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New Nuclear Energy: Assessing the National Security Risks

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The climate crisis has renewed interest in nuclear energy as a way of reducing greenhouse gas emissions. In 2023, the United States and 21 other countries pledged to triple nuclear energy by 2050. Lost in the noise about meeting net zero goals are the national security implications of attempting such an enormous expansion of nuclear energy.

The nuclear energy future that is being proposed now – small, flexible reactors distributed everywhere for many uses besides electricity – will not reduce, but will add to the national security risks that are unique to nuclear energy. On top of this, cooperation among key states essential to minimize the safety, security and proliferation risks of nuclear energy is at an all-time low.

Proliferation of nuclear weapons and nuclear terrorism are the top two security risks associated with nuclear energy. To limit those risks, nuclear energy has required a network of agreements, treaties and voluntary understandings. Even if that network were perfect – and we know it is not by the examples of Iran and North Korea – the war in Ukraine has reminded us of the danger that nuclear power plants present when governance crumbles and the risks of sabotage, coercion, or even weaponization skyrocket.

To date, the concentration of nuclear power in fewer than three dozen countries worldwide has also helped limit these risks. Yet a highly nuclearized world will present more targets across the globe and some of these will be in countries with fragile governance and limited experience and resources. Proposals to widen applications of nuclear energy beyond electricity will require fuels and technologies that require reprocessing -- a sensitive fuel cycle technology that increases proliferation risks. Absent a concerted effort to restrict sensitive fuel cycle technologies, proliferation risks will inevitably rise.

The call to triple nuclear energy coincides with the disintegration of cooperation, the unraveling of norms and the loss of credibility of international institutions that are crucial to the safe and secure operation of nuclear power. The United States should avoid turning its nuclear energy export competition with Russia and China into great power competition. Rather, it should seek to reinvigorate a shared understanding of the risks of nuclear weapons proliferation with those key countries. In particular, the United States should convene an international study on the national security risks of small modular reactor designs.

U.S. government promotion of nuclear power needs to be informed by objective, technology-based assessments as well as geopolitical analysis. The U.S. State Department should commission a new International Security Advisory Board study on how the national security risks posed by nuclear energy have changed over the last two decades and broaden its focus to include not just proliferation but also the prospects for nuclear terrorism, sabotage, coercion and weaponization of power plants.

For itself and other countries, U.S. climate objectives should not favor specific technologies but focus on the most efficient and most feasible measures to achieve net zero in the shortest amount of time. Above all, the United States needs to weigh nuclear solutions to climate change against other low-carbon options that pose fewer national security risks and may be more resilient to disruption. If the international security environment further degrades under the stresses of extreme climate, it may become increasingly difficult, if not impossible, to carve out “safe zones” for nuclear power plants.

INTRODUCTION

The climate crisis has generated strong interest in nuclear energy as a way of reducing greenhouse gas emissions. The scope and urgency of the challenge is enormous – to eliminate the use of fossil fuel across multiple sectors, especially electricity, within two decades. The United States, along with twenty-one other countries, called for a tripling of nuclear energy capacity by 2050 on the margins of the COP-28 climate summit in December 2023.[1]

This is an ambitious goal, particularly considering that most countries do not have nuclear power plants and two-thirds of those that do (31 countries plus Taiwan) tend to operate just one or two reactors. Why? Cost has been a big reason for many countries, but so are concerns about safety and what to do with radioactive waste. Keeping reactors safe and secure poses added challenges. In 2011, the tsunami that devastated Japan demonstrated the high environmental and political costs when severe weather events damage nuclear power reactors. More than ten years after the crisis, most of Japan's nuclear reactors still sit idle. And in 2022, the risks to nuclear power plants suddenly widened when Russia invaded Ukraine. Its occupation of the Chernobyl nuclear power plant and ongoing occupation of the Zaporizhzhia nuclear site prompted experts to consider the unthinkable: operating nuclear power reactors safely and securely in zones of conflict.

Nonetheless, the nuclear industry and governments are eager to make nuclear energy relevant again after decades of stagnation.

An effort to make nuclear energy more affordable, safe and flexible, and thus more attractive to a broader range of uses and users, has centered on Small Modular Reactors (SMRs). Few SMRs are actually operating to date, but more than 80 designs have been proposed worldwide. In a bid to "reinvent nuclear energy," designers have proposed a host of new applications of nuclear energy including heating, desalination, industrial manufacturing processes and hydrogen production, for both densely populated cities and off-grid, remote locations. The United States and China are even considering so-called nuclear batteries and microreactors for military forces and bases. The U.S. State Department is promoting SMRs as:

- Requiring little land and scalable to meet energy needs
- Designed to incorporate advanced safety, security and nonproliferation features
- Requiring less capital investment
- Flexible in their siting
- Designed for multiple uses (including district and process heat, clean hydrogen, and other industrial applications)[2]

The landscape of SMRs, for the moment, is largely fictional. With so few SMRs operating, it is hard to tell whether their reality will meet expectations. Although they are marketed as new and advanced, SMRs so far feature few true innovations among the scores of designs. Quite a few are old wine in new bottles. And while they may be designed to reduce vulnerabilities, some feature technologies that will increase proliferation risks. Most importantly, promoting nuclear power for countries with significant governance challenges could present new national security risks.

This analysis traces the historical development of small modular reactors, discusses the current trends in designs and applications, and describes where such reactors might be deployed. It analyzes a range of national security risks posed by the potential widespread deployment of nuclear power that SMRs may exacerbate. The report concludes that as the nuclear energy industry has sought to reinvent itself, it has not only failed to solve old problems, but created new ones.

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[1] Jenny Gross, "22 Countries Pledge to Triple Nuclear Capacity in Push to Cut Fossil Fuels," *The New York Times*, December 2, 2023

[2] See State Department webpage on Project Phoenix, https://www.state.gov/project-phoenix/

The term "small modular reactors" describes an array of designs, approaches and uses of nuclear power that look different from the 434 power reactors currently in operation. The International Atomic Energy Agency (IAEA) at times has defined SMRs as emerging technology, as advanced nuclear reactors, and as "newer generation reactors."[3] There are now at least 83 designs in various stages of development across the world. The one constant element is a cap on their size at 300 MW(e) of electricity.[4]

To get an idea of why size is important, consider how commercial reactors evolved from the 1950s. Most countries embarking on commercial nuclear energy typically started with small, prototype reactors and then expanded the size of their reactors as they gained more expertise.[5] For the United States, construction starts between 1954 and 1963 featured reactors with capacities ranging from 6.5 MWe to 257 MWe. The following decade, U.S. reactor new construction ranged between 436 MWe to 1257 MWe and from 1974 to 1983, grew to 905 MWe to 1314 MWe capacities. In other words, as experience grew so too did reactor sizes, in part to take advantage of economies of scale.

Experience in other countries mirrored those of the United States. Russia's first VVER in 1964 produced 210 MWe but within a decade, VVERs scaled up to 1000 MWe. China's indigenous reactors grew from a range of 300-600 MWe in the 1980s to today's 1400 MWe range. India and Pakistan, however, have operated smaller indigenous power reactors for many decades. Foreign construction in both countries has aimed to build 1000-MWe power reactors.

The IAEA, established in 1957 with a mandate to spread the peaceful uses of nuclear energy, long has promoted nuclear power for the developing world, particularly small- to medium-sized power reactors below 700 MWe. But widespread deployment failed to materialize. The IAEA suggested major nuclear vendors were uninterested in catering to this new market, which would require smaller reactors to match smaller electricity grids.[6] Commercial nuclear power reactor design was moving in the opposite direction toward larger reactors to achieve economies of scale, which also allowed investment costs to be recouped faster, given the larger volumes of electricity produced.

As demand for nuclear power dropped in Western Europe and North America in the mid-1980s, the IAEA foresaw that traditional vendors might be attracted to design reactors for export. In 1985, the IAEA identified 23 designs from 17 vendors that featured power reactors of between 300 and 600 MWe.[7] But the next year, the Chernobyl accident prompted many countries previously interested in nuclear power to shelve their plans.

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[3] See, for example, the following IAEA documents: Deployment Indicators for SMRs (IAEA-TecDoc-1854; 2018); "Advances in Small Modular Reactor Technology Developments, A Supplement to IAEA Advanced Reactors Information System" (ARIS) 2018 and 2020 editions. See also https://www.iaea.org/newscenter/news/ what-are-small-modular-reactors-smrs

[4] There is one exception – Rolls Royce's 470 MWe SMR. IAEA, "Advances in Small Modular Reactor Technology Development," 2022 edition, A supplement to: Advanced Reactor Information Systems (ARIS).Available at: https://aris.iaea.org/Publications/SMR_booklet_2022.pdf Hereafter SMR booklet 2022.

[5] Two exceptions are France and Germany, both of which moved up the economy of scale curve very quickly.

[6] The general rule of thumb developed is that no single reactor should provide more than 10% of total grid capacity to minimize risk of grid failures should a single plant shut down unexpectedly. IAEA, Electric Grid Reliability and Interface with Nuclear Power Plants, IAEA Nuclear Energy Series, No. NG-&-3.8, 2012, p. 61. available at: https://www-pub.iaea.org/MTCD/Publications/PDF/Pub1542_web.pdf

[7] International Atomic Energy Agency, "Small and Medium Power Reactors: Project Initiation Study Phase I," IAEA-TECDOC-347, Vienna, Austria, July 1985.

In the early 2000s, renewed hopes for industry growth were pinned on a nuclear renaissance. Surging electricity demand would spur new construction in Asia beyond China, Japan and South Korea, and the need to decarbonize would make nuclear energy attractive.[8] The rising tide of energy demand, however, failed to lift the nuclear boat: as a share of global electricity generation, nuclear energy peaked at 17.5% in 1996 and now hovers slightly below 10%.[9] Electricity demand in Asia outpaced nuclear construction, which in turn could not keep pace with the need to decommission aging reactors elsewhere. The 2011 Fukushima accident also delayed ongoing and new construction in many countries for a few years.

Adapting nuclear energy to the particular demands and challenges of developing countries sparked interest in small reactors that could be modularly constructed and/or deployed. The IAEA came to describe SMRs by 2020 as systems "whose components and systems can be shop fabricated and then transported as modules to the sites for installation as demand arises."[10] Understanding why the term "modular" is routinely and indiscriminately applied to these reactors is extremely important to understanding the appeal of SMRs.

Modular construction implies cost-savings. Large reactor projects typically require significant on-site construction. While specialty components (like reactor pressure vessels, turbines, etc.) are fabricated off-site, they are typically assembled, welded, and tested on-site. Design changes often contribute to considerable delays, which raise financing costs, already one of the major cost-drivers in nuclear plant construction. Off-site construction and assembly allows greater process control, theoretically simplifying and speeding deployment. Smaller-sized reactors could be either partially assembled or fully assembled off-site and transported to the reactor site.

The concept of modular construction is nothing new, even for nuclear power. Both the United States and the Soviet Union constructed and operated transportable reactors for naval and military purposes in the 1950s and 1960s. It is no accident that the only modularly constructed reactor operating commercially so far is the Russian floating barge, *Akademik Lomonosov*.[11]

Modular manufacturing for land-based nuclear power plants has not been as successful. In the United States, problems with modular construction are now widely recognized as a contributing factor in the failure of the V.C. Summer project in South Carolina in 2017 and the extensive delays and cost overruns at the Vogtle plant in Georgia. In fact, the Shaw Group's failure to modularly produce key components for new AP1000 reactors in those two states was a key factor in Westinghouse's 2017 bankruptcy.[12]

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[8] John Ritch, "The Future Of Nuclear Energy In An Era Of Environmental Crisis And Terrorist Challenge," Remarks by John Ritch, Director General, World Nuclear Association, IAEA Symposium on Verification and Nuclear Materials Security, Vienna, 1 November 2001, IAEA-SM-367/19/01, available at: https://www-pub.iaea.org/MTCD/publications/PDF/ss-2001/PDF%20files/Session%2018/Paper%2018-01.pdf

[9] Mycle Schneider and Antony Froggatt, *World Nuclear Industry Status Report 2022*, p. 17

[10] The designer of the reactors, OKB Afrikantov, has been building naval propulsion units since 1945, and is responsible for at least seven of the nineteen SMR designs on offer from Russian vendors. IAEA, SMR Booklet 2020; available at: https://aris.iaea.org/Publications/SMR_Book_2020.pdf

[11] IAEA, "Status of Small and Medium Sized Reactor Designs," A Supplement to the IAEA Advanced Reactors Information System (ARIS) available at: https://aris.iaea.org/Publications/smr-status-sep-2012.pdf

Modularity can also refer to deployment of reactor "packages." The idea is that once an SMR package is procured (possibly two, four, six or twelve reactors for the NuScale VOYGR), a utility could add identical capacity to match electricity demand as it grows. Adding capacity at a power plant site would be predictable, because of experience operating standardized units. The appeal of "plug-n-play" is high in an industry where building to unique site specifications has resulted in rising costs over time rather than declining costs. This is the exact opposite of what should occur as experience is gained. It is not clear whether the plug-n-play approach will lower costs, given uncertainties about how control rooms and emergency planning might be able to accommodate additional modules.[13]

Advocates have even suggested that "plug-n-play" also can be applied to decommissioning: "The 'plug and play' nature of small modular reactors may allow for the 'unplugging' and storage of an entire module upon decommissioning, thus reducing much of the energy and material demands of the decommissioning process."[14] These same advocates have suggested the reactor and waste could be shipped back to the manufacturer to "reduce costs and scope of activities on the locality, increase nuclear and radiation safety and acceptance of SMR use."[15]

In other words, suppliers would not only take waste back but the reactor itself. Given that few countries have proven their ability to take back commercial spent fuel (the Soviet Union notwithstanding), this is a highly doubtful proposition.[16]

Frequently, SMRS are described as new and/or advanced. Yet the 83 SMR designs in an IAEA 2022 catalogue feature quite a few that have been in development for decades.[17] For example, Argentina's 32-MWe CAREM reactor was publicly announced in 1984, but the first concrete was only poured in 2014 and first criticality is now targeted for 2027.[18] And the IAEA catalogue admits that "Not all small reactor designs presented can strictly be categorized as SMRs. Some strongly rely on proven technologies of operating large capacity reactors, while others do not use a modular or integral design approach."

Enhanced safety is another feature frequently attributed to SMRs. Designers claim that smaller reactors allow for integral designs (where high pressure primary cooling loops can be placed inside the pressure vessel) that can lower the risk of loss-of-coolant accidents and that smaller reactors also can make better use of passive cooling. The U.S. Department of Energy stops short of endorsing SMRs as inherently safer, although it states that "advanced SMRs are a key

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[12] Tom Hals and Emily Flitter, "How two cutting-edge U.S. nuclear projects bankrupted Westinghouse," *Reuters*, May 2, 2017, available at: https://www.reuters.com/article/us-toshiba-accounting-westinghouse-nucle/how-two-cutting-edge-u-s-nuclear-projects-bankrupted-westinghouse-idUSKBN17Y0CQ/ Reportedly, quality assurance problems and lagging production forced the subcontractor to outsource modular construction to other factories, leading to the company's acquisition by Chicago Bridge & Iron, which was then taken over by Westinghouse.

[13] "US NRC Approves emergency planning rule for SMRs," August 17, 2023, *Nuclear Engineering International*, available at https://www.neimagazine.com/news/newsus-nrc-approves-emergency-planning-rule-for-smrs-11080971. A 2023 Nuclear Regulatory Commission rule facilitated this approach by lowering emergency planning requirements for SMRs, adopting "a technology-inclusive and consequence-oriented approach," that includes "a scalable method to determine the size of the offsite emergency planning zone around a facility." But it is by no means clear this approach will ever prevent the offsite release of radiation in the event of an accident.

[14] See SMR Booklet 2022, available at: https://aris.iaea.org/Publications/SMR_booklet_2022.pdf, p. 393.

[15] Ibid, p. 391.

[16] The United States decommissioned and removed the PM-3 reactor at McMurdo Station in Antarctica in 1979, but this was not a commercial reactor and therefore subject to different cost, safety, liability, environmental, and waste constraints than would be the case for future commercial SMRs. See "McMurdo Station Reactor Site Released For Unrestricted Use," *Antarctic Journal of the United States*, Volume XV, No. 1. March 1980.

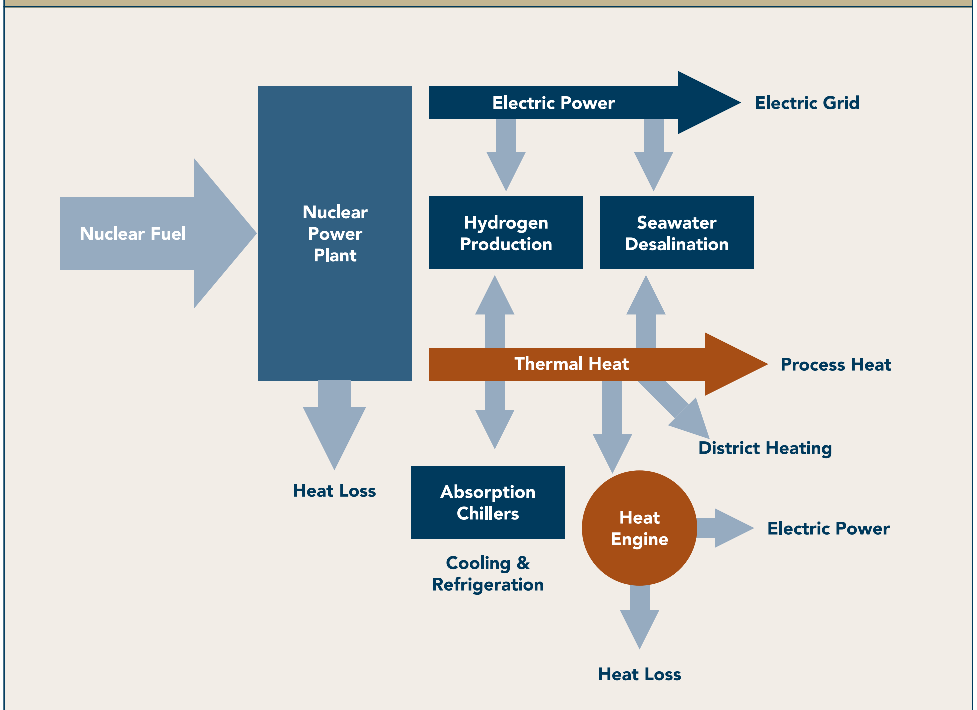
[17] See SMR Booklet 2022, available at: https://aris.iaea.org/Publications/SMR_ booklet_2022.pdf

[18] "The Carem in Argentina is a very important project in developing nuclear energy using small plants," October 21, 2022 in Gateway to South America newsblog, available at: https://www.gatewaytosouthamerica-newsblog.com/the-carem-in-argentina-is-a-very-important-project-in-developing-nuclear-energy-using-small-plants/

part of the Department's goal to develop safe, clean and affordable nuclear power options." Further, DoE suggests that SMRs offer "distinct safeguards, security and nonproliferation advantages." The IAEA suggests that enhanced safety performance is one of the "key driving forces of SMR development," along with "fulfilling the need for flexible power generation for a wider range of users and applications, replacing ageing fossil-fired units… and offering better economic affordability."

Although simplified designs can reduce opportunities for component failure, enhanced safety is unlikely to drive widespread deployment, and the increased unit cost of producing electricity from small reactors works against it. This is perhaps why vendors and governments have been eager to promote SMRs for a variety of other uses, for example, providing a source of cogeneration for industry, military, and the general public. The diagram below shows different cogeneration options for nuclear energy, including electricity, district heating, industrial heat, hydrogen production, and desalination.

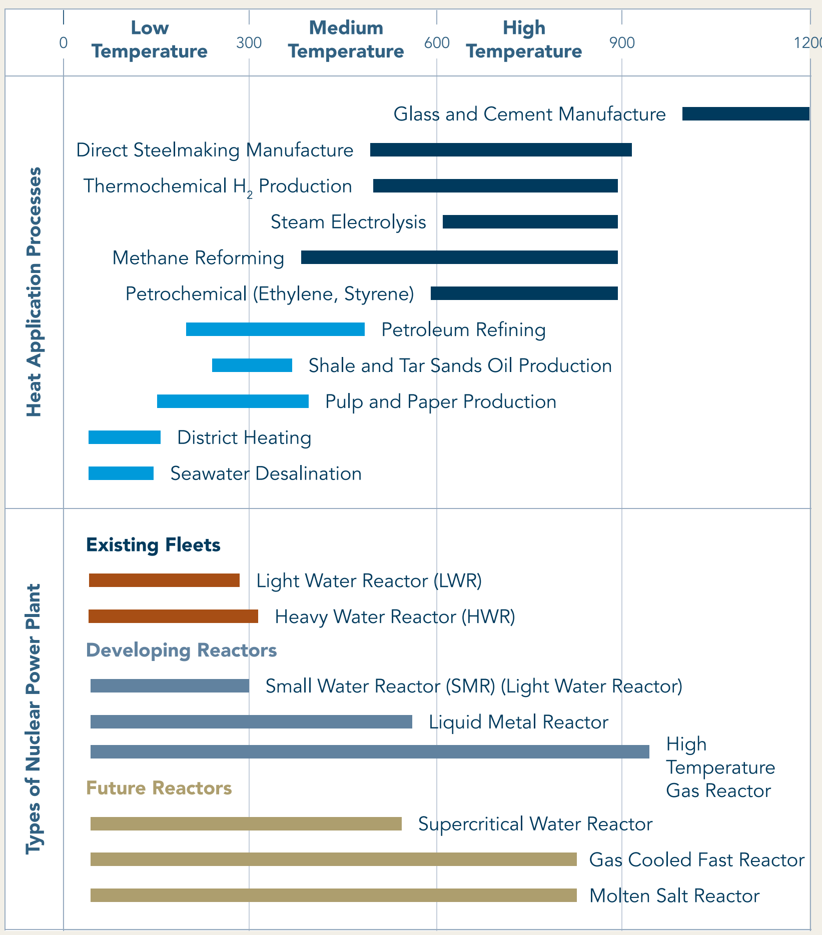
Figure 1: Nuclear Energy Multi-Tasking: Cogeneration



Source: International Atomic Energy Agency, https://www.iaea.org/topics/non-electric-applications/industrial-applications-and-nuclear-cogeneration

Cogeneration is neither new nor unique to nuclear energy. Eighteen of the 434 nuclear power reactors worldwide have been used to cogenerate power for desalination plants (mostly in Japan and one in the U.S.); 56 cogenerated electricity and district heat (mostly in Russia and Ukraine); and four produced electricity and process heat (now three).[19] Those numbers are low because in most cases it has been cheaper to use fossil fuels for those co-generation tasks. In the case of district heating, diverting energy away from electricity to heat production makes economic sense only in climates with persistent cold temperatures, such as Russia and Ukraine. An additional obstacle to cogeneration from large nuclear power plants is the lack of economic means of transporting steam over long distances. SMRs, if they could be safely deployed in urban areas, would not face this additional tax, but their cost-effectiveness would be challenged in other ways.

Figure 2: Temperature Ranges Of Heat Application Processes And Types Of Nuclear Power Plants



Source: World Nuclear Association and IAEA's Opportunities for Cogeneration with Nuclear Energy, May 2017.

Figure 2 shows the kinds of reactors that will be required to replace fossil fuels in industrial processes and hydrogen production. Existing light water reactors now are only able to provide district heating and desalination. Reactors will need to produce higher temperatures for other industrial applications. This would require a widespread deployment of fast reactors such as high temperature gas reactors, molten salt reactors and liquid metal reactors. These all come with technical and safeguards challenges.

[19] IAEA Nuclear Energy Series, "Opportunities for Cogeneration with Nuclear Energy," No. NP-T-4.1, 2017, available at: https://www-pub.iaea.org/MTCD/Publications/PDF/P1749_web.pdf

Increasingly, SMRs are marketed for their supposed flexibility – increasing or decreasing power according to demand (known as load-following) or turning on or off quickly. Yet nuclear power plants have not been as inherently flexible as other sources of electricity generation. The IAEA has acknowledged that "frequent operation in load-following or automatic frequency control modes leads to poorer reliability of the nuclear plant, less efficient use of the nuclear fuel, increased maintenance requirements and possibly shorter plant life."[20] Moreover, in the event of grid faults or failures (e.g., severe weather, equipment faults, human error or malicious acts) that result in a blackout, nuclear power reactors require off-site power to restart and therefore need to be paired with other generation sources that have "blackstart" capability. It may take several days, in fact, to bring such reactors back on-line.[21]

Similarly, the U.S. Department of Energy declared that "there are no technical or safety-related impacts in operating power reactors this way, [but] there are some limitations. Operators can't flex power output as much toward the end of the fuel cycle and it takes a lot of planning, forecasting and time to decrease the power output." [22] DoE's solution to flexibility is for SMRs to operate independently of each other and produce different products (steam, hydrogen, purified water) simultaneously. Former Chairman of the U.S. Nuclear Regulatory Commission Dr. Allison Macfarlane noted that some SMRs (like TerraPower's Natrium) will seek to combine energy storage into their designs to enhance their ability to add power when needed. But she noted that this will increase the reactor's cost.[23]

Lastly, the U.S. Department of Energy has suggested that "From remote islands to the heart of an urban city, nuclear can flexibly meet any communities' energy needs." Historical experience in the United States suggests otherwise: Small reactors were neither successful nor cost-effective in remote locations or more populated communities.[24] This has not kept the Energy Power Research Institute (EPRI) and industry from promoting microreactors for district energy systems (so-called NuIDEA).[25] EPRI's plan envisions using 5 microreactors (roughly 10MWe or 20MWt) at each site to supply steam-generated heat, cooling and water for connected buildings at airports, college campuses, municipalities, and healthcare, government and military facilities.

This likely will be an uphill climb. Despite operating the world's largest nuclear fleet, the United States has only one reactor (Diablo Canyon) that has provided electricity and desalination and none that has provided district heating. Although there are more than 660 district energy systems operating in the United States, few present the right economics for large nuclear cogeneration plants.[26] Smaller plants sprinkled among population centers might overcome the costs of heat transportation but technical issues like the availability of large dual-purpose turbines to produce electricity and extract steam at suitable temperatures and pressures may continue to persist.[27]

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[20] IAEA Technical Document, "Electricity Grid and Integration of Nuclear Power Plants," 2012.

[21] The August 14, 2003 blackout affected 9 US reactors and 11 Canadian reactors, which automatically shutdown. They reconnected to the grid in a period ranging from 3 to 11 days. Four reactors disconnected but then were able to provide reduced power within 6 hours. See U.S.-Canada Power System Outage Task Force, "Final Report on the August 14th 2003 Blackout in the United States and Canada: Causes and Recommendations," April 2004, available at: https://www.energy.gov/oe/articles/blackout-2003-final-report-august-14-2003-blackout-united-states-and-canada-causes-and

[22] https://www.energy.gov/ne/articles/3-ways-nuclear-more-flexible-you-might-think

[23] Statement during virtual symposium, "US-Japan Nuclear Energy Cooperation in Fast Reactors" co-hosted by the New Diplomacy Initiative and George Washington University, held on March 10, 2023. Video available at: https://www.youtube.com/watch?v=GhxP7VYrqEk

[24] M.V. Ramana, "The Forgotten History of Small Nuclear Reactors" IEEE Spectrum, April 27, 2015, available at: https://spectrum.ieee.org/the-forgotten-history-of-small-nuclear-reactors

[25] Electric Power Research Institute, "NuIDEA Action Plan," February 2023, available at: https://www.epri.com/research/products/000000003002026195

[26] Energy Information Administration, "US District Energy Services Market Characterization," February 2018, available at: https://www.eia.gov/analysis/studies/buildings/districtservices/pdf/districtservices.pdf

[27] Ishai Oliker, "District Heating Supply from Nuclear Power Plants: Technical and Economic Aspects," *Power*, March 1, 2022, available at: https://www.powermag.com/district-heating-supply-from-nuclear-power-plants-technical-and-economic-aspects/

Despite a wealth of ideas, just two commercial reactors are now operating that could be considered SMRs – the high- temperature, gas-cooled reactor built by China, the HTR-PM, and a Russian floating nuclear power barge, the Akademik Lomonosov.[28] These reactors likely are not representative of the future fleet of SMRs for many reasons but nonetheless demonstrate the overall challenges inherent in promoting SMRs.

China's HTR-PM is a two-unit demonstration power reactor based on a smaller test reactor, the HTR-10, that has operated for twenty years.[29] Each reactor has a capacity of roughly 100 MWe, and modules for two (200 MWe), six (600 MWe), and ten (1000 MWe) reactors have been proposed.[30] However, only one of the two 100-MWe units was connected to the grid briefly in 2021.

The HTR-PM began on-site construction in 2012, after years of equipment installation and testing. Asked in 2020 why several target dates were missed, a Tsinghua engineer involved in the project pointed to problems in the "fabrication of the components." The engineer provided no further details but there was speculation that he might be referring to difficulties producing steam generators suitable for the high-temperature conditions.[31]

The so-called "pebble bed" design of the HTR-PM uses uranium enriched to 8.5% in U-235 in the shape of spherical balls coated in carbon. Two proliferation risks stand out: the higher enrichment increases the attractiveness of the material for either further enrichment or use in a nuclear weapon, and the fuel fabrication, spent fuel storage and reprocessing (if any) will be more challenging to monitor than is typical for current light water reactors. Safeguarding the reactor itself (not done in the case of China, which only applies safeguards voluntarily as a state with nuclear weapons) may be more difficult because the reactor features on-line fueling; a 2009 U.S. national laboratory report concluded that pebble-bed reactors fell between IAEA definitions of item facilities (reactors) and bulk handling facilities (such as enrichment and reprocessing plants). Bulk handling facilities require more inspection days because the processes are more complicated. The 2009 lab report suggested devising new criteria and approaches. The same issues affect the HTR-PM's spent fuel, which is stored on-site. The 2009 report concluded that "The fissile isotope content per pebble (especially Pu-239) are small but sufficiently large to be attractive to a would-be proliferator."[32]

The other SMR reactors in operation are Russia's 40 MWe light water reactors paired on the floating barge, *Akademik Lomonosov*. While floating nuclear barges may solve one issue that some countries face – scarce land for nuclear power plants that require large emergency planning zones – they may create others. Tethered down far out in the ocean, they might be invulnerable to tsunamis, but closer to shore they could be inundated.[33] There are potential risks of ship collisions if located close to shipping lanes. The storage of spent fuel and radioactive

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[28] The IAEA lists two other high-temperature gas-cooled reactors as operating, but both of these are older test reactors, one in Japan (HTTR, operating since 1999) and one in China (HTR-10, operating since 2003 at Tsinghua University).

[29] The HTR-10 began development in 1992, reaching operating capacity in 2003; the HTR-PM project was launched in 2001, with the first concrete poured in 2012, installation of reactor pressure vessels in 2016, and the initial operation of one reactor in 2021.

[30] IAEA, SMR Booklet 2022 edition, p. 146.

[31] Phil Chaffee, "China:HTR-PM Commissioning Pushed Back to 2021," *Energy Intelligence*, June 23, 2020, available at: https://www.energyintel.com/0000017b-a7da-de4c-a17b-e7daeb400000

[32] Philip Casey Durst, David Beddingfield, Brian Boyer, Robert Bean, Michael Collins, Michael Ehinger, David Hanks, David L. Moses, Lee Refalo, "Nuclear Safeguards Considerations for the Pebble Bed Modular Reactor (PMBR)," October 2009, Idaho National Laboratory, available at: https://inldigitallibrary.inl.gov/sites/sti/sti/4374060.pdf

[33] The French Flexblue proposed a control room on land, but the submerged nuclear cylinder could have been unmoored or damaged in a tsunami.

wastes present another potential risk and/or target. "Radioactive leaks to the environment could cause serious hazards for human and the ocean's ecological system if the vessel carrying this plant is rammed by a ship at high speed, or its hull is destroyed in turbulent weather, or if the vessel itself is scuttled in shallow or deep waters."[34] The South China Sea, which accounts for a third of global shipping, would pose considerable risks for floating nuclear power plants.

With no natural defense barriers, floating nuclear power plants are open to attack either from the surface of the sea or beneath it. Pirates, terrorist groups or other non-state actors could threaten damage for purposes of coercion or blackmail or steal radioactive material for eventual use in a dirty bomb.[35]

The two SMRs operating currently do not show appreciably shorter incubation periods than their larger cousins. The HTR-PM took nine years from design to grid connection, relying on the earlier HTR-10 test reactor begun in the 1980s but it is still not commercially operated, and the second unit has yet to be connected to the grid; the Akademik Lomonosov took more than 12 years from design to grid connection, even though its reactor design rested on two generations of designs, most recently from 1980-vintage nuclear-powered icebreakers. In the United States, the vendor NuScale took four years to obtain design approval, certification and licensing, and the first VOYGR unit was expected to reach operational capacity by 2029 – a total of 13 years from start to finish (although some date the start of the project from 2000).[36] The cancellation of the NuScale project in Utah in late 2023 leaves the company with two foreign projects – one in South Korea and the other in Romania – that have been heavily subsidized NuScale currently estimates manufacturing to take 42 to 54 months, or 3.7 to 4.5 years. This is about on par with the shortest construction times demonstrated by Korean and Chinese vendors building nuclear reactors on-site.[37]

The two SMRs operating currently do not show appreciably shorter incubation periods than their larger cousins.

[34] V.F. Demin, and V.P. Kuznetsov, "Issues of insurance of civil liability for nuclear damage from nuclear low power plants," *Proceedings of the ASME 2014 Small Modular Reactors Symposium SMR2014*, April 15-17, 2014, Washington, DC, USA.

[35] M.J. Ford, A. Abdulla, and M.G. Morgan, "Evaluating the cost, safety, and proliferation risks of small floating nuclear reactors," *Risk Analysis* 37:11, 2017

[36] David Schlissel and Dennis Wamsted, "NuScale's Small Modular Reactor," Institute for Energy Economics and Financial Analysis (IEEFA), February 2022, available at: https://ieefa.org/wp-content/uploads/2022/02/NuScales-Small-Modular-Reactor_February-2022.pdf?

[37] Schneider and Froggatt, *World Nuclear Industry Status Report 2022*, p. 55.

Table 1 arrays the current 83 proposed reactors by type and design stage, drawing from information the IAEA compiled from vendors. At the end of 2022, three SMRs were operating; one was close to operational, three were under construction and two were manufacturing equipment for assembly. One floating reactor was in the licensing stage. In short, only ten reactor designs of more than eighty have progressed beyond the design stage with a third of them roughly a decade from operation.

Table 1: Types of SMRs According to Design Stage

Stage	P(H)WR	BWR	"Floating"	HTGCR	Liquid Metal FR	Molten Salt FR	Micro-reactors	Total	Years to operation
Pre-Conceptual Design				1		2	2	5	25-30
Conceptual Design	6	2	1	6	4	6	5	30	17-20
Conceptual Design Completed	2						1	3	15-17
Preliminary Design				1	1			2	15-17
Preliminary Design Completed	1			2		2		5	15-17
Basic Design	4		2	3		1	1	11	10-15
Basic Design Completed			1					1	10-15
Detailed Design	4	2	1	1	2	2	2	14	10-15
Detailed Design Completed	1							1	10
Final Design			1					1	7-10
Licensing Stage			1					1	7-10
Equipment Manufacturing in Progress	1						1	2	7-10
Under Construction	2				1			3	5
Operable				1				1	1
In Operation			1	2*				3	0
Total	21	4	8	17	8	13	12	83	

PHWR – Pressurized Heavy Water Reactor; BWR – Boiling Water Reactor; HTGCR – high temperature gas-cooled reactor; FR – fast reactor
* One of these is a Japan's HTTR, which has been operating since 1999 as a prototype, and the other is China's HTR-10, in operation since 2000.
** Author's estimates. Actual time varies significantly with licensing and manufacturing experience, subject to financing delays
NB: Reactor designers use different categories. According to CANDU Energy Inc, Conceptual Design precedes contract & can be completed within 1 year, followed by detailed design completion (+3 yrs); construction start (+5 years); Initial operation (+8 years). CNNC suggested 8 years between conceptual and basic design of its CAP-200; SPIC (China) suggests 10 years between concept design and start of construction (lasting 2yrs. NUWARD's schedule: Yr 0 Preliminary design; Yr 5 Preconceptual design; Yr 7 Conceptual Design; Yr 11 Basic Design; Yr 13 Commercialization; Yr 14 Detailed Design; Yr 18 First concrete. NUWARD is a light water reactor design with 2 reactors, designed for cogeneration and load-following.

SMRs are unlikely to be built in quantities that will revolutionize nuclear energy. Advocates maintain that SMRs based on well-understood light water reactor technology are a "short-term answer to the high capital costs and long construction times that currently hamper new nuclear builds, especially in Europe."[38] Yet, even the current light water reactor SMR designs are not appreciably further in their development compared to their more exotic counterparts (Table 1).

Because nuclear energy's global market share (10%) of electricity is now less than half that of renewables (26%), there are incentives to market nuclear power as complementary to intermittent renewables. In the past, advocates promoted nuclear power as the only scalable, baseload generation that could replace fossil fuels. For countries with significant investments in intermittent renewables, however, SMR designs capitalizing on flexibility, new applications and locations, especially remote ones, may be more appealing than large baseload-generating reactors.

Countries that already deploy nuclear power might build or purchase SMRs for niche markets. For example, China may build floating nuclear power reactors or microreactors for artificial islands in the South China Sea and could export some of these. Russia, China, and the US may build microreactors for remote locations or for military purposes. Industrial entities may be interested in high-temperature SMRs to meet their carbon neutrality goals, but any large-scale deployment would likely need significant commitments by governments to handle the spent nuclear fuel. Yet such niche applications won't triple nuclear energy capacity.

Increasingly, advocates have suggested replacing coal-plants with SMRs. The United States is funding feasibility studies as part of Project Phoenix, proposed by Climate Envoy John Kerry at COP27, to speed the clean energy transition by converting coal plants to "reliable and safe zero-carbon SMR nuclear energy generation."[39] The potential market is huge, since coal plant capacity outnumbers that of nuclear energy by a factor of five.[40]

The costs of such an approach will be enormous. In the United States, for example, the smallest coal plant would require a 6-pack of NuScale VOYGR SMRs, now estimated to cost $9.3 billion.[41] As noted earlier, at least one NuScale project in the United States has been cancelled for reasons of cost. Other countries and other technologies may find a way to make this more cost-effective.

That said, SMR construction in states that currently deploy large reactors is not likely to transform the economics of nuclear power from economies of scale to economies of numbers. For that, countries new to nuclear power – some 150 – would need to buy SMRs in large quantities.

SMRs are unlikely to be built in quantities that will revolutionize nuclear energy.

[38] Lorenzo Malerba, Abderrahim Al Mazouzi, Marjorie Bertolus, Marco Cologna, Pai Efsing, Adrian Jianu, Petri Kinnunen, Karl-Fredrik Nilsson, Madalina Rabung and Mariano Tarantino, "Materials for Sustainable Nuclear Energy: A European Strategic Research and Innovation Agenda for All Reactor Generations," *Energies*, Vol 15, 1845, 2022.
[39] See website: https://www.state.gov/project-phoenix/ ; accessed March 4, 2024.
[40] Coal plant produce 2000 GWe compared to nuclear's 377 GWe. China built half of the coal capacity; the US has twice the coal capacity as nuclear.
[41] https://ieefa.org/sites/default/files/2023-01/UAMPS%20Talking%20Points%20_%20Class%203%20_%2020230102%20_%20Final.pdf

One Princeton University analysis assessed that with a learning rate of 10% (assuming this rate kicks in once 10 plants have been manufactured), 700 plants would need to be produced before the benefits of serial production outweigh the penalties suffered from the diseconomy of scale.[42] To put this in perspective, this is roughly the total number of commercial nuclear power reactors ever built. If each plant produced 200 MWe, 700 plants would only produce 140 GWe (about one-third the current global capacity. If the learning rate in manufacturing is smaller, many more plants would need to be built to achieve the break- even point with larger reactors. With a 5% learning curve, "the costs of large and small units cross only after 60,000 small units have been produced."[43]

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[42] The main cost of generating electricity from nuclear power depends on the capital cost of constructing the plant. However, a plant one-fifth the size of a larger one is not 5x less expensive to build, thus it suffers a diseconomy of scale that can be overcome by producing many such plants.
[43] Alexander Glaser, MV Ramana, Ali Ahmad and Robert Socolow, "Small Modular Reactors: A Window on Nuclear Energy," An Energy Technology Distillate from the Andlinger Center for Energy and the Environment at Princeton University, June 2015. Available at: https://acee.princeton.edu/distillates/small-modular-reactors/

The proliferation of nuclear weapons is the key national security risk associated with nuclear energy. But nuclear power plants also pose risks for nuclear terrorism and have been targeted for sabotage, coercion, and military operations. A less acute but persistent national security challenge is dependence on foreign suppliers.

To date, treaties, agreements, inspections, and monitoring together have managed these risks, but the concentration of nuclear power worldwide has helped. A different future is being charted that is likely to feature much less cooperation and potentially greater dispersal of nuclear capabilities across the globe. Small modular reactor designs do little to reduce the existing national security risks of nuclear power and may in fact increase those risks under some circumstances.

Proliferation and nuclear terrorism risks. Misusing materials, equipment, technology, and skills acquired for peaceful purposes to support and build a nuclear weapons program is the most prominent national security risk associated with the spread of nuclear power. The larger and more sophisticated a nuclear energy program is, the easier it is to use facilities and equipment for malign purposes without detection. Over time, the risks of commercial reactors have been downplayed relative to the risks of fuel cycle facilities like uranium enrichment and spent fuel reprocessing. Government officials largely have convinced themselves that as long as states only buy reactors, and don't dabble in fuel-making processes, they can avoid the emergence of new nuclear weapon states.

And yet Iran has demonstrated the weakness of this thinking. Iran never purchased uranium enrichment equipment openly; instead, it procured blueprints from Pakistan and supporting technologies to produce uranium compounds essential to uranium conversion and enrichment from China.[44] Many of its purchases were legal, although not checked for end-uses. The blueprints from the Pakistani A.Q. Khan network helped Iran cobble together a shopping list of components. Iran fell afoul of the Nuclear Nonproliferation Treaty by failing to declare activities and imports, but it had (and has) every right under that treaty to enrich uranium if it complies with its nuclear safeguards agreement.

The lack of an absolute prohibition on the further spread of enrichment and reprocessing capabilities remains a challenge for the nonproliferation regime. Even the United States reportedly was considering supplying Saudi Arabia with a uranium enrichment plant as part of a deal for political rapprochement between Saudi Arabia and Israel in mid-2023. Temporarily derailed by the conflict in Gaza, such a deal would have overturned decades of U.S. policy not to further spread enrichment or reprocessing technologies and provide Saudi Arabia with a latent capability for nuclear weapons.[45]

Although states within the nonproliferation regime largely have restricted sharing sensitive technology, states outside the regime (India, Pakistan, Israel, North Korea) are not bound by norms of non-transfer. North Korea once supplied Syria with a plutonium-production reactor and it could provide enrichment or reprocessing advice, assistance, or equipment to other states. Likewise, there are no restrictions on new types of reactors or fuels, including breeder reactors that create more plutonium than they consume.

[44] David Albright and Corey Hinderstein, "The centrifuge connection," *Bulletin of the Atomic Scientists*, March/April 2004, Vol. 60, No. 2, pp. 61-66, available at: https://journals.sagepub.com/doi/pdf/10.2968/060002017#:~:text=China%20was%20the%20most%20important,corrosive%20gas%20used%20in%20centrifuges.

[45] Sharon Squassoni, "Nuclear Mirage: US Nuclear Cooperation with Saudi Arabia," *Arms Control Today*, December 1, 2023, Volume 53.

The risks of diversion and misuse also apply to non-state actors and terrorists.[46] Commercial nuclear power plants are a relatively unattractive target for terrorists seeking material for radiological dispersal devices compared to less well-secured facilities using radiation sources like hospitals, but they are potentially a source of material for diversion, particularly if stocks of fresh fuel (preferably highly enriched uranium, or HEU) are on hand. Obviously, enrichment and reprocessing facilities are the best sources from which to divert material, but there are fewer of these sites around the world.

Sabotage. The risk of sabotage of nuclear power plants is well-known and well-documented over the seventy years of commercial nuclear power operations. At its worst, a successful attack could cause billions of dollars in damage, produce casualties, early fatalities and delayed fatalities numbering in the tens to hundreds of thousands of people, and contaminate large areas of land for months to decades. Panic, disruption of electricity supply and temporary or permanent shutdowns of nuclear power plants in that country and perhaps around the world (akin to what happened in the wake of Fukushima Daiichi powerplant meltdowns in 2011) could ensue. A 2002 U.S. National Academy of Sciences report suggested that while it would not be easy to attack a nuclear-energy facility so that it releases large amounts of radioactivity, it is not impossible and "may not even be unlikely over the course of time unless additional protective measures are taken that can offset the likely increases in the capabilities of terrorists."[47]

National-level nuclear regulations generally require powerplant operators to defend against insider and outsider threats. Most nuclear power facilities have multiple barriers, guard forces and "hard target" characteristics designed to make them difficult to breach from the outside.[48]

Experts have noted however that "in the event that a determined and knowledgeable saboteur gains access to a nuclear power plant, all theoretical calculations concerning reactor reliability become meaningless."[49] Fortunately, most saboteurs have been more determined than knowledgeable, and the damage done by the dozens of attacks against nuclear power plants over the decades globally has been limited.[50]

Coercion. Domestic actions against nuclear facilities for the purposes of coercion are possible, but rare. In the United States, the only recorded incident occurred in 1972 when hijackers of Southern Airways Flight 49 threatened to crash their plane into the High Flux Isotope Reactor at the Oak Ridge National Nuclear Laboratory unless they received $10M.[51] Internationally, Russian military forces in Ukraine obviously have used their control of the Zaporizhzhia nuclear power plant for coercive purposes. Their treatment of nuclear power plant staff, including detaining plant managers at times and psychologically and physically pressuring them, jeopardized the safety and security of the reactors.

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[46] Many studies have documented the national security implications of nuclear terrorism. See Graham Allison, Nuclear Terrorism: the Ultimate Preventable Catastrophe (Harvard University Press, Cambridge MA) 2004 and Matthew Bunn, Securing the Bomb, Report Commissioned by Nuclear Threat Initiative, editions from 2004-2010.

[47] Quoted in Holdren, "Threats to Civil Nuclear-energy Facilities," in Science and Technology to Counter Terrorism: Proceedings of an Indo-U.S. Workshop (Washington, D.C. The National Academies Press, 2007). See also National Research Council, Making the Nation Safer: The Role of Science and Technology in Countering Terrorism, National Academies Press, Washington, D.C. 2002. https://nap.nationalacademies.org/catalog/10415/making-the-nation-safer-the-role-of-science-and-technology.

[48] John Holdren, "Threats to Civil Nuclear-energy Facilities," in Science and Technology to Counter Terrorism: Proceedings of an Indo-U.S. Workshop (Washington, D.C. The National Academies Press, 2007).

[49] John Holdren, "Hazards of the Nuclear Fuel Cycle," *Bulletin of the Atomic Scientists*, Vol. 30, No. 8, 1974, pp. 14-23.

[50] In one year (1975-1976), NRC licensees in the United States received forty bomb threats, a sabotage attempt, a case of arson and three intrusions. J. Samuel Walker, "Regulating Against Nuclear Terrorism: The Domestic Safeguards Issue, 1970-1979," *Technology and Culture*, January 2001, Vol 42, No. 1, p . 125. One database, the Nuclear Facilities Attack Database, lists 80 incidents worldwide between 1961 and 2014 of assaults, sabotages, and unarmed breaches at nuclear facilities; less than half of those occurred at commercial nuclear power plants. https://www.start.umd.edu/nuclear-facilities-attack-database-nufad

[51] The hijackers got $2.5M and landed in Cuba after a 30-hr flight, spending 8 years in Cuban jails, followed by another 20-25 years in U.S. prisons.

Military Operations. Armed insurgent attacks on nuclear facilities have been rare and even rarer against nuclear power plants. Two such incidents include the People's Revolutionary Army seizing the Atucha I plant under construction in Argentina in 1973 and the African National Congress's detonation of four bombs at the Koeberg nuclear power plant under construction in South Africa in 1982. Neither incident resulted in radiological contamination.

Foreign military strikes against nuclear reactors, however, have not been as rare. Iran and Iraq bombed each other's research and power reactors under construction in the 1980s and Israel destroyed Iraq's Osirak reactor in 1981 after Iran failed to destroy it several months earlier. Israel also destroyed a clandestine reactor under construction in Syria in 2007.[52] The United States' bombing of Iraq's two small research reactors at the Tuwaitha Nuclear Research Center during the opening hours of the 1991 war marked the first time an operational reactor had been bombed.[53] But not until Russian forces shelled Ukrainian nuclear power plants in 2022 has an operating commercial nuclear power reactor been attacked. So far, Russia has not sought to destroy the reactors, but instead to co-opt them.

Any kind of nuclear facility may be an attractive military target because of its cost and importance, but large, operating nuclear power plants especially carry the potential for widespread radioactive contamination. This risk is presumably why nuclear power plants were added to the set of prohibitions in the 1977 Protocol Additional to the Geneva Conventions of August 12, 1949. Article 56 states that "nuclear electrical generating stations shall not be made the object of attack, even where these objects are military objectives, if such attack may cause the release of dangerous forces and consequent severe losses among the civilian populations." The same prohibition applies to attacks against military objects near nuclear power plants, with the same proviso.

This may seem airtight, but the prohibition is not absolute. First, it depends on a subjective analysis of whether that attack would cause not just the release of dangerous forces, but also severe losses among the civilian population. Second, paragraph 2(b) of Article 56 grants an exception if the nuclear power plant "provides electrical power in regular, significant and direct support of military operations and if such attack is the only feasible way to terminate such support." Third, acceptance of the 1977 Protocol Additional is not yet universal. The United States, Iran, Pakistan have signed but not ratified the protocol and about twenty other states, including Israel and India, have neither signed nor ratified. Russia signed Protocol I in 1992 and withdrew in 2019.

The United States itself claims that nuclear power plants may constitute military objectives, including for "denial of electric power to military sources, use of a dangerous facility (e.g., by causing release from a dam) to damage or destroy other military objectives, or to pre-empt enemy release of the dangerous forces to hamper the movement or advance of U.S. or allied forces."[54] Such attacks would be permissible as long as they are conducted inline with the principles of discrimination and proportionality; in fact, the United States objected to Protocol Additional I on the grounds that it deviated from the regular application of discrimination and proportionality. In 1985, the United States blocked a vote at the IAEA General Conference on a resolution that called for "the prompt adoption of binding international rules prohibiting armed attacks against all nuclear installations devoted to peaceful purposes." It may be time to revisit this resolution.

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[52] See William Broad, "Decades of Nuclear Reactor Strikes Predate Ukraine Power Plant Crisis," *The New York Times*, October 9, 2022, available at: https://www.nytimes.com/2022/10/09/science/ukraine-nuclear-power-plant-crisis.html

[53] Larry B. Stammer, "Attacks on Reactors Set a Precedent," *Los Angeles Times*, January 26 1991, available at: https://www.latimes.com/archives/la-xpm-1991-01-26-mn-722-story.html

[54] Department of Defense, *Law of Warfare Manual*, 2016, p. 270. https://ogc.osd.mil/Portals/99/department_of_defense_law_of_war_manual.pdf

Commercial power reactors are not designed or regulated to operate in a conflict zone, so the wisest course of action would be to shut them down once conflict erupts. Yet even shutdown reactors require cooling systems that could be endangered in conflict. Ukrainian plants have suffered unstable power frequencies, missile attacks that have damaged power lines, and automatic shutdowns. At Zaporizhzhia, plant managers initially shut down three of the reactors (one was already shutdown for repairs) and operated the other two for as long as possible. Of course, their decisions were not entirely their own because Russians controlled the site.

Figure 3: Russia's Actions Against Nuclear Reactors in Ukraine

Sevastopol Research Reactor. During the takeover of Crimea in 2014, Russia took control of a small research reactor (IR-100, 200 KWe) at the Sevastopol University of Nuclear Energy and Industry. The Ukrainian nuclear regulator, SNRIU, revoked its license.

Chernobyl site. Russian forces invading Ukraine from Belarus on February 24, 2022 captured the Chernobyl nuclear site without damage and forced the 300 staff and associated workers to remain onsite. The site lost offsite power on March 9. Russian forces departed on April 1, 2022 as part of a larger withdrawal from the Kiev area.

Rivne, Khmelnytskyi and South Ukraine plants. Rivne (4 reactors), Khmelnytskyi (2) and South Ukraine (3) sites all operated at full power until November 2022. Two lost transmission lines, requiring reduced operations (South Ukraine) and Khmelnytskyi shut down entirely when missile strikes severed connection to the grid. Drops in power frequency at all three have triggered automatic disconnections from the grid. Rivne and South Ukraine and one reactor at Khmelnytskyi are operating.

Zaporizhzhia site. The largest nuclear power plant in Europe, Zaporizhzhia hosts six 950-MWe commercial nuclear reactors. Russian forces fired on the site on March 4, 2022, causing a fire and then stationed personnel and munitions there, using the nuclear reactors as a shield for offensive operations. Despite the initial fire, no essential equipment was damaged and Ukrainian staff continued to operate units 2 and 4 (unit 1 was out of operation; unit 3 disconnected and moving towards cold shutdown and units 5 and 6 were cooling down). Offsite powerlines were damaged in August, causing SNRIU to order Units 1 and 2 into cold shutdown. Power outages led plant operators to disconnect all reactors from the grid. Connections to the main power line and backup power were cut in November, triggering diesel generators to provide electricity for cooling. In February 2023, SNRIU banned operations at power levels. In 2023, the site suffered 8 losses of external power.

Sources: Nuclear Energy Agency and SNRIU websites. See https://www.oecd-nea.org/jcms/pl_66130/ukraine-current-status-of-nuclear-power-installations and https://snriu.gov.ua/en/timeline?&type=posts&category_id=5

The International Atomic Energy Agency and European Union member states have repeatedly called for Russian forces to vacate Ukraine's nuclear sites and indeed the entire country. In September 2022, the IAEA created guidelines for operating nuclear power plants under armed conflict.[55] The wish-list included physical integrity of facilities, functional safety and security systems and equipment, autonomous operations staff (free from undue pressure), secure off-site power supply, uninterrupted logistical and transportation supply chains, effective on- and off-site radiation monitoring systems (and emergency preparedness and response measures) and reliable communication between the regulator, plant operators and others.[56] In the midst of an ongoing war, however, all of these requirements are obviously difficult to secure. In March 2023, President Volodymyr Zelenskyy told IAEA Director General Rafael Grossi that "Without the immediate withdrawal of Russian troops and personnel from the ZNPP and adjacent territories, any initiatives to restore nuclear safety and security are doomed to failure."[57] In May 2023, Grossi recommended to the UN Security Council that both sides adhere to five principles: no attack from or against the plant; no use of the plant as storage nor as a base for heavy weapons or military personnel; no placing off-site power at risk; protection of all essential structures, systems and components from attack or sabotage; and refraining from any action to undermine these principles.

All wartime scenarios are alarming, whether they include accidental or incidental attacks near operating reactors or targeted actions against nuclear power plants to achieve military tactical and strategic aims. So far, Russia has used operating nuclear reactors to shield Russian forces and equipment, to gain control over Ukraine's energy system, and to gain leverage with European countries fearful of radiation contamination.[58] In short, Russia weaponized Ukraine's nuclear assets, a tactic that perhaps had been contemplated but never before used.[59]

Critics may contend that an active war between two countries with considerable numbers of nuclear power reactors like Russia and Ukraine is unusual, but consider that Pakistan, India, China, North Korea, South Korea, Japan and Taiwan all have unresolved conflicts.[60] Although India and Pakistan have agreed not to attack each other's nuclear facilities, other countries have not made such bilateral commitments. [61]

All wartime scenarios are alarming, whether they include accidental or incidental attacks.

[55] INFCIRC/1019—Communication dated 12 August 2022 from the Delegation of the European Union to the International Organizations in Vienna, "Joint Statement dated 12 August 2022 on the situation at the Zaporizhzhia Nuclear Power Plant." Available at: https://www.iaea.org/sites/default/files/publications/documents/infcircs/2022/infcirc1019.pdf

[56] Reproduced in IAEA, "Nuclear Safety, Security and Safeguards in Ukraine: February 2022-February 2023" on the IAEA website, https://www.iaea.org/

[57] "President met with Director General of the IAEA on the territory of the Dnipro HPP," March 28, 2023, available at: https://www.president.gov.ua/en/news/glava-derzhavi-zustrivsya-z-gendirektorom-magate-na-teritori-81853

[58] Mykhaylo Zabrodskyi, Jack Watling, Oleksandr V Danylyuk and Nick Reynolds, "Preliminary Lessons in Conventional Warfighting from Russia's Invasion of Ukraine: February-July 2022," Royal United Services Institute for Defense and Security Studies, p. 11. available at https://static.rusi.org/359-SR-Ukraine-Preliminary-Lessons-Feb-July-2022-web-final.pdf

[59] Bennett Ramberg, "Military Sabotage of Nuclear Facilities: Implications," *Annual Review of Energy*, 1985, Volume 10; pp. 495-514, available at: https://www.annualreviews.org/doi/pdf/10.1146/annurev.eg.10.110185.002431 See also https://outrider.org/nuclear-weapons/articles/could-nuclear-power-plants-become-radioactive-weapons

[60] Although Taiwan has decided to phase out nuclear power by 2025, some critics have suggested that only nuclear energy can provide sustained power should China blockade Taiwan. Dominic Faulder, "Asia's nuclear power dilemma: Ukraine war drives energy turnarounds," *Nikkei Asia*, April 20, 2022.

[61] Note that China, the ROK and the DPRK are all parties to the Protocol Additional I of the Geneva Conventions.

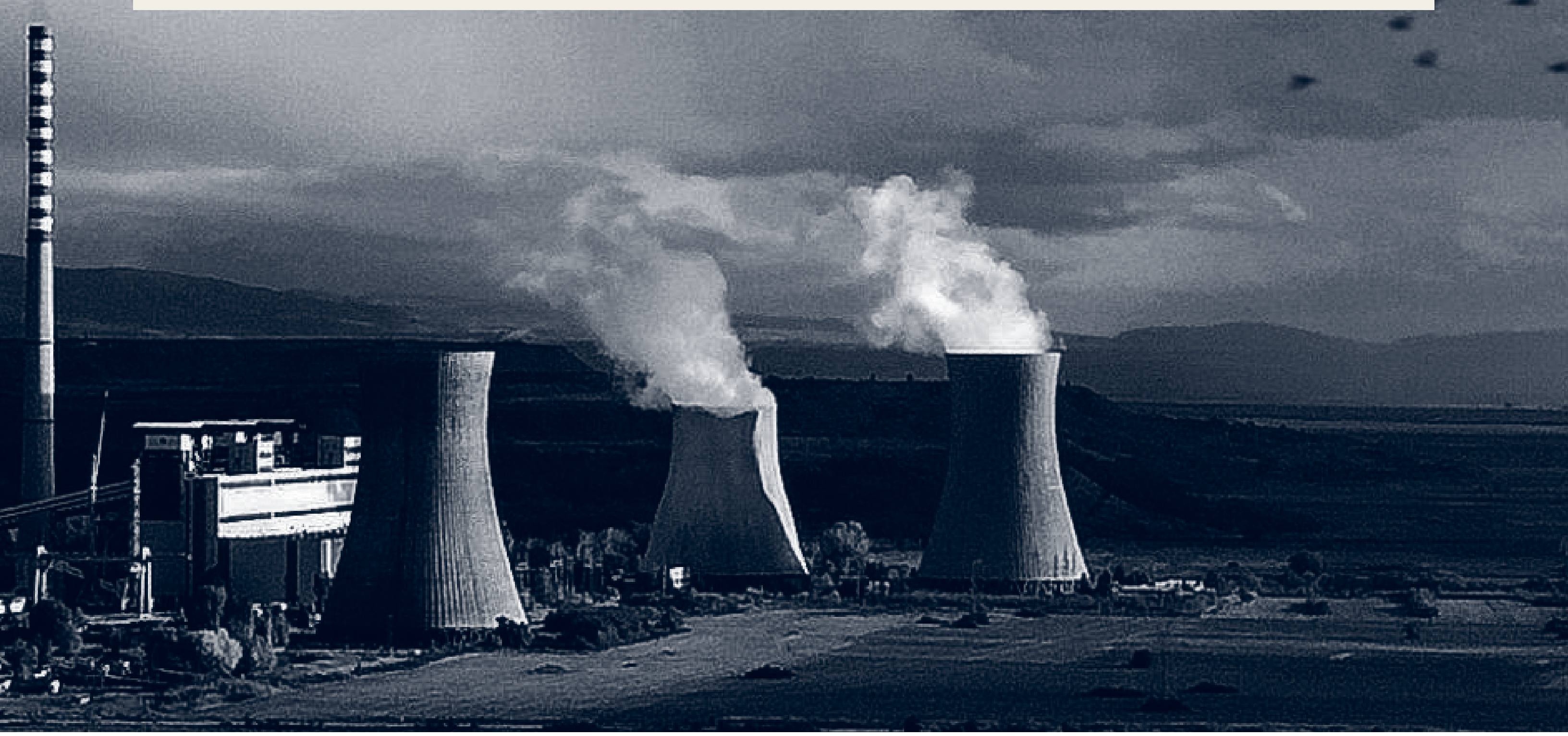
Figure 4: Ukraine: A Few Lessons from Operating Nuclear Power Plants in War Zones

Russia's unprecedent actions at Ukraine's nuclear power plants in 2022 suggests some lessons for the safety and security of nuclear power plants in war zones.

Operating nuclear power plants during a war may be essential but dangerous. In peacetime or in war, reliable electricity saves lives, placing a premium on keeping nuclear power plants operating. However, chaotic environments make it much more difficult and dangerous to operate such plants. Even shutdown plants have residual heat production, which needs to be removed. Systems that rely on active pumps will be at a greater disadvantage. Older plants with significant stores of spent nuclear fuel in pools will also need electricity for cooling.

Vulnerabilities rise as dependence on nuclear power grows. Six of the ten most nuclear-dependent countries are former Eastern bloc states, all of which rely on nuclear power for more than 30% of their electricity: Ukraine (55%); the Slovak Republic (52%); Hungary (46.8%); Slovenia (36.9%); the Czech Republic (36.6%) and Bulgaria (34.6%). High reliance on nuclear power plants increases vulnerabilities generally, but especially in war zones.

Designs may leave safety elements outside of the "fortress." For many large commercial nuclear power plants, some important safety systems are located in the reactor buildings, which may be robustly designed, but probably not bunkered. Some vital safety systems, like parts of the cooling chains or the power supply, transformers, diesel generators for emergency power and their fuel, switchgear, and the control room can be housed in other traditional industrial facilities. All of these can be subject to accidental, collateral, or intentional damage during conflict.



Foreign supply dependence. Countries dependent on foreign sources of oil and gas have come to view nuclear energy as a more reliable alternative to the tyranny of petro-states. But the reliability of nuclear power has specific limits, especially when foreign dependence is unavoidable.

Given the steep barriers to enter the nuclear field, most nuclear newcomers will depend on traditional suppliers of uranium and fuel services to keep costs down. There are not many to choose from. About 90% of the world's reasonably assured uranium supply is concentrated in ten countries, with half coming from two countries --Australia and Kazakhstan.[62] Just five entities worldwide provide uranium conversion services and there are three major commercial uranium enrichment services providers (Orano, Rosatom, URENCO). Only two entities commercially reprocess foreign spent fuel -- Orano in France and Mayak in Russia.[63]

Despite the lack of diversity, nuclear supply has generally been reliable; the few cases of failure were politically motivated. For example, Iran was cut off from its Eurodif uranium enrichment investments and from U.S. reactor fuel supply after its 1979 revolution, and India was cut off (more or less) after its 1974 nuclear test. As long as the supply of sensitive fuel cycle technologies related to uranium enrichment and spent fuel reprocessing are constrained to prevent proliferation, fears of dependence will persist as will efforts to overcome dependence.

The case of Ukraine highlights the risks. Ukraine's reactors were all Russian-designed and fueled with Ukrainian uranium, but dependent on Russian conversion, enrichment, fuel fabrication and reprocessing in the former Soviet Union. In exchange for Ukraine's signature on the Nuclear Nonproliferation Treaty (NPT), Russia promised in 1993 it would continue supplying fuel to Ukraine's 15 reactors. Not trusting Russia, Ukraine quickly campaigned to establish its own fuel cycle facilities, including reprocessing but excluding enrichment facilities because of the cost. However, even efforts to build a fuel fabrication plant failed. In 2005, however, Ukraine began to replace Russian fuel with Westinghouse-fabricated fuel. After Russia invaded Crimea, Ukraine accelerated fuel replacement, switching over entirely in mid-2022.

For other countries, the risks of dependence on Russia for nuclear supply have grown since the Cold War, as Russia has captured more of the global market. Right now Russia is building 17 reactors abroad and 3 at home: 4 each in China and India, 3 in Turkey, 2 each in Bangladesh and the Slovak Republic, and 1 each in Belarus and in Iran. In contrast, China is building 17 reactors at home and none abroad. Both France and South Korea are currently building 2 reactors abroad, in the UK and the UAE respectively.

Beyond reactors, Russia supplies uranium milling, conversion, enrichment and fuel fabrication services. Russia reportedly is the only supplier of conversion services for reprocessed uranium, which can be used in a wide variety of reactors and of high-assay, low-enriched uranium (HALEU) necessary for some reactor designs and isotope production, such as the Natrium reactor scheduled to be built in Wyoming. It is therefore no coincidence that Russian nuclear activities have not been sanctioned as a result of its invasion of Ukraine. Industry officials have suggested it could take several years to replace the capabilities Russia now currently provides. So, while countries may seek to diversify their energy portfolios into nuclear energy in an effort to avoid dependence on Russia, this may not be as simple as it appears.

[62] Sharon Squassoni, *Nuclear Energy: Rebirth or Resuscitation?* Carnegie Endowment for International Peace Report, (Washington DC: 2009).
[63] Russia reportedly only reprocesses spent nuclear fuel for reactors that it has provided.

Figure 5: Poland's Nuclearization

Poland, a non-nuclear NATO country, has moved quickly following Russia's invasion of Ukraine to transition from oil and gas supplied by Russia to nuclear energy. Although it had been gradually reducing oil imports both by choice and necessity, it still imports about 10% of its oil supply from Russia. Poland is also seeking to replace its 33 GWe of electricity generated from coal (which provides 70% of the total) to meet greenhouse gas emission reduction targets and is participating in the U.S. Project Phoenix feasibility study. Poland also announced its intention to partner with the United States in November 2022 to purchase three AP-1000s, with construction estimated to begin in 2026 and the first reactor coming on-line in 2033. A few days later, it announced another partnership with Korean vendor KHNP and a future one may be in the works with France's EDF.

Poland is also pushing ahead with SMR vendors, including Rolls Royce and GE-Hitachi. Officials announced their intention to place 79 BWRX-300s at 25 sites in Poland in the next decade. Deputy Prime Minister Stasin stated, "We need sources of cheap and stable energy in Poland…Nuclear energy is indispensable in Polish conditions, especially in the current geopolitical situation."

Sources: https://www.world-nuclear-news.org/Articles/Poland-s-Industria-selects-Rolls-Royce-SMR-for-hyd; https://notesfrompoland.com/2022/10/28/poland-picks-us-as-partner-for-first-nuclear-power-plant/; https://notesfrompoland.com/2022/11/01/south-korea-and-poland-sign-agreement-on-developing-nuclear-plant/

SMRs: RAISING OR LOWERING THE RISKS OF NUCLEAR ENERGY?

In 2008, the U.S. State Department's International Security Advisory Board (ISAB) concluded that the rise in nuclear power worldwide, and particularly within Third World countries, inevitably increases the risks of proliferation.

Some developments in the interim arguably have worsened the scenario. First, U.S. capabilities to shape nuclear supply have declined. The bankruptcy of Westinghouse in 2017 and continued low prices of uranium have atrophied U.S. mining, milling and conversion capacities. Second, the United States' forceful promotion of an exception for India to Nuclear Suppliers Group (NSG) guidelines for nuclear trade in 2008 alienated China, which has proceeded to supply Pakistan with several power reactors in contravention of the NSG guidelines.

Perhaps the most crucial change has been Russia's shift from collaborator in nuclear nonproliferation to international pariah, beginning with its annexation of Crimea in 2014 and continuing with its 2022 invasion of Ukraine. Fifteen years ago, Russia had been a willing partner in nuclear arms control with the United States, in cooperative threat reduction programs, in efforts to rein in Iran's clandestine nuclear program and in negotiations with North Korea in the Six Party Talks. It was a member of the G-8 and the Russia-NATO Council. Today, most of those ties of cooperation have been broken. While Russia remains on the UN Security Council, its actions are now more destructive than constructive. Cooperation between China and Russia, on the other hand, has strengthened in a number of fields.

At the time of the 2008 ISAB report, small modular reactors were not being widely considered as potentially influencing the spread of nuclear power.[64] Yet a successful "SMR revolution" could lower the political, technical, and financial barriers to entry into the nuclear field significantly. In some regions, political instability or terrorist activity could increase risks for nuclear energy. For those countries that do not already have nuclear research reactors, developing the scientific and engineering skills associated with nuclear power would enhance their proliferation potential, triggering concern in neighboring states about the possibility that these countries could develop weapons programs.

In addition to more states deploying nuclear energy, more reactors will require more fuel services. An "SMR revolution" limited to light water reactor designs may not increase proliferation risks if countries forego reprocessing. But it would still require expanded enrichment capacity. In particular, small modular reactors that require infrequent refueling operate less efficiently with that fuel, requiring more uranium to be mined, processed and enriched.[65] An increase in the number of enrichment plants around the world, particularly if they are located in new countries, would raise proliferation risks.

Widespread use of reactors fueled by HEU or plutonium would certainly increase the risks of proliferation and terrorism since those materials are weapons-usable. But even the greater use of high-assay low-enriched (HALEU) fuel could heighten proliferation and terrorism risks compared to the status quo. HALEU would be impractical to use directly in a nuclear weapon, but it is not impossible. One calculation is that 300kg of 19.75% enriched HALEU would be needed in a nuclear weapon; a single Oklo microreactor would contain enough material for 10 bombs.[66]

[64] International Security Advisory Board, "Proliferation Implications of the Global Expansion of Civil Nuclear Power," Department of State, April 7, 2008. https://2001-2009.state.gov/documents/organization/105587.pdf
[65] Glaser, et al, op cit. p. 15.
[66] Edwin Lyman, *Advanced Isn't Always Better*, p. 47.

Similarly, reactor designs that feature lifetime cores begin with a higher load of fissile material and continue to produce plutonium in the fuel. One estimate is that a 200 MWe lifetime core reactor could contain 1000kg of plutonium after seven years and 3000 kg of plutonium after 30 years.[67] This is hundreds of weapons' worth of plutonium in a single core.

Lastly, SMR designs that incorporate continuous recycle of fuel may pose the highest proliferation risk. These can include designs that integrate pyroprocessing, a version of reprocessing

As in 2008, nuclear energy is still highly concentrated in a comparatively small number of countries. The top generators of nuclear electricity constitute about seventy percent of global capacity. Two-thirds of countries with commercial nuclear power have 5 or fewer reactors while fewer than ten countries have ten or more. The promotion of SMRs could change those numbers drastically, with two to three times as many countries operating nuclear power plants. Even if the risk of proliferation remains constant, a growing number of reactors provides additional targets for sabotage, coercion, blackmail or military operations. Reactors that are housed underground could mitigate some of the risks that might accrue from increased numbers of reactors, likely at an increased cost.

For many countries, the attacks on, coercion of and misinformation propagated about Ukraine's nuclear energy program since last year may be perceived as local, aberrant risks brought about by war. Indeed, before Russia's invasion of Ukraine, the shelling of nuclear power plants was unthinkable in the context of central Europe. However, national security risks can materialize in situations short of war if nuclear energy expands to countries with fragile governance structures and experience.

The 2008 ISAB study identified 30 countries that did not have nuclear power but were interested in moving ahead. The table below lists those countries according to how far their plans have developed and their supplier relationships as well as other countries that have a developed an interest in nuclear power since 2008.[68] Most importantly, Table 2 includes all countries' ranking in the 2022 Fragile States Index. (The Fragile States Index ranks countries in terms of their sustainability, using three measures in four areas: cohesion, economics, political legitimacy and social/cross-cutting indicators.) Finally, the table highlights where countries have specifically noted an interest in SMRs and those that might have potential interest based on the existence of an electrical grid smaller than 20 GWe. Those countries highlighted in bold text already have nuclear power plants under construction, all by Russian vendors.

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[67] Glaser, et al, op cit., p. 16.

[68] In 2021, the IAEA suggested there were 28 seriously interested countries: 4 with reactors under construction; 2 with contracts; 6 ready to take a decision; 8 preparing but without a decision and another 8 considering nuclear power. IAEA, "International Status and Prospects for Nuclear Power 2021, Report by the Director General," GOV/INF/2021/32-GC(65)INF/6*. The World Nuclear Association has a separate list of 30 to 60 countries.

Table 2: Potential New Nuclear Energy States

	Country	Stage	Supplier	Fragile States Index Score	Interest in SMRs	Grid Size (GWe)	Identified in 2008 ISAB Report
Eastern Europe	***Belarus***	Under Construction	Russia	Warning	Potential	11.3	YES
	Serbia	Preliminary	Russia	Warning	Potential	1.8	x
	Croatia	Preliminary		More Stable	Potential	4.6	x
	Poland	Proposed	US, ROK, France?	More Stable	YES	10.1	YES
	Estonia	Preliminary	US	Very Stable	YES	2.7	x
	Latvia			More Stable	Potential	2.9	YES
	Lithuania	Proposed	US (GE)	Very Stable	Potential	3.4	YES
	Romania	Proposed	US	Stable	YES	20.5	x
	Turkey	Under Construction	Russia	Warning	YES	95	YES
Middle East	Saudi Arabia	Proposed	Argentina, ROK, US?	Warning	YES	96	YES
	Qatar		Russia?	More Stable	Potential	10.5	YES
	Kuwait			Stable		20	YES
	Iraq		ROK, Russia?	Alert		27	x
	Yemen			Very High Alert	Potential	1.7	YES
	Syria			High Alert		10	YES
	Jordan	Proposed	Russia, China	Elevated Warning	YES	5.6	YES
	Egypt	Under Construction	Russia	High Warning		59.5	YES
Africa	Tunisia		Russia	Warning	Potential	6.2	x
	Libya			Alert	Potential	10.5	YES
	Algeria	Preliminary	Russia, China	Elevated Warning	Potential	23	YES
	Morocco		Russia, China	Elevated Warning	YES	14.4	YES
	Sudan		Russia, China	High Alert	YES	3.9	--
	Nigeria			Alert	Potential	12	YES
	Ghana		Russia, US?	Warning	YES	5.2	YES
	Senegal			Elevated Warning	Potential	1.5	x
	Kenya	Preliminary	China, ROK	High Warning	YES	3.1	--
	Uganda	Preliminary	China	Alert	Potential	1.2	x
	Tanzania			Elevated Warning	Potential	1.6	--
	Zambia		Russia	High Warning	Potential	3.0	x
	Namibia			Warning	Potential	.610	YES

Table 2: Potential New Nuclear Energy States

	Country	Stage	Supplier	Fragile States Index Score	Interest in SMRs	Grid Size (GWe)	Identified in 2008 ISAB Report
Africa	Rwanda		Russia	High Warning	Potential	.238	x
	Burundi		Russia	Alert	Potential	.08	x
	Ethiopia		Russia	Alert	Potential	4.5	x
	Congo	Preliminary	Russia	Alert	Potential	.83	x
Americas	Cuba		Russia	Warning	Potential	6.6	x
	Chile			More Stable		30	YES
	Ecuador			Warning	Potential	8	x
	Venezuela		Russia	Alert		33	YES
	Bolivia		Russia	Warning	Potential	3.7	x
	Peru			Warning	Potential	15.2	x
	Paraguay		Russia	Warning	Potential	8.7	x
Asia	Azerbaijan		Russia	Elevated Warning	Potential	7.6	YES
	Georgia			Elevated Warning	Potential	3.7	YES
	Kazakhstan		Russia	Stable	Potential	25.9	YES
	Mongolia		Russia	Stable	Potential	1.5	x
	Bangladesh	Under Construction	Russia	High Warning		2.1	x
	Sri Lanka		Russia	Elevated Warning	YES	4.4	x
	Uzbekistan	Proposed	Russia	Warning	Potential	17.5	x
	Indonesia		Russia	Warning	YES	81.2	YES
	Philippines		Russia	High Warning		26.8	x
	Vietnam	Deferred	China	Warning	YES	78	YES
	Thailand		China	Elevated Warning	YES	49.5	x
	Laos		Russia	Elevated Warning	Potential	9.9	x
	Cambodia		China	High Warning	Potential	2.9	x
	Malaysia			Stable		35.8	YES
	Singapore			Sustainable	YES	12	x
	Myanmar		Russia	High Alert	Potential	6.8	x
	North Korea	Under Construction	Indigenous	?	YES	8.2	x

Sources: World Nuclear Association, Emerging Nuclear Energy Countries, https://world-nuclear.org/information-library/country-profiles/others/emerging-nuclear-energy-countries.aspx, IAEA, International Status and Prospects for Nuclear Power 2021, https://www.iaea.org/sites/default/files/gc/gc65-inf6.pdf Fragile States Index, available at: https://fragilestatesindex.org/2022/07/13/fragile-states-index-2022-annual-report/ Electrical grid capacity are from 2020, UNstats.org

Many of the countries that have expressed an interest in nuclear power may never move forward. More than half, however, appeared in the Fragile States Index with a rating of "Warning" or higher and three– Syria, Sudan, and Myanmar – appeared in the "High Alert" category.

Russia currently has agreements (although not necessarily contracts) with 28 countries. Only Kazakhstan and Malaysia ranked as "stable" on the Fragile States Index. The rest were given ratings of "warning" (8), "elevated warning (7), "high warning" (5), alert (5) and "high alert" (2).

China is pursuing nuclear exports with as much vigor as Russia but with less to show for it. In 2019, Chinese officials announced they would seek to export 30 nuclear power plants. China's target countries are ranked from elevated warning to high alert levels for conflict potential by the Fragile States Index.

One recent anecdote illustrates how even low levels of nuclear capability combined with political turbulence can raise risks. In mid-March 2023, the IAEA discovered that 10 barrels of uranium ore concentrate (2.5 tons of natural uranium) had gone missing in Libya. War-torn Libya has research reactors but no nuclear power plants, although it did have a bare-bones clandestine nuclear weapons program uncovered in 2003.[69] It is likely to be much more difficult to recover those barrels of uranium in a conflict-torn country than in a well-regulated, peaceful country. The Libyan nuclear security case and the crisis surrounding Ukraine's war-zone nuclear power plants point to another feature of a potentially more anarchic world – the limited role and authority of the IAEA in ensuring safe, secure and peaceful nuclear energy in conflict-prone regions.

A recent count of non-international armed conflicts currently taking place in North Africa and the Middle East numbered 45, and involved several states interested in nuclear power: Egypt, Iraq, Libya, Morocco, Syria, Turkey and Yemen. Africa has 35 non-international armed conflicts that involve, among other countries, Nigeria and Sudan. In Asia, there are currently 19 non-international armed conflicts active in India, Pakistan, Myanmar and the Philippines.[70] SMRs may provide lower-profile targets for would-be attackers than large reactor sites, but they might also be more widely distributed and thus increase the chances of attack.

[69] Alina J. Khan, "Tons of uranium have gone missing from Libya, raising nuclear security fears," NBC News, March 16, 2023, available at: https://www.nbcnews.com/news/world/tons-uranium-missing-libya-nuclear-fears-un-watchdog-rcna75218
[70] See https://geneva-academy.ch/galleries/today-s-armed-conflicts

CONCLUSIONS

As countries consider radical approaches to reducing carbon emissions, they also need to consider the national security implications of their choices. Nuclear energy poses unique national security risks, including proliferation of nuclear weapons and nuclear terrorism. But the war in Ukraine reminds us that nuclear power plants can also be sabotaged, used for coercive purposes, or even weaponized. As long as the war goes on, there is the looming risk that Ukrainian nuclear reactors could be targeted, intentionally or unintentionally.

All electricity generation plants can be targets of attack, but only two are called out in the 1977 Protocol Additional to the Geneva Conventions as necessary to avoid targeting: hydroelectric dams and nuclear electricity generating stations. Yet several key governments do not accept this prohibition, including the United States, Russia and Israel. The risk is not hypothetical, as military attacks on reactors in Iraq, Iran, and Syria, spanning from the 1980s to 2007, demonstrate. Proliferation of precision- guided munitions may make attacks on reactors more prevalent, particularly if attackers believe they can be accomplished without radiological releases.

To add to the dilemma, cooperation among key states essential to minimize the safety, security and proliferation risks of nuclear energy is at an all-time low. The call to triple nuclear energy coincides with the disintegration of cooperation, the unraveling of norms and the loss of credibility of international institutions that are crucial to the safe and secure operation of nuclear power. From treaties on nuclear weapons to voluntary understandings about nuclear export controls, expected levels of cooperation have fallen off drastically.

In the past, the United States has been able to coax active cooperation from many countries, including Russia and China. Increasingly, however, Russian and Chinese cooperation in key fora, like the International Atomic Energy Agency, the Nuclear Suppliers Group, and the UN Security Council, has not only declined, but is marred by significant disinformation. A shared interest in nuclear nonproliferation and avoiding nuclear war may now be falling prey to broader efforts by China and Russia to undermine existing institutions and arrangements in a bid to reduce U.S. international influence.

In this context, it is hard to see how a tripling of nuclear energy could occur without exacerbating existing risks of proliferation, nuclear terrorism, sabotage, coercion and weaponization. The widescale introduction of SMRs could potentially add new risks.

The push to make SMRs more versatile has increased security risks in several ways. Reactors fueled with highly enriched uranium or plutonium will increase risks of proliferation and terrorism because those materials are weapons-usable. Reactors designed to include lifetime cores will build up plutonium over time. Fast reactor designs that require reprocessing, especially continuous recycling of fuel, could ultimately confer latent nuclear weapons capabilities to many more states. In sum, the kinds of reactors now under consideration do nothing to reduce known risks, and some pose heightened risks. There appears to be no attempt to forge agreement among suppliers or governments to restrict reactor choices that pose greater proliferation risks.

Finally, if the mass production of small modular reactors lowers barriers to entry into nuclear energy, there will be many more states deploying nuclear power reactors. The fragility of governance in some of these states will pose additional risks. Russian and Chinese programs to promote nuclear energy target many of those states.

POLICY RECOMMENDATIONS

Mitigating the national security risks of expanded nuclear energy will require cooperation among many states, especially key nuclear suppliers. This suggests that the United States should refrain from making its nuclear energy export competition with Russia and China into great power competition. Instead, it should seek to reinvigorate a shared understanding of the risks of nuclear weapons proliferation with those key countries. The United States still wields considerable influence in international fora associated with nuclear energy, nonproliferation, and nuclear security and it should use this influence to ensure that any expansion of nuclear energy does not exacerbate national security risks. But first, it will need to get its own policy house in order.

Nuclear energy promotion activities and programs within the US government rooted in climate change objectives fail to account for the national security risks of the spread of nuclear power, especially SMRs. One result is that U.S. officials have failed to qualify their promotion of nuclear power. In the best case, they may be privately trying to dissuade countries from purchasing systems that present higher proliferation risks (e.g., fast reactors using HEU or Pu fuel, with in-line processing) and in the worst case, they may be saying nothing at all or advocating any system that the buyer is interested in. Two studies are needed: an objective, technology-based assessment and one focused on geopolitical risk. A technology-based assessment could help set guardrails around a more proliferation- resistant nuclear future. For the technology-based assessment, national laboratories with expertise in proliferation risk should take the lead rather than laboratories seeking to promote technologies and approaches they themselves have developed in order to minimize bias. This needs to include a clear-eyed and unbiased assessment of the proliferation risks of fast reactor designs that promote reprocessing.

For the study on geopolitical risk, the State Department should commission a new International Security Advisory Board study on how the national security risks posed by nuclear energy have changed over the last two decades and not limit its assessment to proliferation but also include the prospects for nuclear terrorism, sabotage, coercion, and weaponization of power plants. It should be free from promotional bias.

Nuclear energy promotion activities and programs within the US government rooted in climate change objectives fail to account for the national security risks of the spread of nuclear power and especially SMRs.

POLICY RECOMMENDATIONS

Second, the United States should approach cooperating with other countries on energy and climate mitigation strategies more holistically. While nuclear energy cooperation needs to be vetted more thoroughly than other kinds of energy cooperation precisely because of its risks, it should not be elevated to strategic avenues where it becomes a sweetener for other high profile deals like the Saudi-Israeli rapprochement or elevating India to counter China per the 2005 US-India nuclear deal. If climate crisis mitigation is a global objective, strategies should prioritize the fastest and most efficient measures rather than technology-specific options.

Third, the United States should propose an international study of the conditions under which multinationally controlled enrichment plants could reduce proliferation risks. Previous studies and proposals assumed that such institutional arrangements would provide earlier warning of diversions but did not explain how. Finally, to encourage wider understanding of the proliferation risks of SMRs, the United States should convene an international assessment of those risks.

Above all, the United States needs to weigh nuclear solutions to climate change against other low-carbon options that pose fewer national security risks. If nuclear energy cannot be deployed fast enough, a more extreme climate may make even existing nuclear power plants a greater liability. And if the international security environment further degrades because of the stresses of extreme climate, it may become increasingly difficult, if not impossible, to carve out “safe zones” for nuclear power plants.