercial nuclear power activities.

The BRC recommended that the United States search for nuclear waste management facilities and that the search be premised on obtaining the consent of the local and state governments, as opposed to imposing a federal selection. The US Department of Energy has a consent-based siting program in place to look, in particular, for states and local governments that are interested in learning more about what hosting a nuclear waste management facility would entail.[37] Congress has appropriated money for the program to work toward a consolidated interim storage facility to host commercial spent nuclear fuel on a temporary basis. However, as has been noted many times previously, states will be less likely to accept consolidated interim storage facilities inside their jurisdictions if the disposal program is moribund, fearing that a facility described as "interim" will in reality be long term if there is nowhere for the material to go. Several states have already indicated this position. Therefore, reconstituting a repository program—including steps such as updating the EPA's generic standards for repositories—will likely be necessary for the consolidated interim storage program to succeed.

Advanced reactors have a variety of fuel forms and operational characteristics that impact spent fuel considerations.[38] All of them will inevitably generate some long-lived radionuclides, such as iodine-129 and technetium-99, that will require long-term isolation from the biosphere, presumably in a deep geologic repository. Reactors operating at higher temperatures than conventional light water reactors, however, should be able to achieve higher conversion efficiencies in the production of electricity, thereby reducing the amount of fission products created per megawatt-hour (MWh). Some fast reactors plan to operate on a "once through" fuel cycle where the spent fuel is sent to a deep geologic repository, while others plan to reprocess their spent fuel and recycle some of the actinides into fresh fuel for the reactor. This approach would reduce the amount of actinides generated during the reactor's lifecycle on a per-MWh basis, though it would not reduce the fission products generated for the same reactor operating on a once through cycle.

35 "States Restrictions on New Nuclear Power Facility Construction," National Conference of State Legislatures, n.d., https://www.ncsl.org/environment-and-natural-resources/states-restrictions-on-new-nuclear-power-facility-construction, accessed April 24, 2023.

36 Peter Swift, Michael Apted, Lake Barrett, John Kessler, and Steven Nesbit, "New Generic Repository Environmental Standards: Draft Recommendations from ANS," *Nuclear Newswire,* February 17, 2023, https://www.ans.org/news/article-4736/new-generic-repositoryenvironmental-standards-draft-recommendations-from-ans/.

37 "Consent Based Siting," Office of Nuclear Energy, US Department of Energy, n.d., https://www.energy.gov/ne/consent-based-siting, accessed May 2023.

38 National Academies of Sciences, Engineering, and Medicine, *Merits and Viability of Different Nuclear Fuel Cycles and Technology Options and the Waste Aspects of Advanced Nuclear Reactors,* (Washington, DC: The National Academies Press, 2023), https://doi.org/10.17226/26500.

IV. Workforce Development

The workforce that underpins the nuclear sector draws in part upon professionals trained at universities in related fields, such as nuclear engineering. Correspondingly, to support the long-term maintenance of the existing fleet and advanced reactors, national governments will need to invest in workforce capabilities to ensure that a sufficient talent pool is available in the future. For example, the American Nuclear Society, in partnership with the US Department of Energy, has developed a curriculum program to empower educators to teach K-12 student about the uses of the atom.

For example, in 2009, the US Department of Energy created the Nuclear Energy University Program to consolidate university support into one initiative and better facilitate the integration of university research within the Office of Nuclear Energy's technical programs.[39] The engagement with universities supports new research infrastructure, stu-

A welder works during a training at the Hefais school (the Haute Ecole de formation en soudage) for nuclear welders co-financed by EDF, in La Hague, France, December 7, 2022. REUTERS/Benjamin Mallet

39 "Nuclear Energy University Program," Office of Nuclear Energy, US Department of Energy, n.d., https://www.energy.gov/ne/nuclear-energy-university-program, accessed May 2023.

dent education, and long-term R&D, which in turn promotes workforce capability by attracting and training talent that can be employed in the nuclear sector.

A. Requirements to support the growth of nuclear energy

Direct employment during the preparation and construction of a gigawatt-sized nuclear reactor uses about twelve thousand person-years, and for the subsequent fifty years of operations, approximately six hundred administrative, operations and maintenance, and permanently contracted staff (i.e., thirty thousand person-years).[40] Adding in other direct employment, indirect employment, and induced employment raises the total person-years of labor up to one hundred thousand. The large demand for jobs associated with a new reactor construction project is attractive to communities looking to grow or at least maintain population and economic development. For some communities, the energy transition may mean fossil energy plant closures, which would lead to negative economic impacts if the associated jobs are not replaced in some way with new ones.

For new reactor construction in some regions, whether an adequate workforce is available for a substantial amount of new projects may be uncertain. Even though interest in advanced reactor development has grown in recent years, it comes after years of partial contraction in the nuclear industry along with general workforce challenges stemming from the COVID-19 pandemic. Overall, the number of operating reactors in the United States in the past twenty years has declined, and in other countries such as Germany and Japan, reactors have been idled following the accident at Fukushima or permanently shut down. These trends, along with the uncertainty of the future of nuclear power in the West, have created strains in the workforce available in countries like the United States and Japan.

Professional organizations, such as the American Physical Society, have noted with concern the likelihood of shortages of nuclear scientists, engineers, and technicians in important government sectors, and recommended that federal and state governments train and maintain a viable workforce.[41] Industry has assessed that government programs to attract students to study and develop skills in the areas needed by the nuclear industry will enable the deployment of advanced reactors.[42] A recent US Department of Energy report assessed that, in order to construct and operate 200 GW of new nuclear capacity, the United States would need approximately 375,000 additional workers with technical and non-technical skill-sets.[43]

Competition with other industries for talent could also be a challenge. For that reason, NuScale, an advanced reactor company, has taken early steps to ensure that a trained workforce will be available for its reactors by creating Energy Exploration Centers, which are power plant control room simulators that employ state-of-the-art computer modeling. Three universities have been awarded government grants to help install such centers, and a fourth is planned for Romania to support NuScale development and deployment there.[44]

Community partnerships and stakeholder engagement will be important to the development of future nuclear energy deployment and a workforce to support that deployment. Educational events and programs at the elementary school through high school levels can introduce students to science, technology, engineering, and math concepts, as well as nuclear power in particular. Utilities could also provide opportunities, such as scholarships and educational funding, to local community partners.

40 Nuclear Energy Agency and International Atomic Energy Agency, *Measuring Employment Generated by the Nuclear Power Sector,* 2018, https://www.oecd-nea.org/jcms/pl_14912/measuring-employment-generated-by-the-nuclear-power-sector.

41 American Physical Society, *Readiness of the US Nuclear Workforce for 21st Century Challenges,* June 2008, https://www.aps.org/policy/reports/popa-reports/readiness.cfm.

42 Electric Power Research Institute and Nuclear Energy Institute, "Advanced Reactor Roadmap, Phase 1: North America," https://www.epri.com/about/media-resources/press-release/73SPk7KsrJeMom5sQ5sFLJ.

43 US Department of Energy, *Pathways to Commercial Liftoff: Advanced Nuclear,* 2023. https://liftoff.energy.gov/wp-content/uploads/2023/05/20230320-Liftoff-Advanced-Nuclear-vPUB-0329-Update.pdf.

44 Paul Day, "Finding a Workforce May Be Nuclear's Largest Challenge," *Reuters,* October 3, 2022, https://www.reuters.com/business/energy/finding-workforce-may-be-nuclears-largest-challenge-2022-10-03/.

The workforce to support the construction and operation of a small modular reactor may be somewhat smaller, though also potentially more advanced than the older, larger light water reactors.[45] It is possible that new SMRs may require less staff than what is needed in the current operating reactors, but staff with more diverse skill sets. For example, a field operator at an SMR might perform maintenance and chemistry tasks in addition to traditional operations tasks.[46]

B. China and Russia

China and Russia are not facing the same workforce challenges as the United States, Europe, Japan, or South Korea. As opposed the United States, both have been building domestic reactors regularly over the past twenty years and, especially in the case of Russia, exporting them to other countries.

CHINA

At the beginning of 2023, China had fifty-five power reactors in operation for a total of 52,201 MWe, with eighteen reactors under construction—the largest domestic build program in the world. Moreover, in 2020 the Chinese government announced that the country will aim to have carbon dioxide emissions peak before 2030 and achieve "carbon neutrality by 2060."[47] In its fourteenth five-year plan, China aims to increase nuclear power generation from 50 GW in 2020 to 70 GW in 2025, with some estimating Chinese nuclear capacity at 180 GW by 2035.[48]

As Table 2 shows, China's nuclear energy program has been steadily growing; though the country has to date exported reactors to only Pakistan, other customer countries are on the horizon. Official Chinese government publications aim for the nuclear program to keep growing for decades, and as a result students in China see a vibrant future ahead in related fields.

Table 2. The Chinese Nuclear Energy Program, 2000-2021

Reactors connected to the Chinese electrical grid	50
Chinese reactors connected to other nations' electrical grids	5
Reactors under construction in China at the end of 2021	15
Chinese reactors under construction in other nations at the end of 2021	1

SOURCE: INTERNATIONAL ATOMIC ENERGY AGENCY, "POWER REACTOR INFORMATION SYSTEM," HTTPS://PRIS.IAEA.ORG/PRIS/.

Still, China may have different challenges related to workforce. Independent experts have assessed that for China to significantly grow its nuclear energy enterprise, it would require dramatically increasing the number of trained, experienced personnel in areas such as the design, construction, and operation of power plants.[49] Independent experts have assessed that one of the policy issues China will need to confront, in addition to others, to improve the economics of nuclear energy is maintaining a moderate pace of nuclear construction to support a workforce with experience in nuclear construction and operations.[50]

45 "A Review of Workforce Trends in the Nuclear Community," *Nuclear Newswire,* February 1, 2023, https://www.ans.org/news/article-4677/a-review-of-workforce-trends-in-the-nuclear-community/.

46 Ibid.

47 Matt McGrath, "Climate Change: China Aims for 'Carbon Neutrality by 2060,'" BBC, September 22, 2020, https://www.bbc.com/news/science-environment-54256826.

48 Genevieve Donnellon-May, "Powering China's Nuclear Ambitions," *The Diplomat,* September 20, 2022, https://thediplomat.com/2022/09/powering-chinas-nuclear-ambitions/.

49 Matt Bunn, "Enabling a Significant Nuclear Role in China's Decarbonization," in Henry Lee, Daniel P. Schrag, Matthew Bunn, Michael Davidson, Wei Peng, Wang Pu, and Mao Zhimin, eds., *Foundations for a Low-Carbon Energy System in China* (Cambridge, UK: Cambridge University Press, 2021), https://www.belfercenter.org/publication/enabling-significant-nuclear-role-chinas-decarbonization, 65-100.

50 Ibid.

RUSSIA

Russia has also continued to add reactors to its domestic fleet in recent decades, as Table 3 shows. It has been the leading supplier of reactors to other nations, though its invasion of Ukraine has caused Finland to decide against a Russian reactor supply.

Table 3. The Russian Nuclear Energy Program, 2000-2021

Russian reactors connected to the Russian electrical grid	13
Russian reactors connected to other nations' electrical grids	12
Russian reactors under construction in Russia at the end of 2021	4
Russian reactor under construction in other nations at the end of 2021	15

SOURCE: INTERNATIONAL ATOMIC ENERGY AGENCY, "POWER REACTOR INFORMATION SYSTEM," HTTPS://PRIS.IAEA.ORG/PRIS/.

Given the reactor construction activity at home and abroad, Russian students see a growing nuclear sector on the other side of their degrees. Due to Russian reactor exports to other countries, foreign citizens are also being trained in Russia for work at water-water energetic reactor (VVER) plants back in their home countries.[51] Russia has even offered scholarships to foreign students to study nuclear science in Russia that include fully funded tuition and partly funded living expenses, as it did for Indian students in 2019.[52]

51 "Turkish Students Receive Russian Master's Degrees for Work at Akkuyu," *Nuclear Engineering International,* August 24, 2021, https://www.neimagazine.com/news/newsturkish-students-receive-russian-masters-degrees-for-work-at-akkuyu-9025516.

52 "Rosatom Announces Scholarships for Indian Students in Nuclear Energy Studies," *India Express,* January 22, 2019, https://indianexpress.com/article/education/study-abroad/rosatom-announces-scholarships-for-indian-students-in-nuclear-energy-studies-russia-study-en-5549459/.

V. International Regulatory Harmonization

The approach of national regulators in licensing advanced reactors will play some role in determining their future deployment levels. If advanced reactors are deployed for non-electricity purposes, this will be a break from the past in how reactors have typically been used —at least in some countries, such as the United States. In early 2023, for example, Dow and the advanced reactor company X-energy signed a joint development agreement to develop a four-unit Xe-100 facility at one of Dow's US Gulf Coast sites.[53] The companies later announced that Dow's Seadrift, Texas location would be the specific site for deployment.[54] Using X-energy's high temperature gas reactor concept could help Dow reduce its carbon emissions by replacing fossil fuel use with high temperature heat from nuclear reactors. How the US Nuclear Regulatory Commission (NRC) and other regulatory bodies will treat such instances from a regulatory standpoint is uncertain but will influence future investments to some degree.

A. Complexities of the regulatory process for advanced reactors

Sections of existing nuclear regulations in the United States were developed with the licensing of large light water reactors in mind, not the types of advanced reactors under deployment today. For example, the General Design Criteria in Appendix A of 10 CFR Part 50 were often developed primarily for large light water reactors. What that means is that even for small modular reactors that use water as a coolant, there is still the challenge for associated companies of explaining why different sections of the regulations are or are not applicable to their design.

For example, NuScale compared its VOYGR design functions/characteristics to those of typical large light water reactors and looked at NRC requirements and guidance for relevance and applicability. The company determined at each point whether the regulation or regulatory guidance was relevant and applicable to the NuScale design or whether it was "partially applicable," "not applicable," or a "unique feature." In the end, NuScale submitted a document to the NRC during pre-application interactions that identified a number of gaps to be resolved to enhance the probability of an efficient and favorable review of the design certification application.[55]

It is possible that the licensing of non-light water reactors will be even more challenging as their designs are an even greater departure from large light waters. To help prepare for advanced reactor deployment, the US Congress directed the NRC in 2018 to develop a technology-neutral, risk-informed approach to licensing advanced reactors by 2027.

However, if each regulator around the world goes through the same learning experience independent of one another, it might mean lower reactor deployment and thus less progress at addressing greenhouse gas emissions. A more efficient approach to advanced reactor licensing based on regulator collaboration could help.

B. Potential benefits of international regulatory harmonization

The International Atomic Energy Agency launched an initiative in 2022 to bring together policymakers, regulators, designers, vendors, and operators to develop common regulatory and industrial approaches to SMRs.[56] The aim is to facilitate the safe and secure deployment of SMRs and maximize their ability to help achieve the goals of the Paris Agreement and reach net-zero emissions by mid-century. For instance, for prefabricated modules to be produced in factories and assembled at sites in multiple countries, common industrial standards, codes, and licensing requirements will be needed across borders.

Harmonizing national regulatory approaches would also be helpful, and one recent example of regulatory collaboration may be instructive for the future: the joint work by the US

53 Dow, "Dow and X-energy Advanced Efforts to Deploy First Advanced Small Modular Nuclear Reactor at Industrial Site under DOE's Advanced Reactor Demonstration Program," Press release, March 1, 2023, https://corporate.dow.com/en-us/news/press-releases/dow-x-energy-collaborate-on-smr-nuclear.html

54 X-energy, "Dow's Seadrift, Texas location selected for X-energy advanced SMR nuclear project to deliver safe, reliable, zero carbon emissions power and steam production," May 11, 2023. https://x-energy.com/media/news-releases/dows-seadrift-texas-location-selected-for-x-energy-advanced-smr-nuclear-project-to-deliver-safe-reliable-zero-carbon-emissions-power-and-steam-production.

55 NuScale Power, LLC, *Gap Analysis Summary Report,* Revision 1, July 2014, https://www.nrc.gov/docs/ML1421/ML14212A831.html.

56 Jeffrey Donovan and Paula Calle Vives, "Accelerating SMR Deployment: New IAEA Initiative on Regulatory and Industrial Harmonization," International Atomic Energy Agency, April 1, 2022, https://www.iaea.org/newscenter/news/accelerating-smr-deployment-new-iaea-initiative-on-regulatory-and-industrial-harmonization.

Nuclear Regulatory Commission and the Canadian Nuclear Safety Commission (CNSC) on the GE-Hitachi BWRX-300. In December 2021, Ontario Power Generation selected the BWRX-300 for the new Darlington nuclear site.[57] In the United States, the Tennessee Valley Authority (TVA) announced in early 2022 that it would explore the construction of multiple advanced reactors at its Clinch River site in Tennessee, starting with a GE-Hitachi BWRX-300.[58] TVA and GE Hitachi Nuclear Energy later entered into an agreement to support planning and preliminary licensing.[59]

In 2019, NRC and CNSC signed a memorandum of cooperation to increase collaboration on technical review of SMRs and advanced reactor technologies.[60] The terms of the memorandum allow the NRC and CNSC to consider each other's experiences and regulatory information when performing technology assessments. In October 2022, US and Canadian regulators announced a charter that documented collaboration concerning a project under the memorandum involving the BWRX-300.[61] Overall, the two regulators' collaboration is intended to reduce duplication of licensing review efforts and identify areas for collaborative verification, among other goals.

The Tennessee Valley Authority, Ontario Power Generation, and Synthos Green Energy entered into an agreement in March 2023 to invest in the development of the BWRX-300 design. GE HITACHI NUCLEAR NUCLEAR ENERGY

57 "OPG Chooses BWRX-300 SMR for Darlington New Build," *World Nuclear News,* December 2, 2021, https://www.world-nuclear-news.org/Articles/OPG-chooses-BWRX-300-SMR-for-Darlington-new-build.

58 Sonal Patel, "TVA Unveils Major New Nuclear Program, First SMR at Clinch River Site," *Power,* February 10, 2022, https://www.powermag.com/tva-unveils-major-new-nuclear-program-first-smr-at-clinch-river-site/.

59 "TVA, GEH Cooperate on BWRX-300 Deployment at Clinch River," *World Nuclear News,* August 3, 2022, https://www.world-nuclear-news.org/Articles/TVA-GEH-cooperate-on-BWRX-300-deployment-at-Clinch.

60 See "CNSC Signs Memorandum of Cooperation with the U.S. Nuclear Regulatory Commission," Canadian Nuclear Safety Commission, 2019, https://nuclearsafety.gc.ca/eng/resources/international-cooperation/international-agreements/cnsc-usnrc-smr-advanced-reactor-moc.cfm and also "Memorandum of Cooperation on Advanced Reactor and Small Modular Reactor Technologies between the United States Nuclear Regulatory Commission and the Canadian Nuclear Safety Commission," United States Nuclear Regulatory Commission, 2019, https://www.nrc.gov/docs/ML1927/ML19275D578.pdf.

61 "US, Canadian Regulators Further SMR Collaboration," *World Nuclear News,* October 7, 2022, https://www.world-nuclear-news.org/Articles/US,-Canadian-regulators-further-SMR-collaboration.

The utilities involved, Ontario Power Generation and Tennessee Valley Authority, announced a partnership in 2022 to develop SMRs,[62] and in October of 2022, Ontario Power Generation submitted an application for a license to construct the BWRX-300 to the CNSC.[63] In 2021, TVA's board approved an investment of up to $200 million for a new nuclear initiative that would include the Clinch River site—where TVA already has an early site permit license for an SMR. TVA has said that it is aiming for a construction license application to be submitted to the NRC in 2023 or 2024.[64] In March 2023, the CNSC completed phases 1 and 2 of the Canadian pre-licensing review, where no fundamental barriers to the licensing were identified.[65]

In addition to the work related to the BWRX-300, the NRC and CNSC have also issued joint reports on other nuclear topics, such as X-energy's reactor pressure vessel construction code.[66]

C. Pathways for cooperation on regulation

Cooperation between the United States and Canada on the regulation of SMRs could provide a model for the future. Canada also recently joined the Foundational Infrastructure for Responsible Use of Small Modular Reactor Technology (FIRST) program and will provide funding and in-kind support.[67] As additional countries consider SMR deployment, and in particular US SMR designs, the NRC could consider similar actions with respective regulators. For example, Romania has indicated its intention to potentially deploy a US SMR design, the NuScale VOYGR. Its independent regulator, the National Commission for Nuclear Activities Control, already regulates two Canadian CANDU (Canada deuterium uranium) reactors that are in operation.

Japan's cabinet also recently adopted a policy that calls for developing advanced reactors and aims to have them begin operation in the 2030s.[68] Japanese investment is supporting the development of both the GE-Hitachi BWRX-300 and the NuScale VOYGR designs, which could potentially be part of future deployments. Following the 2011 earthquake/tsunami and the resulting accident at the Fukushima Daiichi power plant, Japan's government moved to separate the function of promotion and regulation of nuclear energy, and created the Nuclear Regulation Authority in 2012. The relatively new regulatory body in Japan might see potential benefits to engaging with regulators such as the NRC and CNSC and using the collaborative model described above between the United States and Canada.

Finally, the NRC has been working on licensing issues related to reactors potentially operating past sixty years of age and possibly as long as eighty years.[69] Other national regulators, especially those with plants that will approach sixty years of age in the coming decades, may be interested to learn from the NRC's experience in that regard. In February 2023, Japan, for example, changed its national law regarding operating reactor lifetimes, potentially extending the lifetimes of some plants in its fleet.[70]

62 Abie Bennett, "TVA Partners with Ontario Power Generation on Advanced Nuclear, SMRs," S&P Global Market Intelligence, April 19, 2022, https://www.spglobal.com/marketintelligence/en/news-insights/latest-news-headlines/tva-partners-with-ontario-power-generation-on-advanced-nuclear-smrs-69881949.

63 Ontario Power Generation, "OPG Applies to Canadian Nuclear Safety Commission for Licence to Construct," Press release, October 31, 2022, https://www.opg.com/news/opg-applies-to-canadian-nuclear-safety-commission-for-licence-to-construct/.

64 "TVA Eyes Late 2023 or Early 2024 for SMR Licence Application," *World Nuclear News,* May 13, 2022, https://www.world-nuclear-news.org/Articles/TVA-eyes-late-2023-or-early-2024-for-SMR-licence-a.

65 "BWRX-300 Completes Phases 1 & 2 of Canadian Pre-licensing Review," *World Nuclear News,* March 15, 2023, https://www.world-nuclear-news.org/Articles/BWRX-300-completes-Phases-1-2-of-Canadian-pre-lice.

66 "Joint Reports of the Canadian Nuclear Safety Commission (CNSC) and the NRC," US Nuclear Regulatory Commission, last updated May 31, 2022, https://www.nrc.gov/reactors/new-reactors/advanced/international-cooperation/nrc-cnsc-moc/joint-reports.html.

67 The White House, "Joint Statement by President Biden and Prime Minister Trudeau," March 24, 2023, https://www.whitehouse.gov/briefing-room/statements-releases/2023/03/24/joint-statement-by-president-biden-and-prime-minister-trudeau/.

68 "Japan Cabinet Approves Use of Nuclear Reactors beyond 60 Years," Nikkei Asia, February 10, 2023, https://asia.nikkei.com/Business/Energy/Japan-cabinet-approves-use-of-nuclear-reactors-beyond-60-years.

69 US Nuclear Regulatory Commission, "Status of Subsequent License Renewal Applications," accessed on March 7, 2023, https://www.nrc.gov/reactors/operating/licensing/renewal/subsequent-license-renewal.html.

70 "Cabinet Approves Change in Japanese Nuclear Policy," *World Nuclear News,* February 10, 2023, https://www.world-nuclear-news.org/Articles/Cabinet-approves-change-in-Japanese-nuclear-policy.

VI. Policy Recommendations

There are a number of actions that national governments in NATO countries and Japan and South Korea could pursue to help overcome the challenges described in this report. Pursuing them would assist with creating nuclear energy supply options to address the energy and environmental challenges described in Section 1, and help these countries compete with Russia and China to supply other nations. In the absence of options from NATO countries and Japan and South Korea, countries that are looking to begin or expand nuclear energy programs would be more likely to go with Russian and Chinese designs.

Finding ways for governments to cooperate could also help with that competition. For example, in October 2022 the United States and Japan announced a partnership with Ghana that would support Ghana's goal to be the African mover on small modular reactor deployment.[71]

Similarly, cooperation on financing could help counter the attractive financing offers that Russia and China have been making in support of their reactor exports.[72] It is possible, however, that even with cooperation on financing terms, NATO countries may not be able to match the financing offers made by Russia and China. Still, enhanced cooperation might at least help close the gap. Along those lines, US export-import banks and the US International Development Finance Corporation recently announced financing support for deployment of the GE-Hitachi BWRX-300 in Poland.[73] If the delivery performance and overall cost of Western reactors can surpass Russian and Chinese supply, that might further even the competition or even tip it away.

A. Nuclear RD&D

The 2020s offer a clear window for advanced reactor development to pave the way for potential deployment in the 2030s and 2040s.

Recommendation: National governments should support advanced reactor demonstration efforts in the 2020s to increase the likelihood that new options will be available in the 2030s. Though the US DOE announced cost-share agreements in 2020 with various developers for first-of-a-kind demonstration, there is uncertainty over whether the US Congress will fund all of these agreements. Federal power purchase agreements, in which a federal facility or group of federal facilities agree to take power from a first-of-a-kind power plant, are another policy option that could be utilized to help with reactor demonstration.

Lifetime extension for the existing fleet of reactors is low-hanging fruit for keeping the costs of transitioning to a low-carbon grid to a minimum. It is critical that safety-related technical aspects of lifetime extension be addressed with research.

Recommendation: National governments should conduct R&D into topics that relate to extending the lifetime of the existing fleet of reactors, including the effects of material aging and irradiation, as well as advanced nuclear fuels, which could increase operating safety margins. In the United States, some reactors will reach 60 years of age in the next decade and a US research program could examine the technical issues involved and uncertainties associated with operations beyond 80 years. Advanced nuclear fuels could provide greater tolerance to accident conditions, extend reactor operation times between refueling, and potentially reduce fuel costs for the rest of a given reactor's lifetime.[74]

71 US Department of State, "United States and Japan Announce Partnership with Ghana to Support Its Goal of Being the Mover in Africa for Small Modular Reactor Deployment," October 26, 2022, https://www.state.gov/united-states-and-japan-announce-partnership-with-ghana-to-support-its-goal-of-being-the-mover-in-africa-for-small-modular-reactor-deployment/.

72 Matt Bowen and Alec Apostoaei, *Comparing Government Financing of Reactor Exports: Considerations for US Policy Makers,* Center on Global Energy Policy, Columbia University, August 25, 2022, https://www.energypolicy.columbia.edu/publications/comparing-government-financing-reactor-exports-considerations-us-policy-makers/.

73 "Polish Plans for Large and Small Reactors Progress," *World Nuclear News,* April 17, 2023, https://www.world-nuclear-news.org/Articles/Polish-plans-for-large-and-small-reactors-progress.

74 DOE, "These Accident Tolerant Fuels Could Boost the Performance of Today's Reactors," January 28, 2020, https://www.energy.gov/ne/articles/these-accident-tolerant-fuels-could-boost-performance-todays-reactors.

In the wake of Russia's invasion of Ukraine, countries are reassessing their supply chain dependencies and vulnerabilities. Russia has maintained a large share of the conversion and enrichment markets[75] for many years, including in North American and European markets, and investments to replace those services are warranted. Russia has also been the sole source of high-assay low-enriched uranium (HALEU), which is needed for many advanced reactor designs. Building out a supply chain for HALEU is another area for national governments to focus on, especially if, as is the case in the United States, they have already made investments in the advanced reactors that require such fuel. Finally, making progress on the back end of the fuel cycle is important too as part of ethical considerations with regard to future generations, and it is another issue that hangs over nuclear power.

Recommendation: National governments should conduct RD&D into fuel cycle topics, such as the production of uranium from seawater; HALEU fuel; and disposal technologies, such as boreholes. Borehole disposal might prove to be economical and perhaps more socially acceptable in some areas of the world and international R&D collaboration on this front could be fruitful.[76]

B. Political and social

In addition to the fuel cycle RD&D described above, governments should take steps to build political and social support for nuclear power.

Recommendation: National governments should explain to their citizens in public documents speeches from their environmental, energy, and regulatory agencies the benefits to society from avoiding carbon dioxide and air pollution, and in particular how firm, low-carbon power can help meet reliability, affordability, and emissions goals simultaneously. In addition, it would be helpful to explain how nuclear power offers some nations greater energy security at a time when energy relationships have seen great disruption. Explaining why low-carbon, firm generation, such as nuclear power, is needed—or alternately why an energy strategy premised solely on renewable energy sources might be unwise—would help with public support and also private investment. The White House or the Secretary of Energy could, for example, convene groups from the utility and investment communities to discuss the need for low-carbon, firm power in deep decarbonization scenarios.

Recommendation: National governments should pursue technology-neutral approaches to addressing climate change, which could include policies that focus on restricting carbon dioxide and air pollution release or adding financial penalties for their emission. For example, the Inflation Reduction Act of 2022 added a technology-neutral tax credit that renewable, nuclear, and fossil energy (the last equipped with carbon capture and sequestration technology) could all qualify for.

C. Workforce

Maintaining the existing fleet of nuclear power plants, and deploying advanced reactors, will require a talent pool from which to draw upon.

Recommendation: National governments should provide support for student education (e.g., PhD programs in nuclear engineering) in related fields. The Nuclear Energy University Program in the United States could serve as one model for other countries to emulate. Support could also be considered for student exchanges to learn about nuclear culture and practice in other countries. K-12 education on nuclear topics could also be enhanced. A curriculum program developed with the American Nuclear Society in partnership with the US DOE is one possible template that could be duplicated in other countries to increase education on nuclear issues.[77]

D. Regulatory harmonization

National regulatory bodies may each end up licensing the same reactor designs. If they must begin from scratch each time, the result may be slower and more expensive than if regulators found ways to collaborate.

Recommendation: To increase efficiencies, regulatory bodies in countries looking to deploy small modular reactors should look for opportunities to collaborate with other regulatory entities in countries that are similarly considering SMR deployment. The actions described in Section 5 involving collaboration between US and Canadian regulators could serve as a template for increasing the efficiency of licensing advanced reactors in multiple countries.

75 Matt Bowen and Paul Dabbar, *Reducing Russian Involvement in Western Nuclear Power Markets,* Center on Global Energy Policy, Columbia University, May 2022, https://www.energypolicy.columbia.edu/publications/reducing-russian-involvement-western-nuclear-power-markets/.

76 Peter Swift and Andrew Newman, *Deep Borehole Disposal of Radioactive Waste: Next Steps and Applicability to National Programs,* Center on Global Energy Policy, Columbia University, November 2022, https://www.energypolicy.columbia.edu/publications/deep-borehole-disposal-radioactive-waste-next-steps-and-applicability-national-programs.

77 American Nuclear Society, "Empowering Educators with Navigating Nuclear," accessed June 30, 2023; https://www.ans.org/nuclear/k12/.

About the Author

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