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Small Modular Reactors: The Next Phase for Nuclear Power in the Indo-Pacific?

EDITED BY
DAVID SANTORO & CARL BAKER

PACIFIC FORUM INTERNATIONAL

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Executive Summary

David Santoro & Carl Baker

In an effort to understand the rising interest worldwide in so-called "small modular reactors" (SMRs) and their companion "floating nuclear power plants" (FNPPs), the Pacific Forum commissioned three papers on this topic. Written by Victor Nian, the first paper unpacks SMR/FNPP technologies and discusses their applicability in the Indo-Pacific. The second paper, authored by Jor-Shan Choi, examines the safety, security, and safeguards (i.e., the "3S") considerations associated with SMRs/FNPPs. Finally, penned by Miles Pomper, Ferenc Dalnoki Veress, Dan Zhukov, and Sanjana Gogna, the third paper addresses the potential geopolitical implications of SMR/FNPP deployments in the Indo-Pacific. By looking at these three areas – the technology, the 3S considerations, and geopolitics – the papers seek to provide a comprehensive, albeit preliminary, analysis of the SMR/FNPP question in the Indo-Pacific.

Key takeaways from the three papers include the following:

Interest for nuclear power is rising globally, and in the Indo-Pacific in particular

The increasingly dominant view is that nuclear power has a role to play to help achieve the seventeen "sustainable development goals" identified by the United Nations General Assembly in 2015 (and intended to be reached by 2030). As a result, there has been rising interest in nuclear power development in several parts of the world, especially in the Indo-Pacific, where growth is the strongest.

National energy and climate objectives are key drivers

This renewed interest comes not long after the failed "nuclear renaissance" of the 2000s. The renaissance never materialized primarily because the devastating accidents at Japan's Fukushima Daiichi Nuclear Power Plant in 2011 led many to reconsider their nuclear power ambitions. Just a few years later, however, national energy and climate objectives are now driving many to put the nuclear option back on the table. This interest has only grown in the wake of Russia's invasion of Ukraine, the subsequent efforts to choke off Russian natural gas and oil exports, and the resulting increase in global prices for fossil fuels.

SMRs/FNPPs have appealing features

SMRs are not new concepts – they date back to the 1950s – but they are at the very center of current discussions about nuclear power. SMRs are popular because they are small, mobile, flexible, have user-centric characteristics, and are empowered by the advanced Generation IV technologies. SMRs can also be placed on floating platforms, such as ships or barges; they are then called FNPPs.

SMR/FNPP technology is not ready yet

Most SMR/FNPP designs are still in the research phase or under development. Few are deployed. In the Indo-Pacific, the land- or marine-based reactor types of interest are water-cooled, high-temperature gas, molten salt, or aqueous-fueled. Two reactors are currently deployed in the region: the KLT40S, a 2x35 megawatt pressurized water reactor FNPP developed by OKBM (Russia) and commissioned in Pevek in the Russian far east; and the HTR-PM, a 2x105 megawatt high-temperature gas reactor developed by the China Nuclear Engineering Corporation and Institute of Nuclear New Energy Technology.

Per the International Atomic Energy Agency (IAEA), SMR/FNPP technologies are unlikely to contribute significantly to the expansion of nuclear power in the next decade. If adoption of such technologies matches the current level of interest, reactor development and deployment will take time to materialize.

SMRs do not have the drawbacks of large-scale nuclear power plants

The advantage of SMRs/FNPPs is that they have the potential to offer cost-competitive and clean energy without the shortcomings associated with traditional large-scale nuclear power plants. SMRs/FNPPs can be easily integrated into national energy planning, especially for newcomer countries with small grid sizes or off-grid/remote communities, and countries that are dependent heavily on energy imports.

There is a pathway to the successful utilization of SMRs/FNPPs

There are several factors associated with the successful utilization of SMRs/FNPPs. Advancing them as early as possible in the industrial supply chain is important for proper integration into energy production. Developing industry standards, to ensure compatibility and interoperability with other systems, and adopting and scaling up SMR/FNPP technologies adequately to enjoy the economies of the multiples are also essential. Finally, ensuring "green passage" for transportable SMRs/FNPPs is a key factor in facilitating safe and efficient mobilization of these technologies for nearshore, offshore, and maritime applications.

3S considerations are a challenge for SMRs/FNPPs

One problem is that SMR/FNPP technologies are not devoid of safety, security, and safeguards challenges. SMRs/FNPPs, notably "first-of-a-kind" reactors, have unique features, specific systems, and novel operating conditions, introducing challenges to the established regulatory bodies, potentially leading to safety concerns. The special features of SMRs/FNPPs, notably their transportability, remote or urban locations, and new fuel designs also present new nuclear security challenges, some possibly more serious than those of large reactors. Moreover, because they use different types of fuel and thus require new technologies in manufacturing and handling of nuclear materials, some SMRs/FNPPs present unique challenges to IAEA safeguards.

The best way to address these safety, security, and safeguards challenges is to adopt a holistic approach. Such a "3S" approach helps better understand the challenges (and opportunities) associated with SMR/FNPP deployments.

SMR/FNPP deployment will happen against the backdrop of a competitive security environment

Nuclear power development has always been intimately linked to geopolitics. There is no reason to think that it will be different this time around, especially given that the security environment is becoming increasingly competitive. Because Russia has been relentless in its intended nuclear energy (traditional and SMR/FNPP) exports, notably in the Indo-Pacific, and because China looms large over the horizon as a major nuclear exporter in the context of its Belt-and-Road Initiative, there are fears in Washington that the United States might lag behind (because it has a limited nuclear export industry) and, therefore, that it could lose potential markets or surrender influence in the region to either Moscow or Beijing, or both. Significantly, a few other regional countries are entering the nuclear export business as well.

It isn't clear (yet) if SMR/FNPP deployment will have far-reaching geopolitical implications

Caution is in order, however. The current renewed interest in nuclear power may not materialize and, if it does, will be a very slow process. The United States, then, should keep an eye on key developments and dynamics but not rush into anything. If Washington wants to help US SMR/FNPP manufacturers gain new markets in the Indo-Pacific, the priority should be Indonesia given Jakarta's urgent (and massive) need for new power sources; doing so in the Philippines, Thailand, or Vietnam would only be judicious if these three countries confirm their intentions to pursue nuclear power. Either way, selling (or failing to sell) US manufactured SMR/FNPP technologies is not likely to radically change the recipients' approach to Washington as a trade or security partner.

The United States should ask itself if it benefits more from expanding or from limiting the nuclear export market

It is an open question whether the United States should focus on competing aggressively to expand the nuclear export market (and shape it to its advantage) or if, instead, it should focus on limiting such expansion. Conducting a thorough study on the benefits, costs, and risks of each option would be useful and timely.

1

Small Modular Reactor Technologies and Floating Nuclear Power Plants in the Indo-Pacific

Victor Nian

Since the operation of the first nuclear power plant in the 1950s, the world has gone through two development phases in nuclear reactor technologies (**Error! Reference source not found.**). The first was the development of exploratory Generation I reactors. The second phase was the rapid scale-up of commercially proven Generation II reactors in the North American and Western European markets. At its peak, nuclear energy supplied nearly 18% of the world's total electricity. Just as the world looked to nuclear as one of the promising energy options, the early success of nuclear energy was plagued by severe accidents, such as Three Mile Island and Chernobyl as well as other issues such as cost escalation, completion-time overruns, lawsuits, and negative public perception.[1]

The second phase is also characterized by a shift toward East Asian markets through technology transfer from and strategic partnerships with western technology vendors. Light water reactor (LWR) technologies from Westinghouse, Combustion Engineering, General Electric, and OKB Gidropress made important contributions to the globalization of modern nuclear power technologies in the process.2 Just as the nuclear industry regained momentum toward a much alluded to "nuclear renaissance" in the 2000s, the incidents at Fukushima Daiichi Nuclear Power Plant in Japan in 2011 caused by a devastating earthquake and tsunami became yet another speed bump for the development of the nuclear energy market.

Driven by the need for safer and more reliable nuclear power technologies to address national energy and climate objectives, the third and four phases of developments came almost in parallel post-Fukushima. The third phase is characterized by the development of radically improved Generation III and evolutionary Generation III+ reactor systems featuring more efficient use of uranium fuel, a much longer operational lifespan of 60 years and beyond, and significant improvements in safety (such as passive safety based on gravity and/or natural convection). The fourth phase is characterized by the development of innovative Generation IV reactor systems with state-of-the-art design of reactor systems and fuel options featuring reactor core in a liquid state, (very) high operating temperature (for hydrogen production), and significantly reduced burden on spent fuel and radioactive waste management.

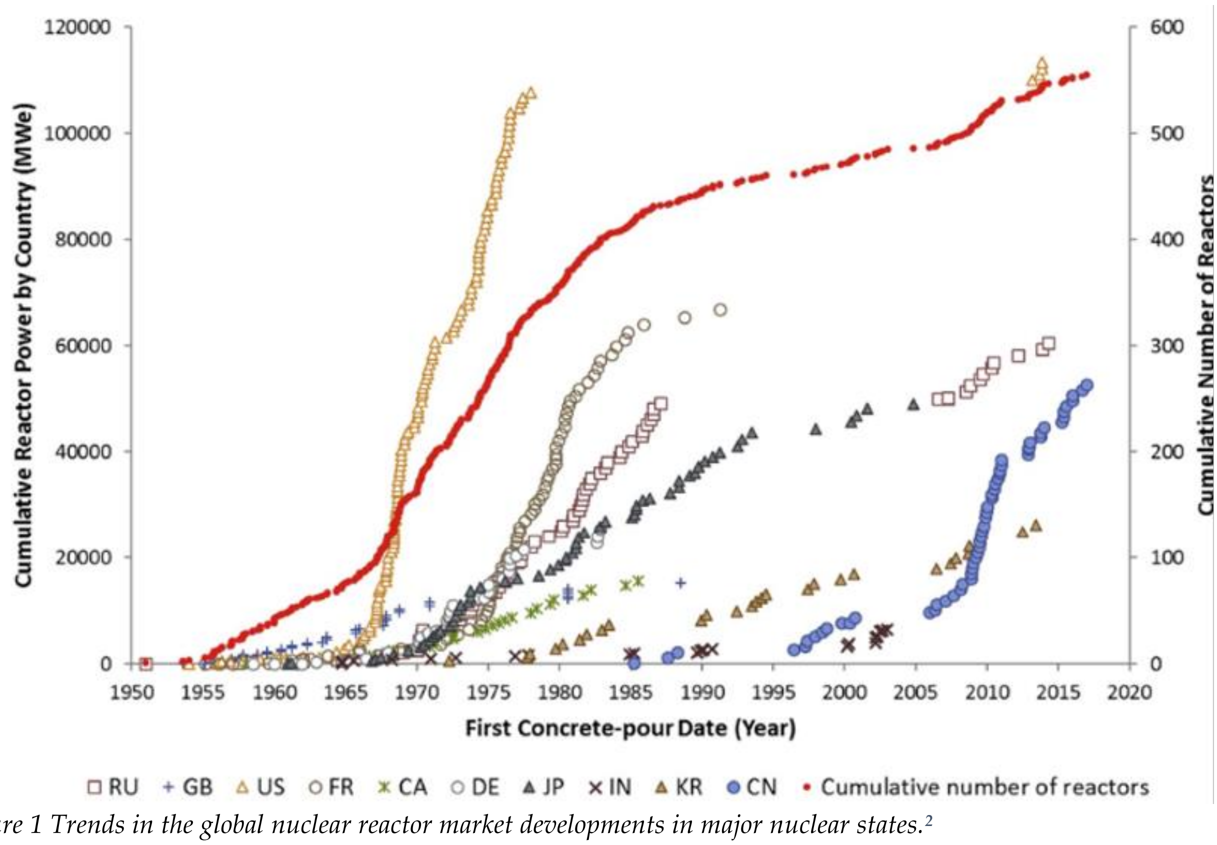

Figure 1 Trends in the global nuclear reactor market developments in major nuclear states.[2]

[1] Victor Nian, "Progress in Nuclear Power Technology," *Encyclopedia of Sustainable Technologies*, July 4, 2017.

[2] Victor Nian, "Technology Perspectives from 1950 to 2100 and Policy Implications for the Global Nuclear Power Industry," *Progress in Nuclear Energy*, Vol. 105, May 2018, pp. 83-98.

Most of the growth in the global nuclear reactor market now comes from Asia, capturing 70% of all reactors under construction as of December 31 2020.[3] China is now ranked first in the number of reactors under construction and second in terms of total nuclear electricity supplied to the domestic grid.[4] Through a strategic partnership and technology transfer from Framatome, and with the success of the CPR-1000, China has developed several indigenous nuclear reactor technologies, especially Hualong One and CAP1400, both for domestic purposes and the overseas market. Other East Asian countries such as Japan and South Korea both have a strong civil nuclear power program, but their national policies and public attitudes toward nuclear energy post-Fukushima have limited the growth of their domestic nuclear reactor markets. Both countries remain interested in exporting nuclear power technologies and projects overseas, however.

The efforts to expand the current reactor fleet in the pursuit of varied national energy objectives in India and Pakistan were faced with different constraints,

and thus opportunities. India's nuclear power program is constrained by limited domestic uranium resources, but it has sought to capitalize on its rich thorium resources by developing Generation IV molten salt reactor (MSR) technologies. Pakistan's nuclear program is constrained because it is not a part of the Nuclear Non-Proliferation Treaty. As a result, Pakistan is largely excluded from the international trade of nuclear power technologies and materials. Pakistan has nonetheless received strong support China with all of its operating reactors imported from China's Indigenous CNP-300 and Hualong One reactor technologies.

Elsewhere in the Indo-Pacific, several economies have maintained interest in nuclear energy in both South and Southeast Asia, with Bangladesh on-track to become the first nuclear user-state with support from Russia and Rosatom's VVER-1200 technologies. The Bataan nuclear power plant in the Philippines was also constructed in the 1980s but was never made operational. Vietnam, meanwhile, began detailed planning in 2006 for several nuclear power plants, but suspended the plans in 2016.

An important innovative concept (from the 1950s) re-emerged in the third and fourth phases: the small modular reactor (SMR). SMRs are generally defined as reactors having a generating capacity of 300 MWe and below.[5] Since almost all SMRs feature a high level of passive safety or inherent safety designs, now with their smaller size potentially minimizing or avoiding the event of a "thermal run away" inside the reactor core, many have suggested that SMRs may help avoid an accident similar to the one that took place in Fukushima.

The benefits of SMRs also go far beyond being a "Fukushima-proof" technology. SMRs are poised to address most of the critical concerns associated with a nuclear power project, including project cost, completion time, financing, flexibility, and adaptability to the local power market environment.[6] They offer reduced upfront capital cost, are suitable for cogeneration and non-electric applications such as hydrogen and ammonia production, and water desalination. In addition, they offer options for remote regions with less developed infrastructure and the possibility for synergetic hybrid energy systems that combine nuclear and alternate energy sources, such as renewables.

State of Technology Development

SMRs are nuclear reactors that rely on the physics of nuclear fission to produce energy without the use of fossil fuels, hence no greenhouse gas and other pollutant emissions. Depending on the nuclear reactor and fuel designs, SMR technologies are similar to large reactors, such as pressurized- water reactors (PWRs), including integral PWRs (iPWRs); sodium-cooled fast-neutron reactors (SFR); lead-cooled fast-neutron reactor (LFR); molten-salt reactors (MSRs); high-temperature gas-cooled reactors (HTRs), including HTR pebble-bed module (HTR-PMs); and many other types found in the International Atomic Energy Agency (IAEA) database.[7] However, SMRs are fundamentally different in that they feature a (potentially much) smaller in capacity and hence size or footprint, simplification, modularity, transportability, and most importantly enhanced safety.

[3] World Nuclear Association, *World Nuclear Performance Report 2021*, September 2021.

[4] World Nuclear Association, *Nuclear Power in the World Today*, October 2021, https://world-nuclear.org/information-library/current-and-future-generation/nuclear-power-in-the-world-today.aspx.

[5] IAEA, Small Modular Reactors, 2017, https://www.iaea.org/topics/small-modular-reactors, accessed December 15, 2021.

[6] Victor Nian, "The Prospects of Small Modular Reactors in Southeast Asia," *Progress in Nuclear Energy*, Vol. 98, July 2017, pp. 131-42.

[7] IAEA, Advanced Reactor Information System, 2021, https://aris.iaea.org/, accessed December 15, 2021.

Most of the global SMR technologies are still in the research and development (R&D) stage and most of the activities are led by state-owned or well-established companies. Two of the most notable technologies currently in the demonstration phase are the Akademic Lomonosov (KLT-40S) developed by Rosatom and the HTR-PM developed by a consortium of China Huaneng Group, China Nuclear Engineering & Construction Group, and Tsinghua University. Several start-ups from other countries, all with strong public and/or private sector funding support, have now also joined the SMR market.

The development of small reactors dates back to the 1950s, when the United States and the Soviet Union both developed small reactors for military purposes. Under the United States Army Nuclear Power Program (1954-1977), Washington developed eight units of small reactors ranging from 0.1-40 MWe. In particular, ML-1 was a 0.3 MWe mobile power plant with a water-moderated HTR fueled by high-enriched uranium. The reactor was about the size of a standard shipping container, which could be transported easily by truck or airplane, and set up in 12 hours. The PM-2A reactor, running as a combined heat and power source for a remote arctic location, was designed to demonstrate the capability to assemble a nuclear power plant from prefabricated components. The 10 MWe MH-1A, fueled with low-enriched uranium (4-7%), was the first floating nuclear power plant (FNPP) and operated in the Panama Canal Zone from 1968-1977 on a converted Liberty ship.

In Soviet Union, the Joint Institute for Power Engineering and Nuclear Research (Sosny) in Belarus developed the 0.6 MWe Pamir-630D air-cooled nuclear reactor, which ran on 45% enriched uranium fuel and zirconium hydride moderator and drove a Brayton cycle gas turbine with dinitrogen tetroxide. Prior to Pamir-630D, a modularly designed PWR prototype, TES-3 (1.5 MWe) was developed with modules (such as reactor, steam generator, turbine, control) mounted on four heavy tank chassis. Each tank chassis was self-propelled so that the different modules could be mobilized for assembly onsite.

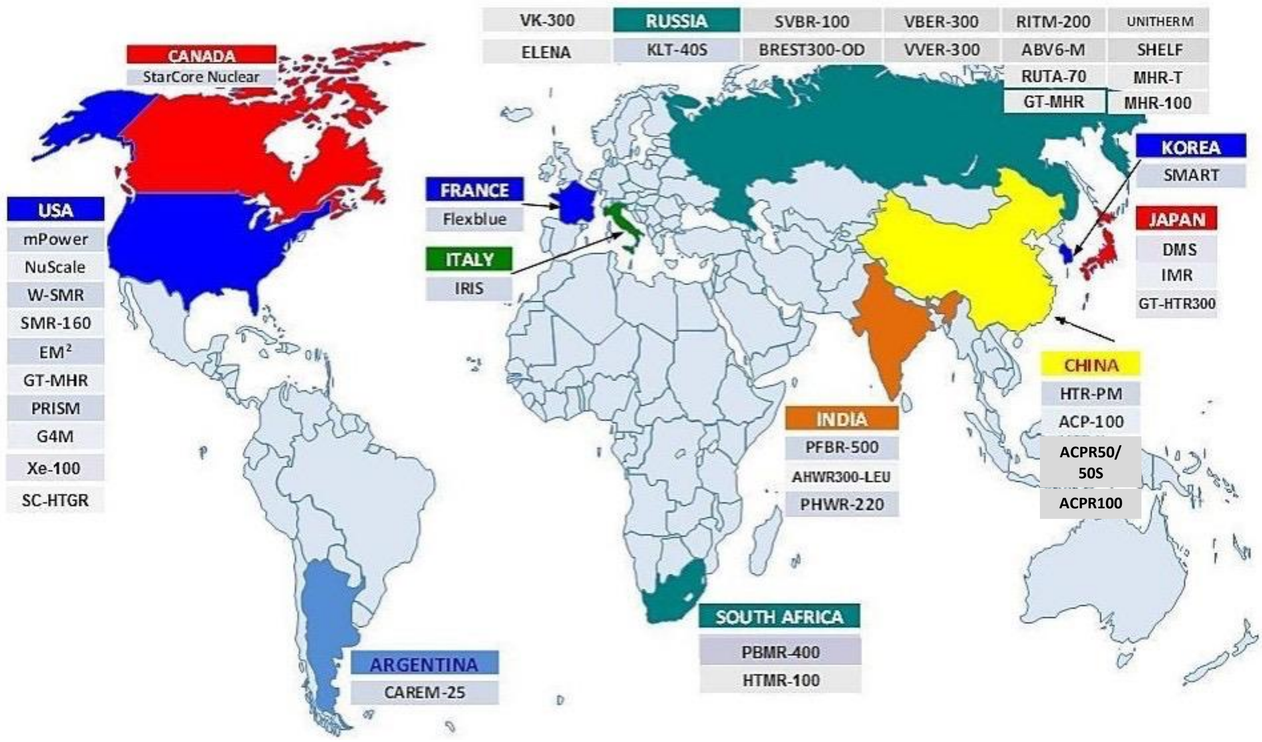

Figure 2 Global developments in SMR technologies.[6]

Fast forward to today: SMRs now include land-based reactors and marine reactors in the form of FNPP.

Land-Based SMR Technologies

Most SMR technologies currently in operation or under advanced stage of development are meant for land-based deployment (Table 1). PWR (including iPWR) remains the preferred design for land-based

SMRs. Both PWRs and boiling water reactors (BWRs) belong to the LWR family, arguably the most mature and proven nuclear power technologies. In the pursuit of Generation IV, SFR and MSR have become increasingly popular among start-ups including joint ventures.

Table 1 Land-based SMR technologies[6]

Name	Capacity (MWe)	Type	Developer(s)
VBER-300	300	PWR	OKBM, Russia
OPEN100	100	PWR	The Energy Impact Centre, USA
SMR-160	160	PWR	Holtec, USA + SNC-Lavalin, Canada
BANDI-60S	60	PWR	Kepco, South Korea
Rolls-Royce SMR	220-440	PWR	Rolls-Royce, UK
NuScale	77	iPWR	NuScale Power + Fluor, USA
SMART	100	iPWR	KAERI, South Korea
RITM-200M	50	iPWR	OKBM, Russia
RITM-200N	55	iPWR	OKBM, Russia
ACP100	125	iPWR	CNNC, China
CAREM25	27	iPWR	CNEA & INVAP, Argentina
BWRX-300	300	BWR	GE Hitachi, USA
PRISM	311	SFR	GE Hitachi, USA
Natrium	345	SFR	TerraPower + GE Hitachi, USA
ARC-100	100	SFR	ARC with GE Hitachi, USA
Hermes prototype	<50	MSR-Triso	Kairos, USA
Integral MSR	192	MSR	Terrestrial Energy, Canada
Moltex SSR-W	300	MSR	Moltex, UK
HTR-PM	210	HTR	INET, CNEC & Huaneng, China
Xe-100	80	HTR	X-energy, USA
BREST	300	LFR	RDIPE, Russia

Floating Nuclear Power Plants

FNPPs or marine SMRs refer to SMRs designed to operate on a floating platform, such as a ship or barge located offshore or near-shore. Today, there are only four companies working on FNPPs (Table 2). Russian and Chinese companies have adopted the proven PWR designs, and UK and Danish companies have embraced the innovative Generation IV MSR designs.

The KLT-40S was derived from the proven KLT-40 reactor used in icebreakers. Being an FNPP means the KLT-40S can be mobilized to power remote communities, such as those in the Arctic[8] supplying 35 MW of electricity and up to 35 MW of heat for desalination or district heating. The KLT-40S is designed with a uranium fuel burn-up of 45 GWd/t over a 3-4-year refueling cycle with on-board refueling capability and spent fuel storage. The operating lifetime is 40 years with a 12-year operating cycle for major overhaul and spent fuel offloading. The present design of the Akademik Lomonosov, a 21,500-ton barge, mounted with two KLT-40S reactor units may become an economical option for cogeneration of power, heat, or hydrogen.[9]

[8] Victor Nian, "Nuclear Power Becomes Critical to Arctic Dominance," 2018, https://oilprice.com/Alternative-Energy/Nuclear-Power/Nuclear-Power-Becomes-Critical-To-Arctic-Dominance.html

[9] Victor Nian and Sheng Zhong, "Economic Feasibility of Flexible Energy Productions by Small Modular Reactors from the Perspective of Integrated Planning," *Progress in Nuclear Energy*, Vol. 118, January 2020.

Table 2 Marine SMR technologies[6]

Name	Capacity (MWe)	Type	Developer(s)	Main Application
RITM-200M	50	iPWR	OKBM Afrikantov, Russia	Marine propulsion (icebreakers)
KLT-40S	35	PWR	OKBM Afrikantov, Russia	FNPP for energy production
ACPR50S	60	PWR	CGN, China	FNPP for energy production
m-MSR	200	MSR	Core Power, UK	Marine propulsion
CMSR	100	MSR	Seaborg Technologies, Denmark	FNPP for energy production
The Can	250	MSR	ThorCon, USA	FNPP for energy production

The RITM series is considered the "flagship" SMR design in Russia. Although KLT-40S is currently in the demonstration stage, it will be replaced by RITM-200M, which will become the commercial offering in FNPPs, or optimized floating power units (OFPUs).[10] The RITM-200M is a 50 MWe iPWR derived from the RITM-200 used in icebreakers with inherent safety features. OFPUs are designed with a servicing cycle of 10-12 years to avoid onboard storage of spent fuel with an operating lifetime of 60 years. RITM-200M units are much smaller than KLT-40S and only require a 12,000-ton barge for a twin-mounted OFPU.

Announced in 2016, CGN's ACPR50S is a 60 MWe marine PWR based FNPP for powering isolated electrical grids such as offshore oil production fields and islands. The ACPR50S is designed to be a conventionally constructed, flat bottom, double hull, and double bottom barge. CGN's FNPP can be self-propelled to allow siting flexibility and to better reach remote locations. The reactor is designed for a refueling cycle of 2.5 years and a lifetime of 40 years.

Both MSRs proposed by Core Power and Seaborg Technologies are designed to have similar electrical output capacity of 100 MWe with a compact reactor design. The key difference lies with the main application in which Core Power aims at marine propulsion and Seaborg aims at non-propulsion energy applications. With reactor fuel in a non-pressurized liquid state, MSRs can enhance the safety of reactor operation significantly.

By design, all FNPPs can be considered a floating offshore energy source for producing carbon-free electricity. All FNPPs can deliver combined heat and power (CHP) supply for remote locations, such as offshore oil drilling platform, offshore mining facilities, and coastal and isolated island communities. In a net-zero carbon emission world, FNPPs can work in synergy with offshore and onshore renewable energy to power future sustainable economic and industrial development. If maritime electrification gains strong momentum, FNPPs can also be transformed into offshore floating charging stations for full electric ocean-going vessels and potentially other man-made marine vessels and apparatus for scientific and strategic applications.[11]

Advantages of SMRs/FNPPs

SMR technologies have several key advantages in comparison to conventional large nuclear reactors. First, design simplification incorporates passive mechanism improvements and greater design integration to reduce the number of components and hence interdependencies among systems. Next, standardization of the dominant or most preferred design allows for the deployment of multiple units of the same design at multiple sites with minimal or no adaptation for different conditions at the sites. Furthermore, modularization and smaller size means much easier transport of modules and the reactor compared to large reactors. With aggressive modularization techniques tailored to local logistical constraints and transport standards, it is possible that 60-80% factory fabrication levels can be achieved for

[10] Sea News, "Russia Develops Optimized Floating Power Unit for Hot Climate," September 22, 2021, https://seanews.ru/en/2020/09/22/en-russia-develops-optimized-floating-power-unit-for-hot-climate/.

[11] Jun Yuan and Victor Nian, "A Preliminary Evaluation of Marinized Offshore Charging Stations for Future Electric Ships," ADBI Working Paper, Asian Development Bank Institute, November 2020.

SMRs with electrical power outputs below 300 MWe.[12] Modularization would also facilitate the implementation of advanced manufacturing techniques such as electron beam welding and diode laser cladding,[13] powder-metallurgy hot isostatic pressing, and additive manufacturing.[14]

Technologies

All modern nuclear power technologies are designed for safe operation over its designed and extended lifetime. In the event of mechanical or human failure or unexpected conditions, the nuclear reactor is designed to be self-limiting, resulting in the run-down and then shutdown of the plant rather than "self-escalating" toward uncontrollable consequences. As a general rule, worst-case accidents depend substantially on size.

The priority is always to avoid explosions and "meltdowns." Explosions arise from pressurized reactor cores, so cores operating at low/atmospheric pressure such as the MSRs might be preferred. In the event of containment failure, radioactive materials (in heavy liquid form) would be deposited only locally rather than being carried across countries and continents by wind. Now with "portable" design associated with the FNPP concept, SMRs can add safety and non-proliferation assurance with autonomous operation without on-site refueling.[15]

The fundamental principle of energy production from a large or small nuclear reactor is the same. The fission process of splitting the uranium isotope U-235 atom releases energy in the form of heat inside the nuclear reactor core, which is then used to raise steam. The steam drives a turbine generator for producing electricity. Depending on the temperature of the steam or hot air at the outlet of the nuclear reactor, other industrial applications using high temperature industrial heat from the nuclear reactor can also be explored, one of the key propositions of some of the Generation IV designs.

The PWR technology is probably the most proven basis for SMR designs. In particular, iPWR is one of the popular concepts among the currently proposed SMR designs. There are five main features in the iPWR concept: an integrated reactor coolant system, multi-modules and modular construction, passive safety, advanced instrumentation and control system, and a longer refueling cycle.[16] These features can lead to a simplified, compact, and light-weight reactor design, enhanced maintainability, extended technical lifetime, and hence cost competitiveness against large-sized PWRs. These features can also allow for better radiation control, which can translate to a more flexible and efficient operation, and increased safety and reliability.[6]

One of the key advantages of SMRs is its smaller electricity generating capacity (approximately 100 MWe). A smaller capacity implies less fuel use inside the reactor core as compared to a large reactor of 1,000 MWe. In the event of an accident, sufficient removal of decay heat is key to prevent a core meltdown. Since the fuel quantity inside an SMR is small, there is less decay heat to remove as compared to a large reactor. Some SMRs are designed so that natural convection would be sufficient to remove the decay heat over an extended period of time in the event of a Loss- of-Coolant Accident. As such, a core meltdown can be prevented even if there is an extended station blackout as in the case of Fukushima.[6]

Post-Fukushima, the development of Generation IV reactors has gained momentum, especially the HTR, HTR-PM, and MSR technologies. The typical enrichment of U-235 in an LWR is 3-5% with a refueling cycle of 18-24 months. In some of the Generation IV designs, such as MSRs, U-235 enrichment is increased to about 20% with a much longer refueling cycle. The goal of a long refueling cycle, especially in the FNPP proposition, is to eliminate the need for on-site refueling, thereby offering additional assurance of safety, security, and safeguards.

Another notable design in early R&D stage is the fast-neutron reactor (FNR) technology. Running on a fast-neutron spectra with higher uranium enrichment,

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[12] C.A. Lloyd, "Modular Manufacture and Construction of Small Nuclear Power Generation Systems," Doctoral Dissertation, 2020, https://doi.org/10.17863/CAM.46941

[13] Chris Lewis, Ray McSweeney, Miranda Kirschel, Will Josten, Tony Roulstone, and Giorgio Locatelli, "Small Modular Reactors: Can Building Nuclear Power become More Cost-Effective? Ernst & Young LLP, March 2016.

[14] "Advanced Nuclear Technology: Demonstration of Powder Metallurgy-Hot Isostatic Pressing," Electric Power Research Institute, June 28, 2018.

[15] Victor Nian and John Bauly, "Nuclear Power Developments: Could Small Modular Reactor Power Plants Be a "Game Changer? – The ASEAN Perspective," *The 6th International Conference on Applied Energy – ICAE2014*, Energy Procedia, Vol. 61, pp. 17-20.

[16] M.E., Ricotti, "Engineering Fundamentals of Modular and Integral-PWR Type SMR Designs and Technologies," *Technical Meeting on Technology Assessment of Small and Medium-Sized Reactors (SMRs) for Near Term Deployment*, 2013.

FNRs can burn plutonium (as a result of the uranium fission process) as additional fuel for the reactor, while addressing concerns over safeguards. Some of the FNR concepts feature a reactor core in liquid state and/or the use of liquid metal as an alternative primary coolant, such as liquid sodium, lead, or lead-bismuth.[17]

Japan has some experience in handling molten sodium since 1977 through the operation of the Joyo experimental reactor and the Monju prototype reactor. Russia is also developing the sodium-cooled BN-series reactor, albeit toward large reactors rather than SMRs. Lead is much more stable than sodium and provides excellent radiation shielding. Lead, however, has a high melting point and a high vapor pressure, which can cause difficulty in refueling and servicing the reactor. Alloying lead with bismuth can lower the melting point, but the lead-bismuth eutectic is highly corrosive to most metals used for structural materials.

The development of HTR is due to the consideration of radically enhancing safety and extending the operating life up to 60 years. The current HTR designs take advantage of inherent safety characteristics by using graphite as the moderator and helium as the primary coolant. Graphite has large thermal inertia and structural stability at high temperature. Helium is an inert gas that has virtually no reactivity with other materials. The reactor fuel is encapsulated in ceramic or silicon carbide, which can help maintain the integrity of fuel particles at a temperature range of 1,600-1,800°C. The outlet temperature of HTR is around 700-1,000°C, which can be used as industrial process heat or running as a CHP facility for more economical energy production.

Applications

The goal of SMR and FNPP technologies is to be user-centric and provide improved safety, efficiency, and economical operation. With a smaller footprint, SMRs offer more flexibility in siting the reactors. Given their transportability, inherent safety designs, and a potentially longer refueling cycle, SMRs can be deployed closer to the user in a decentralized manner, such as a micro grid or distributed grid concept for heat and electricity distribution.

Because they are small, SMRs and FNPPs offer flexibility in capacity expansion planning. When planning for large reactor deployment, there needs to be significant upfront investments poured into the infrastructure development to accommodate the sudden increase in power generating capacity in the range of a gigawatt to tens of gigawatt. The SMR concept allows capacity planning to start with a small-scale MW range deployment suitable for most remote or island communities. As the demand increases, more "power modules" or reactors can be deployed at the same site, possibly within the same containment. This ability to follow the increase in demand also allows flexibility and sufficient lead time for infrastructure planning and expansion in a more economical manner. When paired with energy storage systems or the more advanced power-to-gas concept, SMRs can be further transformed into "load-following" power supply to manage the fluctuating demand.[9]

The development of FNPPs is beginning to alter the competitive landscape of the clean energy technology market. An FNPP is a MW-class mobile power bank that can be transported to the user location to provide 24x7 carbon-free energy. In addition to the ability to supply offshore facilities as mentioned earlier, FNPPs can be connected to an onshore utility grid. The concept is to schedule the rotations of multiple ships at the point of energy consumption. Maintenance and refueling would be carried out in a shipyard, possibly away from the user location or country.

FNPPs can be operated in place of a physical onshore power plant without the need for upfront heavy capital commitment by the user. A proper scheduling of FNPPs can be arraigned to assure a higher availability factor of this virtual land-based power plant leading to more economical energy generation. More importantly, a virtual land-based nuclear power plant allows for a flexible power purchase agreement (PPA) between the vendor and the user in terms of contractual period and quantity, while relieving the user country from the responsibilities of operating a nuclear power plant, refueling, and spent fuel handling, radioactive waste management, and nonproliferation.

As carbon-free CHP technology, SMRs and FNPPs can enable the much-anticipated hydrogen or ammonia economy. Revisiting the proposed SMR designs, while iPWRs are constrained by pressure limitations and thus operate in the 300-400°C range, others can operate at much higher temperature levels.

[17] See https://www.gen-4.org/gif/jcms/c_9353/systems

Liquid metal-cooled fast reactors are in the range of 400-600°C, MSRs in the range of 600-700°C, and HTRs in the range of 600-900°C. Since both ammonia and hydrogen production require industrial grade heat, MSRs and HTRs are plausible candidate to supply carbon-free process heat. More importantly, the small footprint and user-centric design approach allow these SMRs to be deployed close to industrial users, thereby reducing cost and improving efficiency of the overall industrial system.

With SMRs operating as a multi-energy utility, the Indo-Pacific could rely on such advanced technologies to enable a sustainable hydrogen or ammonia economy. Especially in the case of hydrogen, where long-distance transport technology and large-scale storage infrastructure are still under development, SMRs and particularly FNPPs can offer a timely solution to produce hydrogen and ammonia in either existing facilities by providing heat and power or in offshore locations away from heavily populated areas to alleviate negative public perception. Depending on the distance from shore, FNPPs could still function as an offshore clean electricity supply to power onshore economic activities.

With the numerous safety and reliability considerations, SMRs and FNPPs can be designed for deployment at locations with extreme climatic conditions, such as the polar regions. The advantages of a long refueling cycle, and possibly no refueling over the power plant's lifetime, can eliminate the need for the user having to handle radioactive fuel materials. More importantly, there will be no release of harmful pollutants or greenhouse gas emissions from SMRs or FNPPs as compared to diesel generators. All these characteristics are important to ensure the sustainability of an energy source to address energy access in less developed regions and off-grid communities in the Indo-Pacific, especially in areas where renewables are not the most ideal option due to climatic conditions.

With technological innovation, compact SMRs may emerge as a competitive CHP technology for extraterrestrial applications in the longer-term future. The enormous fuel and oxygen requirements for fossil-fuel power generation technologies and low energy density of hydrogen render them impractical for long-term applications beyond the surface of the Earth. The fuel and air requirements of SMRs are negligible as compared to a fossil-fuel power plant. Presently, the extraterrestrial facilities and devices, such as the International Space Station and Mars rover, all rely on PV systems for producing electricity, notwithstanding the use of isotope batteries. A combination of intermittency and limited electricity generating capacity has been a technical barrier to carry out energy intensive research activities.

The portability, onsite assembly, and self-contained feature of SMRs could appeal to leading economies in the Indo-Pacific, especially China, to explore the option of powering future space missions to Tiangong Space Station or Mars missions with SMR or "vSMR" (very small modular reactor) technologies. On that note, the United States National Aeronautics and Space Administration has developed and demonstrated the KRUSTY (acronym for Kilopower Reactor Using Stirling Technology) with 10 kW power output capacity for powering future space missions[18].

Economics

The main argument for supporting the development in nuclear energy lies with its cost competitiveness in decarbonization from a whole-system perspective.[19] Research has shown that the economics of SMRs includes four main considerations. First, SMRs have much smaller capacity, so the total upfront capital commitment as compared to a large nuclear reactor is much smaller. Next, although economies of scale might be less favorable to SMRs as their per unit capacity cost is expected to be higher than that of larger reactors, this problem can be addressed through standardization, batch production in a factory environment, and repeat project implementation. Third, SMRs, especially advanced models, offer user-centric CHP or multi-energy-output applications that can further improve the economics of energy production. Fourth and finally, while the levelized cost of electricity generation from SMRs is likely to be higher than that from large reactors with the first-of-a-kind, SMRs can allow flexibility in financing and contractual arrangements.[6]

[18] NASA, "Demonstration Proves Nuclear Fission System Can Provide Space Exploration Power," May 2, 2018, https://www.nasa.gov/press-release/demonstration-proves-nuclear-fission-system-can-provide-space-exploration-power, accessed December 28, 2021.

[19] OECD, "The Costs of Decarbonization: System Costs with High Shares of Nuclear and Renewables," OECD Nuclear Energy Agency, Paris, 2019.

Beyond the economics of energy production, the early development of advanced Generation IV SMR technologies, such as HTRs and MSRs, offer industrialization opportunities. For newcomers with an established nuclear research program, there are opportunities to cooperate with promising start-ups to co-develop know-hows and intellectual properties relevant to the advanced Generation IV technologies or in nuclear power technology in general. Countries interested in developing indigenous reactor technologies can make long-term strategic plans to establish industrial supply chain development and to testbed critical technologies that would sufficiently support the placement of future nuclear power plant projects onshore or offshore. All can be achieved through partnership with a state and an established nuclear power industry without being constrained by a type of nuclear reactor technology.

From a national-level energy planning perspective, integrating SMRs and FNPPs into long-term energy planning offers additional options to develop a low-carbon or net-zero carbon economy. The advantages of SMRs would be particularly essential in Southeast Asia or for countries with small and/or less developed grid infrastructures. Opting for SMRs and FNPPs can help alleviate concerns over stranded assets to keep up with the incremental demand, while gradually replacing those older or obsolete assets in a more gradual manner to minimize the economic impact on the energy sector. If the ultimate market size and/or consistency in national nuclear policy are of concern, FNPPs could enable newcomers to benefit from an operating expenditure (OPEX) driven approach to enjoy carbon-free electricity without worrying about upfront capital commitments, spent fuel and radioactive waste management, and other long-term obligations.

Regional outlook

China's latest Five-Year Plan underlined an ambition to increase nuclear capacity by 20 GWe from 50 GWe installed capacity in 2019. Most of the new capacity adopted Hualong One, China's flagship indigenous technology. The recent incidents of forced power shutdown reflected China's ambition and determination in reining in domestic coal consumption as part of the country's energy strategy to alleviate the present price hikes and to reduce import dependency for coal, which has been complicated by geopolitical issues with Australia. With the ambition of "Made in China 2025," there is little doubt that China will ramp up nuclear capacity faster than planned to ensure sufficient zero-carbon baseload electricity to power the industrial parks.

China maintains an ambition to export indigenous technologies, such as CAP1400 and especially Hualong One, while offering several project models including EPC (engineering, procurement, construction), BOT (build, operate, transfer) and BOO (build, own, operate). China has had success in the past, with nuclear reactor exports to Pakistan of four units of CNP-300 and two units of Hualong One. At the same time, China is also pushing the development of SMR technologies, such as ACP100, ACPR50S, HTR-PM, and MSR with the ambition to commercialize these technologies rapidly. All these initiatives are in line with China's announcement to stop building new coal-fired power plants in both its domestic and overseas markets, and to help emerging economies in their sustainable development goals. In addition, CGN's ACPR50S would serve China's interest in powering oil drilling facilities and remote land features in South China Sea.

India has about seven GWe of nuclear capacity with slightly over six GWe nuclear capacity under construction. [20] Pressurized heavy water reactor (PHWR) is the dominant technology along with a couple of PWRs from Rosatom and BWRs from GE-Hitachi. India has modest uranium reserves, but all are in the high-cost category. It has been dependent on imported uranium for the reactor fuel supply. Spent fuel from the PHWRs is reprocessed to produce reactor-grade plutonium by the Bhabha Atomic Research Centre with a capacity of about 200 tons per year in Trombay, Tarapur, and Kalpakkam. India and the United States reached an agreement in 2010 to allow India to reprocess imported as well as domestic spent fuel under IAEA safeguards.

India's rich thorium resources has led to its ambition to develop an advanced heavy-water thorium fuel cycle. The idea is to leverage FNR technology to burn plutonium produced in the spent fuel from PHWRs and LWRs through a uranium-thorium fuel blanket in the form of a "breeder" to produce more fissile

[20] World Nuclear Association, Nuclear Power in India, 2021 https://world-nuclear.org/information-library/country-profiles/countries-g-n/india.aspx, accessed December 28, 2021.

plutonium and U-233. Then, the plutonium-thorium fuel will be used in fuel-breeding MSRs and/or Advanced Heavy Water Reactors (AHWR) with the goal of achieving a self-sustaining fleet of fuel-breeding reactors.

India is interested in exporting nuclear power reactor technologies as well as nuclear competencies. It was reportedly developing a small AHWR (around 300 Mwe) for export as an affordable nuclear reactor option to developing or less developed economies. At the same time, India remains an importer of nuclear reactor technologies such as VVER and AP1000. There is no official announcement of Indian plans to develop, import, or export SMRs or FNPPs.

India also played an important role in supporting Bangladesh to become a nuclear power newcomer. In 2017, India's Global Centre for Nuclear Energy Partnership provided support for the construction and operation of the Rooppur nuclear power plant project with two Generation III+ VVER-1200 reactors. Rooppur is in proximity to a high-voltage direct current (HVDC) link with India and has planned an additional 600 kV HVDC link across the western part of the country.[21]

Many blame Fukushima as the trigger point for the halt in nuclear power projects in Japan and South Korea. The Japanese government, for instance, continues to face tremendous challenges in restarting its existing nuclear reactor facilities amid fast rising energy bills and meeting Kyoto Protocol environmental requirements. Yet both countries remain interested in exporting nuclear power reactor technologies to overseas market. In 2009, a Korea Electric Power Corporation (KEPCO)-led consortium was awarded the Barakah nuclear power plant project in the United Arab Emirates (UAE), with a total capacity of 5,380 Mwe and comprised of four units of the ARP-1400, which is South Korea's indigenous reactor technology. Japan and India were reportedly in discussion on a pact that includes collaboration in nuclear, railway, and other infrastructure projects. However, the flagship high-speed railway portion of the project was delayed by at least five years.[22] Japan has also established partnerships with members of the Association of Southeast Asian Nations (ASEAN) with the goal of promoting Japanese enterprises and technologies, especially alternative energy technologies to ASEAN member states (AMS).

Home to about 10% of the world's population, the rapidly growing ASEAN economies are shaping many aspects of the global economic and energy outlook.[23] According to a report published by the ASEAN Centre for Energy, the primary energy demand by AMS reached 625 million tons of oil equivalent (Mtoe) in 2017 with a projected annual growth rate of 4.1% till 2045.[24] The business-as-usual projection in the consumption of fossil fuels, especially coal, would continue to dominate the region's fuel mix given the economic, geographical, and geopolitical circumstances of ASEAN.[25] That would lead to an increase in carbon emissions from 1,686 million tons in 2017 to 4,171 million by 2040. The additional carbon emissions from ASEAN between 2015 and 2040 are expected to be roughly equivalent to those of the world's fifth-highest emitter, Japan, in 2014.[26]

Nuclear energy is not new to ASEAN. Since the 1960s, several AMS, such as Indonesia, Malaysia, the Philippines, Thailand, and Vietnam, have developed nuclear research and/or power programs.[27] The Bataan Nuclear Power Plant in the Philippines started construction in response to the 1973 oil crisis was the first nuclear power plant ever constructed in ASEAN, although it was never fueled or operated after a change in presidential administrations. Although there is no operating nuclear power plant in the region, all five aforementioned AMS have experience with research reactors. Indonesia, Philippines, Thailand, and Vietnam started working with research reactors in the 1950s and 1960s, and Malaysia started in 1982.

[21] Ridoan Karim, Mohammad Karim, Firdaus Muhammad-Sukki, Siti Hawa Abu-Bakar, Nurul Aini Bani, Abu Bakar Munir, Ahmed Imran Kabir, Jorge Alfredo Ardila-Rey, and Abdullahi Abubakar Mas'ud, "Nuclear Energy Development in Bangladesh: A Study of Opportunities and Challenges," *Energies*, Vol. 11, No. 7, June 2018.

[22] Avishek Dastidar, "India's Bullet Train Faces 5-Year Delay: High Costs, Japan Firms Not So Keen," *The Indian Express*, September 6, 2020.

[23] "Southeast Asia Energy Outlook 2019," International Energy Agency, Paris.

[24] The 6th ASEAN Energy Outlook 2017-2040, ASEAN Centre for Energy, Jakarta.

[25] Victor Nian, Muhammad Rizki Kresnawan, and Beni Suryadi, "Setting Emission Standards for Coal-Fired Power Plants in ASEAN," *Policy Brief*, ASEAN Climate Change and Energy Project (ACCEPT), ASEAN Centre for Energy, July 13, 2021.

[26] World Bank, World Development Indicators, 2018 ed. World Bank Group, Washington DC.

[27] ACE, "Civilian Nuclear Energy Factsheet," ASEAN Centre for Energy, Jakarta, 2020.

In 2013, both the International Energy Agency[28] and the Asian Development Bank[29] projected a dire situation in which Southeast Asia would become a net-energy importer around 2030-2035. Due to concern over rising energy security and climate objectives, several AMS remain interested in nuclear energy post-Fukushima.[30] While no official announcement of confirmed nuclear milestones has been made by any AMS, the regional prefeasibility study concluded that the five aforementioned AMS are the frontrunners to establish nuclear power programs and to commit to nuclear energy.

Indonesia is exploring international partnership and cooperation to build the first experimental 30 MWt HTR near BATAN, the country's nuclear research agency.[31] The Russian state nuclear energy corporation, Rosatom, has undertaken the conceptual design of the HTR. BATAN has also signed an agreement with China Nuclear Engineering Corporation (CNEC) on the development of HTR technology with the goal of constructing a small HTR on Kalimantan and Sulawesi from 2027. CNEC reported that Indonesia aimed to construct small HTRs. In August 2015, Rosatom and BATAN signed a cooperation agreement on the construction of FNPPs for consideration to be deployed at Gorontalo province on Sulawesi.[32] Indonesia is also reportedly exploring MSR technology potentially through a floating concept.

Vietnam is the only AMS that previously expressed explicit interest in building modern commercial nuclear power plants with support from Rosatom. An initial four units of VVER-1200 reactors were planned in Ninh Thuan province, which were then meant to be followed by technologies from Japan and South Korea.[33] However, the nuclear plan was eventually deferred indefinitely in favor of the cheaper alternative, especially coal.[34]

Elsewhere in ASEAN, countries with heavy reliance on fossil fuels, especially imported fossil fuels, will face increasing uncertainties associated with the security of energy supply and the volatility of energy prices, notwithstanding the ever-growing pressure from the post-COP26 world. The Philippines welcomed a study by the IAEA that concluded the need to include nuclear energy in the country's energy mix to address energy access, energy security, and ongoing power outages.[35] A prefeasibility study conducted by the Singapore government concluded that the then available nuclear power technologies were not suitable for deployment in Singapore due to concern over factors such as safety, security, and human resources.[36] In addressing energy security without nuclear energy,[37] Singapore is deliberating several risky and challenging options, such as importing solar energy through a 4,200-km subsea power cables from Australia[38] and importing hydroelectricity from Laos via an interconnected ASEAN Power Grid through the Malaysian peninsula.

Conclusions

The nuclear power industry has made significant progress both in terms of technology and business model. With their small size and scalability, SMRs could be an attractive option for the developing economies of the Indo-Pacific, addressing concerns over a reliable and sustainable electricity supply. The small generating capacity and the user-centric design enables significantly greater flexibility in energy systems planning, especially in the context of a distributed multi-energy grid, combining electricity, heat, hydrogen, and other sources. The passive safety and inherent safety features by design, such as the HTR and MSR technologies, will also make future nuclear power plant "Fukushima-proof."

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[28] "Southeast Asia Energy Outlook, International Energy Agency, Paris, 2013.

[29] "Energy Outlook for Asia and the Pacific," Asian Development Bank, Philippines, 2013.

[30] Victor Nian and S.K. Chou, "The State of Nuclear Power Two Years after Fukushima – The ASEAN Perspective," *Applied Energy*, Vol 136, December 2014, pp. 838-848.

[31] Victor Nian, "Are Small Modular Reactors Making their Way to Southeast Asia?" *Sustainability Times*, March 20, 2020.

[32] World Nuclear Association, 2021. Nuclear Power in Indonesia, https://world-nuclear.org/information-library/country-profiles/countries-g-n/indonesia.aspx. Updated January 2021.

[33] World Nuclear Association, Nuclear Power in Vietnam, https://world-nuclear.org/information-library/country-profiles/countries-t-z/vietnam.aspx. Updated July 2020.

[34] Karen Mesina, "Vietnam's Nuclear Implosion: Is the Final Decision a Giant Leap Backwards?" *Asian Power*, 2017, https://asian-power.com/project/in-focus/vietnams-nuclear-implosion-final-decision-giant-leap-backwards.

[35] "Manila's Search for Energy Security," *Sustainability Times*, June 18, 2020, https://www.sustainability-times.com/low-carbon-energy/manilas-search-for-energy-security/.

[36] Ministry of Trade and Industry (Singapore), 2012, Factsheet – Nuclear Energy Pre-Feasibility Study, https://www.mti.gov.sg/-/media/MTI/Newsroom/Parliament-QandAs/2012/10/Second-Minister-S-Iswarans-reply-to-Parliament-Questions-on-nuclear-energy-pre-feasibility-study-in-/pre-fs-factsheet.pdf

[37] Victor Nian and Gerald Goh, "Why Singapore Should Consider Nuclear Power," *Sustainability Times*, December 11, 2020.

[38] Ovais Subhani, "Sun Cable Taps Five Firms to Help Deliver Solar Energy to S'pore via Undersea Link," *The Straits Times*, October 20, 2021.

Compared to the heavy upfront financial commitment and the negative public perception of traditional large nuclear reactors, SMRs offer better project risk management and financial viability. Today, the nuclear reactor market has moved beyond the dominance of the traditional state-owned/linked or established technology vendors like Rosatom, CGN, Westinghouse, and Framatome. Entrepreneurial start-ups and joint ventures developing innovative SMR systems enable a broader choice of technologies for newcomers to consider, potentially in a vendor-neutral approach.[39]

The emergence of FNPPs in this decade represent significant progress in the nuclear power industry by creating a mobile energy bank that potentially disrupts the traditional land-based nuclear power project planning approach. It is particularly important for economies and communities with small grid sizes and/or located in off-grid or remote areas because FNPPs can bring clean energy to the consumer without the need to pull thousands of kilometers of power cable or build mega-infrastructure to accommodate gigawatt-level grid capacity expansion. The FNPP as a mobile nuclear power plant enables a new business model such as asset leasing without the need for user involvement in refueling, spent fuel management, and radioactive waste disposal.

The realization of a sustainable energy future powered by SMRs and FNPPs needs four critical success factors. First, innovative SMR or FNPP technologies and solutions should be advanced as early as possible with cooperation throughout the industrial supply chain. Next, industry standards should be established among SMR technologies to ensure some degree of compatibility and interoperability for energy production. Doing so will help with the regulatory process. Third, user-countries should be committed to adopting and scaling up SMR or FNPP technologies to enjoy the economies of multiples. Finally, and most importantly, "green passage" for transportable SMRs and FNPPs is needed to facilitate safe and efficient mobility of these technologies for nearshore, offshore, and maritime applications.

[39] Victor Nian, Amjad Ghori, Eddie Guerra, Giorgio Locatelli, and Paul Murphy, "Accelerating Safe Small Modular Reactor Development in Southeast Asia," *Utilities Policy*, Vol. 74. February 2022.

2

A 3S Analysis of Small Modular Reactors and Floating Nuclear Power Plants

Jor-Shan Choi

A small modular reactor (SMR) is generally defined as a nuclear reactor with electric-power output between 10 and 300 megawatts (MWe). The SMRs feature compact designs with small fuel inventory and passive safety systems. When compared to large nuclear reactors currently deployed, they require less capital investment and financial risk, are more suitable for small-grids and remote areas, are more adaptable for load-following demands and hybrid nuclear/renewable synergies, and more applicable for off-grid applications, such as process heat, desalination, oil and gas exploration, and hydrogen production. Reactors with power outputs less than 10 MWe, often used for autonomous or semi-autonomous operation are commonly referred to as micro reactors.

SMRs are designed to have a high degree of modularization, with modules manufactured in factories and serially installed on-site as demand arises, which enhances quality control and reduces construction risks. The overall result is higher system-cost benefits for potential customers and more new-market opportunities, which make SMRs a more affordable and attractive option.

SMRs, including those currently in use for maritime applications, e.g., surface ships and submarines, are under active development by many innovative vendors in many countries. Types of reactor designs include water-cooled, high-temperature gas-cooled (HTGR), liquid-metal-cooled with fast-neutron spectrum, and molten salt reactors (MSRs). The 2020 edition of the International Atomic Energy Agency

Table 1 Sample SMRs being developed or deployed in the Indo-Pacific

<table>
<tr><th>Country</th><th colspan="2">Type</th><th>Status</th></tr>
<tr><td>Canada</td><td colspan="2">iMSR</td><td>Canada invested US$15 million to accelerate the development of Terrestrial Energy’s integral Molten Salt Reactor (iMSR).[1]</td></tr>
<tr><td rowspan="7">China</td><td colspan="2">HTR</td><td>HTR-PM, a 2x105 MWe HTGR developed by CNEC and INNET of China, connected to grid in December 2021.</td></tr>
<tr><td colspan="2">FNPP</td><td>• ACP100S, developed by China National Nuclear Corporation (CNNC) and built by Jiangnan Shipyard Co. To be completed in 2023 and provide power to chemical factories[2].
• ACPR50S, developed by China General Nuclear Power Group (CGN) and built by China State Shipbuilding Corp. To be completed in ~2020s, and power oil rigs in Bohai and South China Sea.[3]</td></tr>
<tr><td colspan="2">iPWR</td><td>ACP100, developed by CNNC, which signed an agreement with the Changjiang municipal government in Hainan Province to host the first-of-a-kind (FOAK) demonstration unit. The preliminary safety analysis report was submitted to China’s National Nuclear Safety Authority in 2018, and construction began in 2021.[4]</td></tr>
<tr><td colspan="2">MSR</td><td>TMSR, developed by the Shanghai Institute of Applied Physics, is Thorium-fueled. A 2 MWe prototype began testing in September 2021, with the first commercial version, of about 100MWe to enter service in 2030.[5]</td></tr>
<tr><td rowspan="2">FNPP</td><td>PWR</td><td>BANDI-60S, developed by KEPCO and built by Daewoo Shipbuilding & Marine Engineering. It has been under development since 2016.[6]</td></tr>
<tr><td>MSR</td><td>Developed by KAERI/SAMSUNG HEAVY and built by Geoje Shipyard. The plan was announced in June 2021.[7]</td></tr>
</table>

[1] “Canadian Government Invests in SMR Technology,” *World Nuclear News*, October 16, 2020.

[2] “China’s First Floating Nuclear Reactor May Withstand Once-In-10,000-Years Weather Event,” *SCMP*, September 14, 2021.

[3] “CGN Starts Construction of Offshore Reactor,” *World Nuclear News*, November 7, 2016.

[4] “China Starts Construction of Demonstration SMR,” *World Nuclear News*, July 13, 2021.

[5] “Could China’s Molten Salt Nuclear Reactor Be a Clean, Safe Source of Power?” *SCMP*, July 19, 2021.

[6] Il Hwan Kim et. al., “Development of BANDI-60S for a Floating Nuclear Power Plant,” *Transactions of the Korean Nuclear Society Autumn Meeting Goyang, Korea*, October 24-25, 2019.

[7] “KAERI and Samsung to Develop Nuclear powered Ships,” *Nuclear Engineering International*, June 16, 2021.

Country	Type		Status
Japan	BWR		BWRX-300, developed by GE-Hitachi, is a water-cooled, natural circulation boiling water reactor (BWR) with passive safety systems, based on GEH's US-licensed, Economic Simplified BWR design.[8, 9]
	HTR		HTTR, developed and operated by Japan Atomic Energy Agency (JAEA), is proposed to be used to electrolyze water or through chemical reaction to produce hydrogen.[10]
Russia	iPWR		RITM-200, developed by OKBM, and installed on board the Arktika icebreaker. A land-based RITM-200 is expected in 2027.[11]
	FNPP		• KLT-40S, a 2x35 MWe PWR developed by OKBM, and commissioned in Pevek, Russian Far East in May 2020. • RITM-200M, a 2x50 MWe iPWR being tested on board the Arktika icebreaker.
South Korea	iPWR		System-integrated Modular Advanced Reactor (SMART), jointly developed by KAERI, South Korea, and KA-CARE, Saudi Arabia, with pre-project engineering agreement signed in 2015 and completed in 2019.[12]
	FNPP	PWR	BANDI-60S, developed by KEPCO and built by Daewoo Shipbuilding & Marine Engineering. It has been under development since 2016.[13]
		MSR	Developed by KAERI/SAMSUNG HEAVY and built by Geoje Shipyard. The plan was announced in June 2021.[14]
United States	iPWR		NUSCALE, a 12x60 MWe iPWR developed by NUSCALE VOYGR, obtained design certificate review from the US Nuclear Regulatory Commission (USNRC) in 2020.[15] First commercial plant is expected in 2027.
	HTR		Xe100, developed by X-Energy. Construction expected to begin in 2025[16].
	MSR		ThorCon, developed by ThorCon International, which signed an agreement in July 2019 with PT PAL Indonesia to conduct a development study for building a 500 MWe plant on a 185-metre-long barge built by Daewoo Shipbuilding & Marine Engineering in South Korea.[17]

(IAEA) Advanced Reactor Information System (ARIS) lists over 70 types of conceptual, developed, or deployed SMRs.[18]

<u>SMRs Under Development in the Indo-Pacific</u>

Table 1 provides a sampling of SMRs under development or being deployed in the Indo-Pacific.[19] Reactor types include water-cooled, land- or marine-based; HTGR; and MSR, aqueous-fueled. Most are in their conceptual design stages, but some are more advanced in their developments than others. Two are currently deployed:

- KLT40S, a 2x35 MWe pressurized water reactor (PWR) floating nuclear power plant (FNPP) developed by OKBM, Russia, and commissioned in Pevek, Russian Far East in May 2020;[20] and

- HTR-PM, a 2x105 MWe HTGR developed by the China Nuclear

[8] "Advances in Small Modular Reactor Technology Developments," IAEA 2020 Edition, http://aris.iaea.org

[9] "BWRX-300 (GE Hitachi and Hitachi GE Nuclear Energy) USA," A Status Report, September 30, 2019.

[10] "Japanese Gas-Cooled Reactor Restarts," *World Nuclear News*, August 3, 2021. JAEA said the demonstration plan of hydrogen production by high-temperature test reactor (HTTR) is under discussion.

[11] Darell Procter, "Icebreaker Reactor Approved for Ground-Based NPP," *Power Magazine*, August 9, 2021.

[12] "Korea, Saudi Arabia Progress with SMART Collaboration," *World Nuclear News*, January 7, 2020.

[13] Il Hwan Kim et. al., "Development of BANDI-60S for a Floating Nuclear Power Plant," *Transactions of the Korean Nuclear Society Autumn Meeting Goyang, Korea*, October 24-25, 2019.

[14] "KAERI and Samsung to Develop Nuclear powered Ships," *Nuclear Engineering International*, June 16, 2021.

[15] "NUSCALE SMR Plants Become VOYGR," *World Nuclear News*, December 3, 2021.

[16] "Advances in Small Modular Reactor Technology Developments," IAEA 2020 Edition, http://aris.iaea.org

[17] "Empresarios Agrupados Contracted for First ThorCon Reactor," *World Nuclear News*, January 26, 2022.

[18] "Advances in Small Modular Reactor Technology Developments," IAEA 2020 Edition, http://aris.iaea.org

[19] Table 1 was composed by using and intercomparing SMR data obtained from the IAEA (aris.iaea.org), the World Nuclear Association (world-nuclear.org), and the OECD/NEA No. 7560 (@OECD 2021) after extracting the micro reactors.

[20] "ROSATOM: World's Only Floating Nuclear Power Plant Enters Full Commercial Exploitation," Rosatom, May 22, 2020.

Engineering Corporation (CNEC) and Institute of Nuclear New Energy Technology (INNET), and connected to the grid in December 2021.[21]

SMRs Interest by Newcomer Countries in the Indo-Pacific

The IAEA, in its International Status and Prospects for Nuclear Power 2021, reported that a total of 28 countries have expressed interest in nuclear power and are considering, planning, or actively working to include it in their energy mix.[29] Among them, five countries in Indo-Pacific are interested in SMRs.

In addition, AUKUS, a trilateral security pact among Australia, the United Kingdom, and the United States, announced in September 2021 that it would build a fleet of eight nuclear-propelled submarines for Australia.[30] If these countries succeed in deploying their respective SMRs and submarine reactors, they will be utilizing nuclear power or nuclear-propelled reactors for the first time. Table 2 lists the newcomer countries that may deploy SMRs or submarine reactors in the Indo-Pacific.

Table 2 Newcomer countries potentially deploying SMRs in the Indo-Pacific

Country	Type		Status
Australia	Nuclear-propelled submarine		AUKUS, announced in September 2021, is a trilateral security pact among Australia, United Kingdom, and the United States to build eight nuclear-propelled submarines for Australia. These submarine reactors might be fueled with highly enriched uranium.[22] Construction is scheduled to begin "within the decade" and the first submarines are meant to be in the water before the end of the *next* decade.
Indonesia	HTR		• In March 2018, the National Atomic Energy Agency (BATAN) launched a roadmap for developing a detailed engineering design for a 10 MWe high-temperature gas-cooled reactor (HTR).[23] • In August 2016, CNEC signed a cooperation agreement with BATAN to develop and construct HTRs in Kalimantan and Sulawesi, Indonesia from 2027. • In August 2014, JAEA extended the cooperation agreement with BATAN to include R&D of HTRs.
	FNPP	PWR	In August 2015, ROSATOM and BATAN signed a cooperation agreement on the construction of FNPP.[24]
		MSR	In July 2019, a state shipbuilding company, PT PAL Indonesia, signed an agreement with ThorCon to conduct a development study for building a 500 MWe plant on a 185-meter-long barge built by Daewoo Shipbuilding & Marine Engineering in South Korea.[25]
Jordan	iPWR		In January 2019, the Jordan Atomic Energy Commission (JAEC) signed a MOU with NUSCALE for deploying a NUSCALE SMR in Jordan[26].
	HTR		In mid-November 2019, X-energy signed a Letter-of-Intent with JAEC to accelerate construction of a Xe-100 in Jordan.[27]
Kazakhstan	iPWR		In December 2021, Kazakhstan NPP signed an agreement with NUSCALE to explore SMR deployment in Kazakhstan.[28]

[21] "Demonstration HTR-PM Grid Connected," *World Nuclear News*, December 16, 2021.
[22] Naval submarine reactors can also be fueled with low-enriched uranium, as suggested by James Acton of Carnegie Endowment at https://carnegieendowment.org/2021/09/21/why-aukus-submarine-deal-is-bad-for-nonproliferation-and-what-to-do-about-it-pub-85399
[23] ERIA Research Project FY2021 No.7, sponsored by the Institute of Energy Economic, Japan, July 2021.
[24] Nuclear Power in Indonesia, World Nuclear Association, Updated December 2021.
[25] "Empresarios Agrupados Contracted for First ThorCon Reactor, *World Nuclear News*, January 26, 2022.
[26] "NUSCALE SMR to Be Considered for Use in Jordan," *World Nuclear News*, January 15, 2019.
[27] "US Company Has Deal with Jordan for Nuclear Technology," Power Magazine, January 2, 2020.
[28] NUSCALEPOWER Press Release, December 16, 2021.
[29] International Status and Prospects for Nuclear Power 2021, Report by Director General, July 16, 2021.
[30] AUKUS, announced in September 2021, is a trilateral security pact among Australia, the United Kingdom, and the United States to build nuclear-propelled submarines for Australia.

Country	Type	Status
Philippines	iPWR	The Philippines' Department of Energy completed a pre-feasibility study for deploying a SMART jointly with Korea Hydro & Nuclear Power Co. in 2019.[31]
	FNPP	The Philippines' Department of Energy signed an agreement with ROSATOM in October 2019 for a feasibility study of an FNPP or on-land NPP, probably using RITM-200 reactor.[32]
Saudi Arabia	HTR	In January 2016, Saudi's KA-CARE signed an agreement with CNEC to build an HTR-PM in Saudi Arabia.[33]
	iPWR	In March 2015, Saudi's KA-CARE signed an agreement with South Korea's KAERI to build SMART reactors in Saudi Arabia.

The technological development of SMRs for immediate and near-term deployment is progressing enthusiastically in the Indo-Pacific. Despite the enthusiasm for a large-scale deployment of SMRs, however, these technologies are not expected to contribute much to the expansion of nuclear capacity in the next decade, with the IAEA predicting there could be about 1.6 additional GWe contributed from SMRs by 2030.[34]

Aside from an aspiration for the SMR technology, countries employing SMRs will need to comply with rules, regulations, and requirements associated with utilizing nuclear systems. Chief among these are nuclear safety, security, and safeguards (3S). These requirements encompass national and international regimes that are expressed in national licensing requirements, international treaties, and other bilateral, multilateral, and international arrangements.

Safety, Security, and Safeguards (3S)

With many SMRs still in conceptual design stage, it is prudent to evaluate and ensure that these advanced reactors are safe, secure, and exclusively for peaceful purposes. Nuclear safety, security, and safeguards (3S) are important considerations in the development and deployment of a country's civilian nuclear power program. The implementation of 3S will ensure that the viability, reliability, and acceptability of the country's nuclear power infrastructures, nuclear materials and technologies are safe, secure, and in compliance with its IAEA-safeguards obligations. For instance, the use of highly enriched uranium in the AUKUS reactors may have ramifications for Australia's nonproliferation and safeguards obligations.

In the case of safety, the objectives are protection from the harmful effects of ionizing radiation and limiting radiological releases due to unintended events (accidents).[35] Concerns about radiological releases due to the failure of systems, human errors, or natural phenomena have been a major consideration in the design and operation of large reactors (those in the GWe range). As a result, "SMR safety" benefits from an established comprehensive safety regime that has been in place for many decades. Nevertheless, SMRs have unique safety concerns associated with their compactness, modularization, multi-unit deployment, and supply-chain management.

Security deals with the measures to protect a nuclear facility and its nuclear material against malevolent acts, such as sabotage or theft by criminals and terrorists.[36] Specific features of SMRs, such as transportability, remote or urban locations, floating platform, and new fuel designs, present new nuclear security challenges, which may be more severe than those of large reactors.

The adherence to IAEA safeguards provides assurance to the international community that a country's nuclear activities related to the employment of SMRs are exclusively for peaceful

[31] "Philippines Needs to Push Nuclear Power," March 18, 2021, aseanenergy.com

[32] "Russia and Philippines Plan a Pre-feasibility Study on SMR for Philippines," *ROSATOM News*, January 20, 2022.

[33] Nuclear Power in Saudi Arabia, World Nuclear Association, Updated June 2021.

[34] International Status and Prospects for Nuclear Power 2021, Report by Director General, July 16. 2021.

[35] The IAEA Glossary defines "Safety" as the achievement of proper operating conditions (of a nuclear technology), prevention of accidents or mitigation of accident consequences (from a nuclear facility), resulting in protection of workers, the public and the environment from undue radiation hazards.

[36] The IAEA Glossary defines "Security" as the prevention and detection of, and response to theft, sabotage, unauthorized access, illegal transfer, or other malicious acts involving nuclear material, other radioactive substances, or their associated facilities.

purposes.[37] It is just as important as safety and security. Safeguards and inspection activities are applied by the IAEA and is intended to detect and deter the diversion of nuclear materials or the misuse of nuclear technologies for the development of nuclear explosive devices. In this regard, some SMRs present unique challenges to IAEA safeguards as they use different types of fuel, enrichment, and form, hence requiring new fuel-cycle technologies in manufacturing and handling of nuclear materials.

Successful strategies for developing and deploying SMRs must include these three vital and necessary elements. The following sections assess each element individually, focusing on the gaps and challenges posed by the development and deployment of SMRs in the Indo-Pacific. The 3S are also assessed holistically to provide an effective and efficient examination of the gaps and challenges for the specific types of SMR technologies, such as the FNPP or the molten-salt reactors, among others. These assessments rely on non-propriety design data of SMRs available in the public domain, and hence subject to some interpretation.[38]

<u>Nuclear Safety</u>

Throughout the history of the nuclear industry, protection of workers, public, and the environment has been an important priority. Large, water-cooled reactors in the existing nuclear fleet have multiple safety systems and defense-in-depth barriers against radiological release. Severe accidents damaging the reactor core involve multiple successive failures, making the frequency of occurrence rare. The USNRC evaluates the risk for operating nuclear power plants in the United States against a core-damage-frequency (CDF) goal of less than 1 x 10-4 per year.[39]

Most SMRs utilize a compact core and small fuel inventory, many are equipped with passive safety systems (e.g., reactor coolant in water-cooled reactors flow via natural circulation with no active coolant pumps), and some integrate the pressurizer and steam generators inside the reactor vessel, eliminating the need for large diameter piping to carry primary coolant outside-of-reactor-vessel (e.g., the integral Pressurized Water Reactor, or iPWR). As a result, the CDF for the SMRs is expected to be orders of magnitude below the USNRC's CDF goal (e.g., the total CDF including both internal and external events for NUSCALE is ~ 1 x 10-7 per year).[40] However, many SMRs are FOAK reactors with unique features, specific systems, and novel operating conditions, which pose safety implications and introduce new challenges to regulatory bodies. Some of these challenges include:

- *Compactness* – Some SMRs are compact to enable factory assembly and facilitate transportation to plant sites. However, compactness may make necessary maintenance and inspections, for instance, non-destructive examination of welds and components, more challenging.

- *Integration of nuclear steam supply system (NSSS) Inside Reactor Vessel* – Some SMRs have the entire NSSS contained within the reactor vessel (or in a single module), such as an iPWR (e.g., NUSCALE). There are safety and maintenance concerns if malfunction or failure of a major component (e.g., steam generators) occurs inside the reactor vessel.

- *Modularization or multi-unit* – Most SMRs have multi-modules in a reactor (e.g., NUSCALE). The challenge to safety is to avoid the propagation of common-mode manufacturing defects among modules. Some SMRs have two or more modular reactor units on-site. Lessons from the multi-unit Fukushima-Daiichi nuclear power plant accident indicates that the use of shared systems among modules/units may introduce safety risks in operation among the modules/units.

- *Manufacturability* – The challenge is for the SMR manufacturers to (1) demonstrate the capacity and capability to address nuclear safety requirements, and (2) maintain configuration management from the FOAK

[37] The IAEA Glossary defines "Safeguards" as a set of technical measures applied by the IAEA on nuclear material and activities, through which the Agency seeks to independently verify that nuclear facilities (and associated technology) are not misused, and nuclear material not diverted from peaceful uses.

[38] The assessments also relied on information obtained from several IAEA activities relating to SMR developments, such as the IAEA Regulatory Forum for SMRs; 3S interfaces and challenges for SMRs; or 3S for novel advanced reactors.

[39] US Nuclear Regulatory Commission, "19.0 - Probabilistic Risk Assessment and Severe Accident Evaluation for New Reactors," NUREG-0800, Rev. 3 (2015), ADAMAS Accession No. ML15089A068.

[40] NUSCALE Standard Plant Design Control Document Part 2 – Tier 2, Chapter 19: Probabilistic Risk Assessment and Severe Accident Evaluation, Rev. 2 (2018), ADAMS Accession No. ML18310A342.

SMR to the nth-of-a-kind SMR. Special attention is required for factory-fueled or -sealed transportable reactor modules because the manufacturing process introduces nuclear material in the factory and would trigger a step change in nuclear 3S risks, including safety.

- *Emergency preparedness zoning* – SMRs encompass a variety of nuclear power plant designs and deployment locations. Some SMRs are sited at urban locations close to densely populated centers. There is a need to consider community emergency preparedness, for example, to receive public information and perform response drills.

- *Graded approach* – From a safety perspective, it is challenging for designers and operators of special-case SMRs, such as marine-based reactors, to apply a graded approach to their safety requirements, and demonstrate that their requirements can be graded, as there may be a need for regulators to define specific requirements for some special-case SMRs.

- *Defense-in-depth (DiD)* – An important challenge for DiD in SMRs is to achieve a well-balanced safety concept based on the use of optimal combination of active, passive, and inherent safety features. The use of passive systems may create new challenges, such as new innovative technologies without sufficient operational experience, uncertainties related to qualification and reliability assessments, operational aspects as periodic testing, maintenance, and in-service inspections.

- *Supply chain management* – SMRs may use a variety of supply-chain vendors. The challenges are for licensed operators to establish adequate supply chain management to ensure that safety products are delivered, and services critical to maintaining safety are performed, in a timely manner and in compliance with the appropriate practices, codes, and standards.

- *Convention on Nuclear Safety (CNS)* – The CNS is currently applicable to land-based reactors only. Vendor countries wanting to export marine-based SMRs may need to amend the CNS to include this type of special-case SMRs.

<u>Nuclear Security</u>

Nuclear security focuses on criminal or intentional unauthorized acts and other associated activities. Countries employing SMRs need to establish and implement an overall nuclear security strategy that works to protect people, property, and the environment against the malicious use of nuclear or radioactive material, or sabotage of the SMRs. The most important part of the nuclear security is the physical protection of nuclear or radioactive materials and the SMR facilities. Many FOAK SMRs possess unique design features and operational conditions, which may pose challenges to nuclear security, as briefly discussed below:

- *Transportability of SMRs* – Transportation security may have multiple challenges, including uncertainties with the public domain, the possibility of attack anywhere along the transport route, and the involvement of multiple national, regional, international agencies with multiple security interfaces.

- *Security and demarcation of physical protection perimeters for marine-based SMRs (FNPPs or immersible SMR)* [41] – It is difficult to set physical protection perimeters for marine-based SMRs as they are susceptible to seaborn threats when in transit or docked at a port facility.

- *Remote locations* – The difficulty of physical access to remote sites can present challenges to nuclear security. In the case of an attack, it will be difficult for any offsite response force to access the site in a timely manner. Additionally, the deployment of onsite response force may be difficult or inadequate.

- *Location in urban areas* – The siting of SMRs at locations close to urban population may

[41] FLEXBLUE-160, a transportable reactor concept to be moored on the seafloor, designed by France's Direction of Construction Naval and Submarines and under development since 2011 "Instrumentation and Control Systems for Advanced Small Modular Reactors, FLEXBLUE (DCNS, France) Annex A-4," inis.iaea.org

present challenges to the setting of a physical protection zone and site boundary around the facility. The demarcation of the protected areas around the reactor complex and spent fuel storage facility may be mostly affected.

- *Small size of fuel assemblies* – The shorter (fresh and spent fuel) assemblies or a container-load of fuel pebbles are easier targets for theft, in comparison to the 14-foot-long light water reactor (LWR) assemblies. This concern may be elevated for SMRs located in remote sites with less attention to physical protection of nuclear fuel and materials.

- *New fuel & new fuel cycles* – The new types, enrichments, and forms of fuel, which are used by some SMRs require different fuel-cycle processes and facilities than those that support the current LWR fuel-cycle. This would impose new security challenges in protecting the fuel and fuel-cycle facilities.

- *Graded approach* – The main challenge is to develop a regulatory approach that will consider radiological consequences and health impacts to the public in case of a radiological release caused by design basis security threats for the SMRs.

- *Insider threats* – Insider threats present more challenging problems than external adversaries because they can take advantage of their insider attributes to bypass technical and administrative physical-protection measures to facilitate unauthorized removal of nuclear materials or sabotage. These threats apply to all nuclear facilities, including SMRs.

- *Cybersecurity* – The overall goal of cybersecurity in the physical protection of nuclear material and nuclear facilities is to protect the digital-based systems against attacks aimed at facilitating the unauthorized removal of nuclear material or sabotage of nuclear facilities. The cybersecurity threats apply to all nuclear facilities, including SMRs.

<u>IAEA Safeguards</u>

The IAEA safeguards aim at providing credible assurances that countries are meeting their legal obligations to ensure that nuclear material and technology are being used exclusively for peaceful purposes. The challenges in applying the IAEA safeguards to SMRs relate to the gaps that may exist between the current application of IAEA safeguards to predominantly water-cooled power reactors and those SMRs with novel-advanced designs. These gaps and challenges are briefly discussed below:

- *Transportation of factory-loaded reactors* – In the case of in-factory-built reactors, the challenge is to ensure that the IAEA safeguards can be applied, and that the continuity of knowledge can be maintained at the central factory where the core is loaded with nuclear fuel, in transport of the factory-loaded reactor to, and during, its installation at the sites.

- *Marine-based SMRs* – In the case of a FNPP, the challenge is for IAEA safeguards inspectors to gain access to the reactor and maintain continuity of knowledge. This challenge is due to the special confinement, mobile nature, and a lack of a fixed "site-location" of the marine-based reactor.[42] In addition, the IAEA may not have direct experience with performing inspections for such facilities.

- *Non-electrical end-use and intermittent operations* – Many SMRs are intended to be used for off-grid applications, such as process heat, desalination, oil and gas exploration, and hydrogen production. As a result, these reactors would not be operated in a steady-state condition, and hence may complicate the IAEA's confidence in the correctness and completeness of the countries' reporting on reactor operations.

- *On-load refuelling SMRs* – Some SMRs use pebble fuels where solid fuel spheres are continuously fed, withdrawn from, and recycled back into the reactor core when reactors are in operation, similar to the fuel

[42] The current definition of *site* as in INFCIRC/540 (corrected) assumes it is a geographically precise static area containing the nuclear facility, definable from the design information of the facility itself. Contrary to typical nuclear installations, FNPPs are intrinsically mobile, and no *site* could be identified from their design information.

bundles shuffling in-and-out of CANDU reactors. However, these pebble fuels are more in numbers and much smaller than the CANDU fuel bundles. Also, the recycling path creates a challenge for IAEA safeguards.

- *On-load processing SMRs* – Some SMRs use aqueous molten-salt fuel, which circulates in and out of the core for continuous processing when the reactor is in operation. The IAEA material control and accountancy will be challenging for these MSRs because there is currently no safeguards-ready method to measure the nuclear material directly in the irradiated salt, and because developing a measurement system for nuclear materials in the fuel salt is challenging due to the high radiation fields for short-cooled fuel salt.

- *Size, enrichment, and form of fuel* – As the physical, isotopic, and chemical properties of these fuel are deviated from those of water-cooled reactor fuel, the challenge for IAEA safeguards is to devise new sets of technical measures and accounting procedures to adequately verify the countries' nuclear activities, and to assure that the countries are in compliance with their safeguards obligations.

- *New fuels and fuel cycles* – Many SMRs are designed to use novel fuel (e.g., high-assay low enriched uranium, plutonium-bearing, or thorium-based), and some may require new fuel-cycle processing facilities (e.g., reprocessing/recycling, plutonium-based, or thorium-based manufacturing). [43] The challenge for IAEA safeguards is to develop new verification techniques for these new fuels and fuel-cycle facilities.

- *Limited access* – If it is difficult or impossible to access nuclear material inventory in certain type of SMRs (e.g., in sealed-core or highly-autonomous reactors), the challenge is to devise new and advanced monitoring and surveillance techniques, as current safeguards practices could be unsuitable for these situations.

- *Lack of measurement technologies and verification techniques for SMRs* – Since the ability to measure, or to verify operator's measurements of nuclear material to draw material balances and determine material unaccounted for is central to IAEA safeguards, it is a major challenge for IAEA safeguards to develop specific measurement techniques to address the gaps for SMRs outlined above.

International Legal Instruments for the 3S

Binding international legal instruments are an important part of the implementation of the nuclear 3S. Table 3 includes a brief list of several key international legal instruments for 3S, and Table 4 shows the latest status of compliance with these key instruments by countries in Indo-Pacific that are interested in SMRs, i.e., those listed in Tables 1 and 2.[44]

Table 4 indicates that most countries in the Indo-Pacific interested in SMRs are currently (as of February 2022) in compliance with key international legal instruments relevant for 3S management, except

Table 3 A brief list of international legal instruments for 3S management

3S	Key International Legal Instruments
Safety	• Convention on Nuclear Safety (CNS) • Convention on Early Notification of a Nuclear Accident (CENNA) • Convention on Assistance in Case of Nuclear Accident or Radiological Emergency (CACNARE)
Security	• Convention on Physical Protection of Nuclear Materials (CPPNM) • The Amendment of Physical Protection of Nuclear Materials (A/CPPNM)
Safeguards	• Treaty on the Nonproliferation of Nuclear Weapons (NPT) • Comprehensive Safeguards Agreement (CSA) • Additional Protocol for Verification of Nuclear Safeguards (AP)

[43] Uranium with a ^{235}U enrichment higher than 5% but lower than 20%.

[44] Status, as of February 2022.

Table 4 Compliance with key international legal instruments by Indo-Pacific countries interested in SMRs

	Security		Safety		Safeguards	
Indo-Asia-Pacific Countries interested in SMRs	**CPPNM**	**CPPNM Amendment**	**Early Notification of Nuclear Accident**	**Conv. of Nuclear Safety**	**CSA (Infcirc #)**	**Additional Protocol**
Australia	10/22/1987	5/8/2016	10/23/1987	3/24/1997	217	12/12/1997
Canada	2/8/1987	12/3/2013	2/18/1990	10/24/1996	164	9/8/2000
China	2/9/1989	5/8/2016	10/11/1987	10/24/1996	369, VOA	3/28/2002
Indonesia	2/8/1987	5/8/2016	12/13/1993	7/11/2002	283	9/29/1999
Japan	11/27/1988	5/8/2016	7/10/1987	10/24/1996	255	12/16/1999
Jordan	10/7/2009	5/8/2016	1/11/1988	9/10/2009	258	7/28/1998
Kazakhstan	10/2/2005	4/26/2011	4/9/2010	6/8/2010	504	5/9/2007
Korea, RO	2/8/1987	5/8/2016	7/9/1990	10/24/1996	236	8/19/2004
Philippines	2/8/1987	6/16/2021	6/5/1997	(10/14/1994)	216	2/26/2010
Russia	2/8/1987	5/8/2016	1/24/1987	10/24/1996	327, VOA	10/16/2007
Saudi Arabia	2/6/2009	1/21/2011	12/4/1989	6/16/2010	746	
USA	12/13/1982	7/31/2015	10/20/1988	7/10/1999	288, VOA	1/6/2009

Note: Status as of February 2022; (date) = signed, not yet ratified; VOA = Voluntary Offer Agreement

Saudi Arabia, which is not yet a signatory to the Additional Protocol, and the Philippines, which has not yet ratified the CNS. It would be most helpful if they would be in full compliance with their key international legal instruments by the time SMRs are introduced to their respective countries.

A Holistic Approach of Integrating the 3S

When 3S is considered holistically, as illustrated in Figure 1, the interfaces between each of the 2S pairs are: facility (safety-security), materials (security-safeguards), and technology (safeguards-safety). With the aim of preventing radiological release, Figure 1 indicates that both safety and security focus on the "facility", e.g., a SMR, or a fuel-cycle processing facility. Focusing on preventing weaponization with nuclear "materials", security is to prevent adversaries, including terrorists and insiders from theft and unauthorized removal of materials, to make improvised nuclear devises or radiological dispersal devises, while IAEA safeguards is to ensure that a host country would not divert the material or misuse the technology to develop nuclear weapons. With the focus on preserving countries' inalienable right to pursue the peaceful use of nuclear technology, countries have to ensure that the technology is safe, and safeguard-able by the IAEA to meet countries' obligation to the NPT.

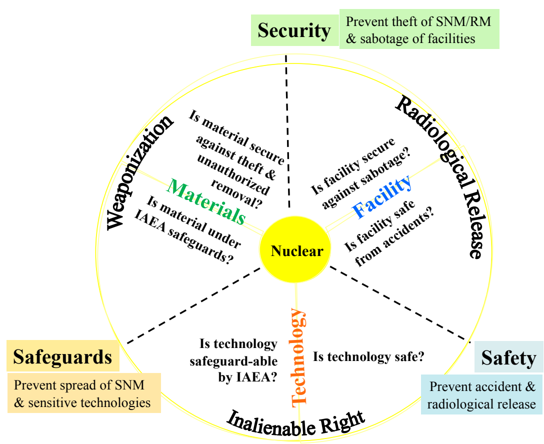

Figure 1 A holistic illustration of nuclear 3S (safety, security, safeguards).

The destinations of these interfaces (or focal points) are not always so rigid. For example, besides its focuses on facility and technology, safety may also have a "materials" focus when criticality safety is considered in a fuel-cycle processing facility. Also, besides its materials and technology focuses, IAEA safeguards may also include "other facilities," for instance in its request for complemental access to a facility during a routine inspection.

A holistic approach, i.e., considering the 3S and their interfaces, is used to assess the challenges to safety, security, and safeguards presented by the FNPP. To present a holistic view on this SMR technology, relevant questions are raised on 3S and their respective interfaces, such as:

- "Facility" interface: "How to establish the emergency-response zone and the physical-protection perimeter?
- "Material" interface: "How to protect fresh and spent fuel on a ship?" and "How would IAEA safeguards maintain containment/surveillance of fresh and spent fuel on a ship?"
- "Technology" interface: "Are the reactor and its higher enriched fuel on a ship safeguard-able by IAEA?" [45] and "Can the CNS, currently applicable to land-based reactors, be applicable?"

An example of relevant questions raised in such holistic approach is shown in Figure 2.

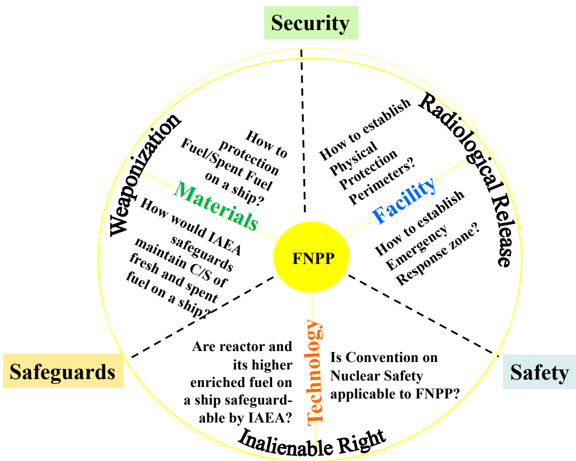

Figure 2 A holistic illustration of the 3S for a FNPP

Another example of a holistic 3S approach for an aqueous-fuel, molten-salt reactor (MSR) is demonstrated in Figure 3. The relevant questions raised for the MSR include the following:

- "Facility" interface: "Would a malfunction or an accident in the aqueous-fuel processing system impact the safe operation of the MSR?" and "What if the malfunction or accident were caused by a cyberattack of the aqueous-fuel processing system?"
- "Material" interface: "How to prevent the siphoning of aqueous fuel in the out-of-reactor processing stream?" and "How would IAEA safeguard the aqueous-fuel streaming in-and-out-of-the-reactor?"
- "Technology" interface: "Is an on-power refueling and side-stream processing MSR safeguard-able by the IAEA?" and "Is the reactor safe to operate with the reactive chemical agents used in the side-streaming process?"

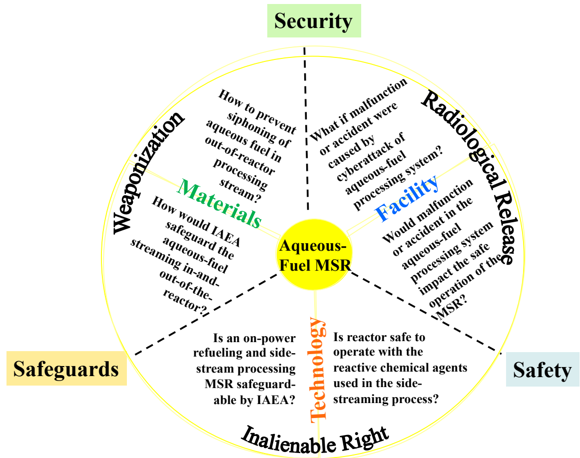

Figure 3 A holistic illustration of nuclear 3S for an aqueous-fueled MSR

These questions should be addressed by all stakeholders (e.g., designers, investors, regulators, IAEA safeguards managers, operators, and country leaders) of the relevant SMRs for a successful development and deployment of such technologies, to ensure that these SMRs are safe, secure, and purely for peaceful purposes.

More importantly, a holistic 3S approach can help highlight 3S challenges and opportunities, as discussed in the next section.

3S Challenges and Opportunities in Deploying SMRs in the Indo-Pacific

Applying a holistic 3S approach to assess the deployments of SMRs in the Indo-Pacific can lead to a better understanding of the 3S challenges and opportunities associated with those deployments, as presented in the examples listed in Table 5 for:

[45] An example of an FNPP is the AUKUS submarine reactors. If Australia gets such reactors, it will be the first Non-Nuclear Weapons State under the NPT to seek IAEA safeguards exemption to remove its approximately 95% highly enriched uranium from safeguards/inspection when this nuclear-weapons-materials are used as fuel in the submarines, in what IAEA calls "non-proscribed military activity." Australia would also be the first to test this "loophole" in the NPT and paragraph 14 of INFCIRC/153 (Corr.).

- Safety: regulatory framework, operation, and maintenance;
- Security: domestic nuclear security framework and spent fuel management;
- Safeguards: proliferation resistance vs. IAEA safeguards, lack of IAEA safeguard technologies for SMR.

Conclusions

The technology development of SMRs for immediate and near-term deployment is progressing enthusiastically in the Indo-Pacific but they are not expected to contribute much to the expansion of nuclear capacity in the next decade. Countries employing SMRs, especially those newcomers committing to nuclear power for the first time will need to comply with a myriad of rules, regulations, and requirements that come as part of the responsibility package when utilizing SMRs. Chief among these are the requirements on nuclear safety, security, and safeguards. These 3S requirements encompass national and international regimes expressed in national licensing requirements, international treaty obligations, and other bilateral, multilateral, and international arrangements.

With many SMRs still in conceptual design stage, it is prudent to evaluate and ensure that these novel-advanced reactors are safe, secure, and exclusively for peaceful purposes. However, many SMRs are designed with unique features, specific systems, and novel operating conditions, especially those FOAK reactors, which would (1) pose safety implications and introduce new gaps in regulatory requirements; (2) present new challenges to nuclear security in protecting nuclear materials and preventing sabotage of SMR facilities; and (3) create major challenges to IAEA safeguards in developing new and specific measurement techniques to address the gaps that exist between the current application of safeguards to predominantly water-cooled power reactors and those SMRs of novel-advanced designs.

These gaps and challenges, presented in a holistic view that integrates the 3S and their interfaces, should be addressed by all stakeholders (i.e., designers, investors, regulators, IAEA safeguards managers, operators, and country leaders) of the relevant SMRs for successful development and deployment of such technologies, to ensure that these SMRs are safe, secure, and for purely peaceful purposes. More importantly, such a holistic 3S assessment can lead to a better understanding of 3S challenges and opportunities.

Table 5 The 3S challenges and opportunities in deploying SMRs in the Indo-Pacific

3S	Challenges	Opportunities
Safety	Regulatory Framework	
	Large number of SMRs are "singular" designs with unproven technology.[46] New regulatory processes (e.g., rules and regulation, safety requirements and guides), which may be different from those for large LWRs need to be adapted. It is challenging to harmonize these regulatory processes among regulator bodies of vendors and recipient countries before SMRs are exported/imported.	Learning from the IAEA Regulatory Forum, which enhances nuclear safety by identifying and resolving common safety issues that may challenge regulatory reviews associated with SMRs, there are opportunities for regulators (such as, ASEANTOM) in Indo-Pacific countries to form cohesive regulatory bodies to govern the safety of all SMRs in the region.[47]
	Operation and Maintenance	
	Many SMRs are FOAK reactors with little or no operational/maintenance experience. This challenge is made worst for common-cause failures in equipment/systems of modular SMRs.	There are opportunities for vendors to learn/gain operational/maintenance experience from a prototype, or first module of the SMR. Recipient countries in the Indo-Pacific interested in that SMR technology can learn with the vendors.
Security	Domestic Nuclear Security Framework	
	Many countries in the Indo-Pacific lack the financial and human resources to establish domestic nuclear security infrastructures to deal with the security aspects of deploying SMRs, notably in remote locations.	There are opportunities for vendor countries to work with recipient countries on securing SMRs (against sabotage) and protecting nuclear fuel and materials (against theft) before exports are made.
	Spent Fuel Management	
	Spreading SMRs implies proliferating nuclear materials in the form of spent SMR fuel to many countries, including some located in conflicting regions or security hotspots. This challenge is made worst as radioactive decay will diminish the self-protecting radiation, making spent fuel attractive targets to adversaries (insiders or terrorists) for theft or direct assault.	SMR vendors and recipient countries may cooperate in new spent fuel management schemes, including spent-fuel take-back or take-away options, especially for spent fuel stored at conflicting regions or security hotspots. In the Indo-Pacific, ASEAN should work on achieving these new spent fuel management schemes before importing SMRs.
Safeguards	Proliferation Resistance vs. IAEA Safeguards	
	Vendors often focus on proliferation resistance as the design goal for safeguards. For example, a sealed SMR is most proliferation resistant as its core is not accessible. However, IAEA safeguards may view the sealed core as a covert plutonium factory as accounting for all nuclear materials in the SMR is its goal.	Vendors of SMR technologies could work with IAEA safeguards managers in the early phase of the design development to establish a common understanding that the SMR technologies are "safeguard-able" by the IAEA.

[46] "Reactors of Singular Designs," defined in the Joint NEA IAEA International Symposium on PSA for Reactors of Singular Designs by OECD/NEA are research reactor, demonstration reactor, prototype reactor, FOAK reactor, SMR, and Generation IV reactors.

[47] The SMR Regulators' Forum, created by the IAEA in March 2015, provides enabling discussions among Member States and other stakeholders to share SMR regulatory knowledge and experience.

3

Geopolitics and the Deployment of Small Modular Reactors in South and Southeast Asia

Miles Pomper, Ferenc Dalnoki Veress, Dan Zhukov & Sanjana Gogna

There has been considerable hype about the possibility of deploying small and modular reactors (SMRs), including floating nuclear power plants (FNPPs) in Southeast Asia. Such hype has been buoyed by the region's thirst for additional energy sources amid soaring demands for electricity, SMRs' perceived ability to overcome previous geographic and infrastructure obstacles, and a search for low-carbon resources to offset many countries' current use of coal and (often imported) natural gas. Such hype has only grown in the wake of the Russian invasion of Ukraine, and subsequent efforts to choke off Russian natural gas and oil exports and the resulting increase in global prices for fossil fuels.[1]

Russia has been relentless in its efforts to increase its nuclear exports (both traditional and SMR) to the region as well as other regions around the globe. Meanwhile, China looms over the horizon as a potentially important supplier and competitor given its strong political and economic influence in the Indo-Pacific and its growing domestic nuclear industry. Given already intense competition for influence in the region – particularly between the United States and China – some in Washington worry that the United States is at risk of losing not only potential markets but surrendering geostrategic influence to its global rivals.

This paper seeks to address these concerns. It looks first at why some believe that nuclear energy exports provide geopolitical benefits to suppliers. Then, it examines how the emergence of SMRs might shift these dynamics from those surrounding conventional larger scale reactors. Next, it delves into how competition for regional influence might play out among SMR suppliers – especially China, Russia, and the United States – both generally and in specific markets. It concludes with a skeptical net assessment of the importance of SMR exports for geopolitical influence in the Indo-Pacific.

The Geopolitics of Nuclear Energy

From a geopolitical perspective, nuclear power plant exports have been viewed traditionally as more significant than that of other fuel plants. This perspective reflects several unique aspects of such exports. First, nuclear energy – especially fuel cycle facilities but even nuclear reactors – cannot shed its association with its "Siamese twin," nuclear weapons. Not just because the same facilities can be used for both purposes. Maintaining a vibrant nuclear energy industry, whether for domestic purposes or exports, indirectly helps support the supply chain for nuclear navies and nuclear weapons as well as jobs for veterans of these military programs.[2] It is no accident that the four largest nuclear energy programs in the world – the United States, Russia, China, and France – also possess the four largest arsenals of nuclear weapons. These countries are also strong exporters of peaceful nuclear technology.

Because of this link, nuclear power plant exports are tightly controlled and regulated by governments. Governments have enacted rules and institutions, such as full-scope safeguards implemented by the International Atomic Energy Agency (IAEA) and the Nuclear Suppliers Group to limit the proliferation risks of nuclear trade. They have also agreed on international conventions on nuclear safety and security to attempt to prevent nuclear accidents (such as the Chernobyl accident) or terrorist sabotage attacks or thefts of nuclear material. In addition, governments engaged in a nuclear transaction require mutual trust as they must work closely together to bring such a project to fruition and throughout the operation of these facilities to ensure they are safe, efficient, and transparent.

Second, countries often prefer to settle on a standardized design for their plants to simplify operation, regulation, and refueling. As a result, initial sales often are viewed as "winner-take-all" propositions, and competition can be intense.

Third, nuclear power plants are expensive – running into the billions of dollars – and construction can take a decade or more, putting an additional premium on trust and financing during the construction period.

Fourth, nuclear plants are technologically complex, generally requiring the supplier to provide extensive training and education to nuclear newcomers and garnering technological prestige for the supplier.

Fifth, each nuclear fuel plant is designed to use only its manufacturer's fuel, unlike an equivalent fossil fuel plant where, for example, natural gas can come from any supplier. As a result, refueling is

[1] Dominic Faulder, "Asia's Nuclear Power Dilemma: Ukraine War Drives Energy Turnarounds," *Nikkei Asia*, last modified April 20, 2022, https://asia.nikkei.com/Spotlight/The-Big-Story/Asia-s-nuclear-power-dilemma-Ukraine-war-drives-energy-turnarounds

[2] Jane Nakano, *The Changing Geopolitics of Nuclear Energy: A Look at the United States, Russia, and China* (Washington, DC: Center for Strategic and International Studies, March 2020), p. 18

traditionally supplied by the plant manufacturer throughout the lifetime of the plant, providing the plant supplier not only with an ongoing revenue stream but also ensuring a decades-long dependent relationship. Jessica Jewell *et al*., for instance, write that while "oil and gas risks are primarily short-term shocks," which can be dealt with by strategies such as excess storage and supplier diversification, "nuclear power risks entail long-term dependencies which cannot be addressed as simply since they lock client countries into particular dependencies that cannot be easily addressed."[3]

Finally, some key nuclear exporters, such as Russia, China, South Korea, and France rely on state-run nuclear plant manufacturers, making the industry an even more direct tool of state power. This is particularly important for China and Russia, since they (unlike France and South Korea) do not belong to the Organization for Economic Cooperation and Development (OECD), which means that their nuclear financing options are not restricted by OECD rules on export subsides.[4] Both Russia and China have offered large amounts of long-term financing at very low interest rates, and both have been willing to invest equity in projects. Also, Russia and China are willing to lend money to risky customers. Their funding has gone primarily to countries that are considered below investment grade.

These factors may make the deals commercially unsound. As Jane Nakano notes:

> In the United States, every single company must find its own individual piece of the deal to be compelling, as a U.S. company can only look to the short-term effect of the commercial considerations within the contract that pertains to its role in the deal. Under the state-led export model, however, a [plant construction] contract that barely breaks even may still be viable if the deal enables profits through other aspects over multiple decades. The provision of fuel supply, spare parts, plant services, and operating services are commercially low-risk areas with strong profit margins.[5]

At the same time, these nuclear ties take place within broader relationships, with many other dynamics. For instance, Russia has been building a nuclear plant in Turkey even as the two countries have been facing off in Libya and the Armenia/Azerbaijan conflict. Ukraine, for its part, has managed to substitute Westinghouse fuel for Russian fuel in some of its former Soviet reactors. Previous large US exports to China also did not prevent the deterioration in relations between Washington and Beijing in recent years and may even have exacerbated them.

In addition, geopolitical leverage cuts both ways. By engaging in nuclear trade, a supplier is vulnerable to efforts by the customer to use the transaction to advance its geopolitical or other interests, by changing the terms of the transaction or slowing construction. Once the supplier has committed money and manpower to the facility, it cannot move them elsewhere easily.

To quote Jane Nakano again:

> Nuclear commerce is geopolitical in nature and creates multi-decadal ties between supplier and recipient countries, but nuclear commerce may not be an effective tool of foreign policy leverage…evidence of nuclear commerce serving as an effective tool of foreign policy leverage in specific instances is limited in nature and hard to substantiate.[6]

Not that the lack of evidence has deterred suppliers from seeking to utilize this perceived leverage. Yet different suppliers view the relationship between nuclear trade and geopolitical interests in different ways.

For Russia, nuclear energy exports and energy exports more generally are key foreign tools to try and maintain global influence outside of its region. The United States is also interested in nuclear exports for geopolitical reasons. However, US geopolitical goals are different. Washington's primary interest lies in continuing to shape the global nuclear, safety, security, and especially nonproliferation regimes to prevent the emergence of new regional nuclear powers. For Japan and South Korea, nuclear exports

[3] Jewell, Jessica, Marta Vetier, and Daniel Garcia-Cabrera, "The International Technological Nuclear Cooperation Landscape: A New Dataset and Network Analysis," *Energy Policy*, Vol. 128, 2019, pp. 838-52.
[4] John Siciliano, "Old rule obstructs Trump nuclear agenda," *Washington Examiner*, June 13, 2019, https://www.ifnec.org/ifnec/upload/docs/application/pdf/2016-06/d.drysdale.oecd_financing_rules_for_nuclear_power_projects_2016-06-03_09-53-8_426.pdf

[5] Nakano, p. 13
[6] Nakano, p. 3.

are a way to support flagging domestic nuclear industries and to deepen economic ties to other countries in the Indo-Pacific, as well as to strengthen their roles as important regional powers. China sees nuclear power as part of its broader efforts to claim greater leadership in technology exports, advance its ambitious Belt-and-Road Initiative (BRI) and other infrastructure export efforts, leverage underused domestic capacity, and fight the United States for global economic and political advantage. India, meanwhile, has long had a disappointing domestic nuclear industry, albeit hopes that in a new era it can become a nuclear exporter, earning it global prestige and money, and can join the "nuclear club" despite not having signed the Nuclear Nonproliferation Treaty (NPT).

A Solution for Climate Change?

Countries that supply nuclear reactors like Russia and the United States stress the important role that nuclear energy can play in mitigating climate change.[7] In Russia, officials from both the export behemoth Rosatom and the Russian government have been quick to stress the importance of nuclear power as one of the required pillars of that solution. For instance, the president of the Russian Academy of Sciences, Aleksandr Sergeev, outlined the role of Rosatom's numerous nuclear power projects in increasing Russia's standing as an exporter of such technologies, thus lending strength to its arguments for including nuclear into the list of "green" sources of energy.[8] Russian President Vladimir Putin himself listed the development of SMRs and FNPPs as a necessary step toward global decarbonization.[9]

The United States also highlights the important role of nuclear energy in combatting climate change. Most recently, the United States Assistant Secretary Kathryn Huff stated at the 2021 United Nations Climate Change Conference (COP26) that the "Biden Administration views nuclear power as vital to meeting our national and global climate goals."[10]

Many of the countries in the Indo-Pacific are among the most vulnerable to climate change, with India, Vietnam, Bangladesh, Japan, and the Philippines suffering from catastrophic typhoons, monsoons, and other inclement weather events.[11] Countries such as India are also prolific users of coal and have contributed greatly to the climate problem. Other countries in the Indo-Pacific with less climate risk have not made a clear commitment to global mitigation of climate change. At the COP26, many countries pledged to reach net-zero carbon emissions, committing to attaining net-zero carbon emissions target dates ranging from 2050 to 2070.[12] Countries in the Indo-Pacific varied in their commitments. Some enshrined these commitments into law. Others stated it in policy documents. Still others merely pledged their commitment at international meetings.

SMRs Versus Traditional Nuclear Power Plants

SMRs are generally defined as power reactors not exceeding 300 MWe (megawatts electric, i.e., the electric power it can produce).[13] [14] The high capital cost of large power reactors and the necessity to serve smaller electrical grids drive the development of smaller units. The reactors are constructed with prefabricated components and tend to be modular in nature. Construction can be expedited, deployment can occur using rail or even truck delivery, and the reactor customized for particular power generation scenarios. FNPPs are a category of SMRs deployed aboard marine platforms and built at a shipyard. They are then towed to, and moored at, a remote site, and refueled once their reactor fuel is depleted.

SMRs are a third to a tenth the size of traditional reactors and could provide baseload power to support wind farms and solar arrays, as well as

[7] Dmitri Trenin, "After COP26: Russia's Path to the Global Green Future," Carnegie Endowment for International Peace Nov 16, 2021. https://carnegiemoscow.org/commentary/85789

[8] Yury Medvedev, Sergey Tikhonov, "Президент РАН Александр Сергеев: Россия может выиграть климатический спор" [RAS President Aleksandr Sergeev: Russia Can win the Climate Debate], *Rossiyskaya Gazeta*, November 23, 2021, https://rg.ru/2021/11/23/prezident-ran-aleksandr-sergeev-rossiia-dolzhna-vyigrat-klimaticheskij-spor.html (in Russian)

[9] "Russian Energy Week International Forum plenary session," President of Russia, October 13, 2021, http://en.kremlin.ru/events/president/news/66916#sel=38:1:Uq4,39:23:2np

[10] Katy Huff, "Delivering a just transition to a clean energy future and supporting the UN SDG's," YouTube Video, 26 min, November 5, 2021, https://www.youtube.com/watch?v=x1IOoN7QWK8.

[11] David Eckstein, Vera Kuenzel, Laura Shaefer, Global Climate Risk Index 2021, German Watch. https://www.germanwatch.org/sites/default/files/Global%20Climate%20Risk%20Index%202021_2.pdf

[12] By law: South Korea (2050), Japan (2050) In policy document: China (2060), Singapore (2060), Shri Lanka (2060) Declaration pledge: Thailand (2050), Vietnam (2050), India (2070) Proposed in discussion: Bangladesh (2030), Myanmar (2050), Cambodia (2050), Indonesia (2060). No targets: Philippines. Source: https://eciu.net/netzerotracker

[13] Reactors can be classified as either MWt (megawatts thermal that is the amount of energy the nuclear reaction produces) or MWe (the actual energy that flows to the grid). A plant's electrical output is usually about one-third of its thermal output.

[14] Joanne Liou, "What are Small Modular reactors (SMRSs)?" IAEA, November 4, 2021, https://www.iaea.org/newscenter/news/what-are-small-modular-reactors-smrs

offshore and island applications, industrial processing, and steam generation. They could also be used for urban heating and desalination projects.

Energy Advantages

One of the perceived advantages of SMRs lies in providing electricity in remote areas. SMRs and especially FNPPs create the possibility of operating the reactor in additional areas that previously did not provide sufficient demand to justify a nuclear reactor, or would normally be inaccessible, such as low-lying coastal areas which are common throughout the Indo-Pacific.

The smaller output of these reactors could also be more suitable for developing country grids more generally. An industry safety rule of thumb is that no nuclear plant should represent more than ten percent of generating capacity on a grid. [15] With current reactors, it generally means that nuclear plants can only be installed in countries with grids of more than ten gigawatts; many developing countries in the Indo-Pacific fall short. Therefore, a smaller output or a reactor capable of running off the grid entirely could pry open many new markets.

Economic Differences

SMR developers promise to provide small increments of nuclear power plants at much lower prices and in much shorter times than traditional power plants. Should these promises be realized, nuclear power could become far more affordable for low and middle-income countries. Many of these countries have been priced out of the international market today because they lack the billions of dollars needed to finance and pay for building a nuclear reactor before it generates any power. Were prices and construction times to drop closer to those of an equivalent natural gas or coal plant, nuclear plants could become far more attractive to low- and middle-income countries in the Indo-Pacific, most of whom are thirsty for more energy, particularly low-carbon sources.

The current major obstacle to nuclear power is commercial, not technological. The key, as one industry expert said, is being able to produce "a financeable package that is deliverable at volume in the near term," something the nuclear industry has rarely accomplished in the past.[16]

This effect could be magnified if suppliers were to shoulder the burden of financing themselves, something Russia has already done with a traditional power plant in Turkey through a "build-own-operate" approach. Under this scheme, Russia will own and operate reactors in Turkey and absorb operational and construction risks with the Turkish government only responsible for paying a fixed price for the electricity generated. Such schemes could be attractive to other suppliers to generate initial sales if costs are sufficiently low. They could also allow suppliers to rely on pools of already well-trained developing country experts, while minimizing the time and expense needed to develop new nuclear cadres in those countries.

The early and unsettled nature of SMR construction could also upend normal nuclear economics. The lower cost of the reactors could provide new leverage for customer countries, allowing them to escape an "all-or-nothing" decision upfront by running several plants as pilot facilities to see which supplier they prefer. Modular construction could also limit financing costs and improve cash flow by allowing plant operators to profit from electricity sales from one unit while another unite was under construction. Yet, with companies eager to land at least one sale, they are unlikely to early on realize the economies of scale that accrue to repeated used of standardized designs in countries such as South Korea. While the overall cost of an SMR may be lower, its smaller output could also mean that the cost per kilowatt-hour of operation over time may be higher than that of standard nuclear plants.[17]
Furthermore, according to expert estimates, the current cost of constructing SMRs and FNPPs far exceeds the cost of fossil fuel- and renewable-based electricity generation for comparable capacities.[18] For example, in the United States, the first proposed SMR project involving the construction of a NuScale reactor design has run into trouble, with many utilities that had signed up for the project choosing to exit the initiative as the high cost became clearer. It is

[15] Ibid.
[16] Paul Murphy, *A Global View of the Nuclear Industry in 2022: The Need for Collaboration*, Global American Business Institute, January 12, 2022.
[17] For a good overview of the economic issues see, B. Mignacca and G. Locatelli, "Economics and Finance of Small Modular Reactors: A Systematic Review and Research Agenda," *Renewable and Sustainable Energy Reviews*, Vol. 118, 2020, https://doi.org/10.1016/j.rser.2019.109519.(https://www.sciencedirect.com/science/article/pii/S1364032119307270)
[18] Valentin Gibalov, "Битва ядерных компактов: рыночные перспективы малых АЭС" [The battle of compact nuclear units: market prospects of small NPPs], *Izvestiya*, January 9, 2019, https://iz.ru/829566/valentin-gibalov/bitva-iadernykh-kompaktov-rynochnye-perspektivy-malykh-aes (in Russian)

also not clear how much the United States, with an already limited nuclear export industry, should focus on trying to compete and expand the nuclear market as opposed to seeking to limit any nuclear expansion to states with solid finances and governance. A Canadian study, for instance, has shown that even if every mine or remote community in Canada was served by an SMR, there would be insufficient demand to justify building factories for such purposes.[19]

SMRs and Geopolitics in the Indo-Pacific

Despite a lack of a strong commitment to nuclear energy from many of the countries in South and Southeast Asia, it is possible to hazard some thoughts on how the development and export of SMRs could shift the nuclear market in the region and affect the geopolitical interest of key nuclear players—China, Russia, the United States, South Korea, Japan, and India. This section focuses on the regional geopolitical interplay among these suppliers and between exporters and importers of SMR technology.

Until recently, much of the Indo-Pacific largely managed to steer clear of geopolitical tensions around nuclear power. Particularly after the 2011 Fukushima accident in Japan, many potential nuclear newcomers decided that nuclear power placed too many financial, regulatory, and practical demands to be feasible in their countries. Countries such as Vietnam that had initiated efforts pulled back, leaving nuclear power plant building in the region limited to existing countries (China, Japan, South Korea, and India) with their own national champion plant suppliers. Moreover, the global pandemic has put a temporary halt to the longstanding rapid growth in energy demand in the region. Once the pandemic subsides, however, foreign suppliers can be expected to compete aggressively again to win business in the region. They will each bring strengths and weaknesses to the competition. Russia's recent invasion of Ukraine, meanwhile, has introduced new geopolitical and geoeconomic considerations into regional states' decision-making when it comes to nuclear energy vis-à-vis other sources of nuclear energy. These include not only efforts to choke up Russian exports of natural gas and oil but also nuclear energy exports and other means of earning foreign exchange, as well as concerns about nuclear safety and security (particularly in potential war zones). [20]

Supplier Strengths and Weaknesses

Russia

Russia is currently the leading global exporter of "concrete" nuclear technology, including nuclear power plant construction.[21] Its state-owned nuclear behemoth Rosatom integrates all aspects of the nuclear industry. Meanwhile, Moscow stands out among nuclear exporters by its attractive offers to accept client's nuclear spent fuel and provide subsidized financing, rather than its technology. As noted above, since Russia is not a member of the OECD, it does not have to abide by OECD rules limiting export subsidies for nuclear power plants.[22]

Key parts of Russia's national security establishment view civilian nuclear exports as an "important tool for projecting influence overseas" and have been willing to consider and conclude deals in places such as South Africa and Turkey, which appear to lose money but shore up its geopolitical influence.[23] This function may become especially relevant in the wake of Russia's February 2022 invasion of Ukraine, while simultaneously creating new difficulties for prospective SMR exports.[24]

Russia is determined to be the first country to commercialize SMR technology and make it available

[19] Froese, Sarah, Nadja C. Kunz, and M. V. Ramana. "Too Small to Be Viable? The Potential Market for Small Modular Reactors in Mining and Remote communities in Canada," *Energy Policy*, vol. 144, 2020, p. 111587.
[20] Dominic Faulder, "Asia's nuclear Power Dilemma: Ukraine War Drives Energy Turnarounds," *Nikkei Asia*, April 20, 2022, https://asia.nikkei.com/Spotlight/The-Big-Story/Asia-s-nuclear-power-dilemma-Ukraine-war-drives-energy-turnarounds
[21] Jewell, Jessica, Marta Vetier, and Daniel Garcia-Cabrera, "The International Technological Nuclear Cooperation Landscape: A New Dataset and Network Analysis," *Energy Policy*, vol. 128, 2019, pp. 838-52.
[22] Organization for Economic Cooperation and Deelopment, "Annex II: Sector Understanding on Export Credits for Nuclear Power Plants," *Arrangement on Officially Supported Export Credits*, Paris, January 2019, pp. 45-8, https://www.oecd.org/officialdocuments/publicdisplaydocumentpdf/?doclanguage=en&cote=tad/pg(2019)1
[23] Andrew S. Weiss and Eugene Rumer, "Nuclear Enrichment: Russia's Ill-Fated Influence Campaign in South Africa," *The Return of Global Russia* (Washington, DC: Carnegie Endowment for International Peace, December 2019).
[24] The Biden administration, the US Congress, and experts are currently in the process of examining how Russia's role in the nuclear market can be curtailed. See, for example, Ken Luongo, "Congress Jumpstarts America's Nuclear Geopolitical Power," Commentary, April 22, 2022, https://partnershipforglobalsecurity.org/congress-jumpstarts-americas-nuclear-geopolitical-power/ or Matt Bowen and Paul Dabbar, "Reducing Russian Involvement in Western Nuclear Power Markets," Center on Global Energy Policy, May 2022, https://www.energypolicy.columbia.edu/research/commentary/reducing-russian-involvement-western-nuclear-power-markets

for foreign export. While there is no clear leader in the race to dominate the emerging SMR market, Russia is the operator of the world's only civilian nuclear-powered icebreaker fleet and has relied on the expertise of perfecting icebreaker reactors to research and develop new SMR designs. Almost all Rosatom's SMR projects are currently run by its subsidiary Afrikantov OKBM, which has been responsible for designing and constructing small reactors for nuclear-powered icebreakers and submarines. [25] Afrikantov has utilized its technical and scientific expertise to design a new RITM-200 SMR with 55 MWe capacity that already serves as the basis for the latest generation of Russian icebreakers.[26]

Floating Nuclear Power Plants. Russia is ahead of the competition when it comes to integrating SMRs onto floating platforms. It began operating the world's first FNPP, the Akademik Lomonosov facility, in May 2020, anchoring the 70 MWe-generating barge near the Arctic city of Pevek in the Chukotka autonomous region, Russia's easternmost territory.[27] In addition to designing and constructing new FNPPs, Rosatom is currently engaged in a project to build the first SMR NPP in the Yakutiya region, which borders Chukotka. Rosatom initiated construction in 2021 and plans to begin operating the plant by 2028.[28] If successful, the plant will employ RITM-200 reactors to supply electricity to several remote Siberian municipalities in Yakutiya and become the land-based analogue to "Akademik Lomonosov." Other smaller reactor designs are also under development.

Outlook for Russia's SMR exports. Before the invasion of Ukraine, Russia's prospects for exporting SMR technology were primarily contingent on the existence of safe and reliable exemplar units at home. This is especially paramount for importer-countries that do not yet have a nuclear power plant. Those countries are supposed to adhere to the "reference-plant" concept, wherein a country's first nuclear power plant should have "essentially the same design and safety features as a nuclear power plant that is already licensed by an experienced regulator." [29] Besides, even countries that already employ nuclear power generation would likely not want to purchase Rosatom-designed SMRs before they can reasonably assess that those SMRs work well in the exporting country. As such, Russia relies on the successful performance of "Akademik Lomonosov" and other SMR projects in development to kickstart its sales of the technology abroad.

Rosatom's head-start has previously drawn other countries' attention and sparked interest in Russia's FNPP lineup (especially in the Middle East and Southeast Asia). Rosatom has also been allegedly designing plans for a FNPP that can operate in tropical waters, hinting at plans to pursue an aggressive SMR export policy in the Indo-Pacific and other tropical regions. [30] An early dominating position in the regional market would enable Russia to further pursue its goals of economic integration within the region, signified by closer Russia-ASEAN cooperation and encapsulated more broadly by Vladimir Putin's dream of a Greater Eurasian Partnership.[31]

However, Russia's unprovoked war in Ukraine has triggered a two-fold effect that may ultimately hurt the country's plans for SMR exports in the Indo-Pacific. On one hand, countries across Southeast Asia begin to reevaluate the benefits of nuclear power as a substitute for the sanctioned coal and gas imports from Russia.[32] On the other hand, if the demand for nuclear power in general and SMRs does grow in the region, these countries would likely think twice before buying Rosatom's FNPPs and deepening their long-term energy dependence on Russia. This hesitation would stem both from the political and economic costs of doing business with Moscow (including trade-related financial sanctions) as well as doubts about Russian ability to service reactors given its economic dire straits and restricted imports of high technology items.

Regulation and the First Mover Advantage. Russia stands to benefit more than economically if its nuclear power plants – including SMRs – gain wide

[25] "Business directions," OKBM Afrikantov, http://www.okbm.nnov.ru/en/business-directions/

[26] "Born in the Arctic," Rosatom Overseas, https://rusatom-overseas.com/smr/rodom-iz-arktiki/

[27] "Akademik Lomonosov begins commercial operation," *Nuclear Engineering International*, May 25, 2020, https://www.neimagazine.com/news/newsakademik-lomonosov-begins-commercial-operation-7938482/

[28] Charles Digges, "Rosatom to build plant running on small modular reactors in eastern Siberia," *Bellona*, January 11, 2021, https://bellona.org/news/nuclear-issues/2021-01-rosatom-to-build-plant-running-on-small-modular-reactors-in-eastern-siberia

[29] "Licensing the First Nuclear Power Plant," International Nuclear Safety Group, Vienna, 2012, https://www-pub.iaea.org/MTCD/Publications/PDF/Pub1573_web.pdf

[30] "Малый источник большой энергии" [A small source of great energy], *TASS*, 2020, https://tass.ru/spec/asmm (in Russian).

[31] "Meeting of Supreme Eurasian Economic Council," President of Russia, October 14, 2021, http://en.kremlin.ru/events/president/news/66927

[32] Dominic Faulder, "Asia's Nuclear Power Dilemma: Ukraine War Drives Energy Turnarounds," *Nikkei Asia*, April 20, 2022, https://asia.nikkei.com/Spotlight/The-Big-Story/Asia-s-nuclear-power-dilemma-Ukraine-war-drives-energy-turnarounds

interest and acceptance. Russia could polish its "green" credentials and challenge US leadership in writing national and industry-wide regulations for SMRs. At the institutional level, being the first or one of the first countries to produce SMR-powered installations serially would likely put Russia in a position to set the tone for global SMR-specific regulations. The ongoing development of new FNPPs and other SMRs may already be laying the foundations for such interactions, as evidenced by the first ever contact between the IAEA officials and employees of the Afrikantov enterprise in November 2021.[33]

A month before the invasion of Ukraine, Rosatom's early advantage in this emerging market had already helped it initiate several land-based SMR export projects. In late January 2022, the company has signed a series of agreements to cooperate in SMR construction or supply electricity from already planned power plants with several countries, including the Philippines.[34] The first land-based SMR project under construction in Yakutia has received its first major customer as well – Rosatom agreed to provide at least 35MW of nuclear power generated by the Yakutia SMR NPP to the mining company Seligdar, which is developing one of Russia's largest gold deposits located in the same region.

To be sure, these advantages may be undone by the Russian aggression against Ukraine and reckless actions that endangered the Chornobyl and Zaporizhzhia nuclear power plants. However, much still depends on whether Rosatom can get both the next-generation FNPP and other SMR NPP "references" off the ground faster than its international competitors. If that occurs, countries that are interested in nuclear power, but not necessarily in working with Moscow following the war in Ukraine, may find themselves hard pressed to find alternatives to Rosatom's offerings. In that event, growing SMR exports by Russia may directly convert into gaining regulatory influence and rebuilding its soft power.

Russia's key target countries for nuclear exports in the Indo-Pacific are Myanmar, Indonesia, the Philippines, Cambodia, Malaysia, Bangladesh, and India.

United States

Over the past few decades, US nuclear exports have declined even as US nuclear technology has continued to be regarded as the world's best, particularly in areas such as design and instrumentation and control. More recently, dozens of US companies have outlined plans to develop SMRs, with Oregon-based NuScale Power leading the pack. NuScale became the first SMR developer to receive design approval from the US Nuclear Regulatory Commission (NRC) in 2020. NuScale Power and Doosan Heavy Industries & Construction (South Korea) plan to build a plant in Idaho, have won a contract to build a plant in Romania, and have won government financing approval for efforts to build a plant in South Africa.[35] No contract has been concluded in the Indo-Pacific. The United States also plans to construct a sodium cooled reactor design known as Natrium (Terrapower) in the location of an existing coal site in Wyoming that had been slated to close. The emphasis from the Biden Administration is not just to bring clean energy, but also to soften the blow from the closure of existing coal plants as they become obsolete.[36]

Throughout the nuclear age, the combination of US nuclear energy exports, technology expertise, and superpower muscle have helped Washington shape the nuclear safety and nonproliferation regimes, serving the paramount US geopolitical interest of nonproliferation. Moreover, the number of technical nuclear cooperation agreements Washington has concluded around the world have made the United States the most active participant in knowledge transfer, training, nuclear safety and security, and regulation; according to a recent study, the United States is involved in more than half of all global safety

[33] "Росатом провел для Секретариата МАГАТЭ семинар по атомным станциям малой мощности и плавучим атомным энергоблокам" [Rosatom conducted a seminar on small nuclear power plants and floating nuclear reactors for the IAEA Secretariat], *Atomnaya Energiya*, November 30, 2021, https://www.atomic-energy.ru/news/2021/11/30/119796 (in Russian).

[34] "Rosatom Signs Agreements in Dubai after Presenting its SMRs," *Nuclear Engineering International*, January 24, 2022, https://www.neimagazine.com/news/newsrosatom-signs-agreements-in-dubai-after-presenting-its-smrs-9422191

[35] "NuScale Gets Letter of Intent for 2500MW Project in South Africa from US Development Finance Agency," *Neutron Bytes*, last modified October 19, 2020, https://neutronbytes.com/2020/10/18/nuscale-gets-letter-of-intent-for-2500mw-project-in-south-africa-from-us-development-finance-agency/. See also:
"US-Romania Cooperation on Small Modular Reactors (Fact Sheet)," US Embassy in Romania, last modified November 4, 2021, https://ro.usembassy.gov/u-s-romania-cooperation-on-small-modular-reactors-fact-sheet/

[36] Katy Huff, "Delivering a just transition to a clean energy future and supporting the UN SDG's," YouTube Video, 26 min, November 5, 2021, https://www.youtube.com/watch?v=x1IOoN7QWK8

and security cooperation.[37] The NRC is still widely viewed as a global standard-setter for safety and security regulation, preserving US influence over these issues, while US influence in bodies such as the IAEA and NSG has helped shape nonproliferation norms.

Washington perceives Russian export efforts and attempts to craft global rules on nuclear energy, particularly with SMRs, as threats to US interests. This threat should be kept in perspective, however. Customer countries are likely to look to the supplier's regulators for regulatory guidance; yet some countries may also want to have a relationship with a third party to ensure safe and secure operation and lessen the influence of the supplier. Still, many are likely to want to maintain strong relations with the United States for broader reasons.

The United States' key target countries for nuclear exports in the Indo-Pacific are Indonesia, the Philippines, Thailand, and Vietnam.

China

After years of having "aggressively forced foreign companies and governments to transfer their intellectual property for nuclear reactors," Beijing is now free of restrictions due to foreign ownership of intellectual property, which would allow it to sell its reactors abroad without first getting approval from countries such as the United States.[38]

China's nuclear companies are under two types of pressure to export. First, China's "going out" export-oriented policy and the BRI have encouraged such exports; dozens of BRI countries have plans to develop nuclear power projects.[39] Second, as China's economic growth slows, its nuclear industry and electricity sector more generally face overcapacity problems with exports serving as a safety valve.[40] As Mark Hibbs has noted, China's stated willingness to export nuclear power plants to countries "where installed energy capacity is limited, economics weak, and industrial levels low, but have good relationships with China" suggests how "China values NPP exports as a means to address overcapacity problems rather than a revenue generator."[41]

China has sought to use generous financing "and a willingness to execute projects others find unattractive" in places like Argentina and the United Kingdom as "a lever to land additional nuclear projects that can advance its interest.[42]

Even with cut-rate financing, Beijing has only had limited success so far. Only in Pakistan are there operational Chinese-exported reactors. Those exports are unique because Pakistan has no other options, given its lack of membership in the NPT and NSG.

Nonetheless, China should bring growing strength to the nuclear competition.

First, China's rise as a regional and global power already gives Beijing considerable influence with potential nuclear customers, especially when coupled with other infrastructure support such as the BRI. Moreover, enhanced nuclear trade in SMRs, like other "consensual inducements," fits well with China's grand strategy to displace US leadership in the Indo-Pacific and beyond, as well as China's effort to battle the United States for dominance in high-technology fields.[43]

Second, China's ongoing nuclear buildup has allowed Chinese vendors to set up a solid supply chain and develop expertise that can be quickly mobilized for new projects. By contrast, US and European firms have lost expertise over the past two decades; their projects to build nuclear power plants outside of China have been few and far between, as well as set back by "massive delays and cost overruns." [44]

Nonetheless, China is beginning to make inroads in conventional nuclear reactors. It lies far behind Russia and US companies in the SMR competition, but the Russian invasion of Ukraine may allow China to leap into the nuclear export fray successfully earlier than it might have been expected to previously.

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[37] Jewell, Jessica, Marta Vetier, and Daniel Garcia-Cabrera. "The International Technological Nuclear Cooperation Landscape: A New Dataset and Network Analysis," Energy Policy, vol. 128, 2019, pp. 838-52.
[38] Mark Hibbs, *The Future of Nuclear Power in China*, (Carnegie Endowment for International Peace, 2018), p. 90 https://carnegieendowment.org/2018/05/14/future-of-nuclear-power-in-china-pub-76311
[39] Ibid, p. 110.
[40] Yan Xu, Junjie Kang, and Jiahai Huan, "The Prospective of Nuclear Power in China," *MDPI,* 2018 https://www.mdpi.com/2071-1050/10/6/2086
[41] Nakano, p. 24
[42] Nakano, p. 15
[43] Rush Doshi, *The Long Game: China's Grand Strategy to Displace American Order* (New York: Oxford University Press, 2021).
[44] Hibbs, p. 90

China's key target countries for nuclear exports in the Indo-Pacific are Cambodia, Indonesia, Sri Lanka, Malaysia, Thailand

South Korea

When in 2009 South Korea won a bid to supply the United Arab Emirates with four reactors, Seoul touted the sale as the beginning of a new era of nuclear exports and said that it aimed to achieve exports of 80 nuclear power reactors worth $400 billion by 2030, with a 20% share of the world market. [45] South Korea pointed to its impressive construction record and vibrant supply chain as key selling points. Seoul has not landed a major commercial contract since then, however. The UAE deal depended on several unusual conditions unlikely to be repeated including an extremely low bid, the involvement of US-based Westinghouse in the deal (convincing the Emirates that its relationship with Washington would not suffer), a minimal need for financing, and a close bilateral relationship between the Emirates and South Korea.

South Korea's hopes have faltered amid the post-Fukushima slowdown in nuclear growth, and particularly after the previous government announced that it would seek to phase out nuclear energy, leaving potential customers fearful that they would lack sufficient support for any purchases. Moreover, South Korea's longtime hopes of forging a strategic alliance with the United States to counter state subsidized companies from Russia and China and leverage Washington's diplomatic muscle have not come to pass. However, current President Yoon Suk-Yeol has a decidedly different perspective than his predecessor about the future of the nuclear industry in South Korea promising to "reinvigorate the nuclear-energy industry by reactivating suspended atomic power plants and resuming building new ones."[46] Yoon also intends South Korea to become a major exporter of nuclear equipment and technology. President Yoon has not made a specific statement with respect to SMRs, however.

South Korea has been an early leader in developing SMRs, however, and its extensive supply chain extends beyond the nuclear industry to include both nuclear and related industries, providing it an advantage over some other suppliers. For example, when it comes to FNPPs, Hyundai Heavy Industries is the world's largest shipbuilding company. Also, Doosan Heavy Industries is one of the few companies that builds large pressure vessels. As a result, there are several strands to South Korea's SMR development from the 330 MWth SMART (System-integrated Modular Advanced Reactor) to the BANDI-60s reactors. Other small reactors being developed for niche markets include the ARA molten salt reactor being developed by the Korea Atomic Energy Research Institute (KAERI), which could also be used as an FNPP and the I-SMR reactor from KHNP, which could be used for hydrogen production and thermal storage as well as nuclear power.

South Korea's key target countries for nuclear exports in the Indo-Pacific are the Philippines, Indonesia, and possibly Vietnam.

Japan

Japan has no plan to build or expand domestic nuclear power plants, including SMRs, due to the Fukushima accident it suffered in 2011. The accident has also ceased many of Japan's hopes for conventional reactor exports.

Japan, however, aims to achieve carbon neutrality by 2050 and announced a Green Growth Strategy in December 2020. The strategy mentions that Japan will participate in demonstration projects of SMRs overseas and plans to become a major supplier, but only in partnership with other countries. For instance, Japanese engineering, procurement, and construction firm JGC Holdings Corporation (JGC HD) has agreed to invest $40 million in NuScale.[47] In addition, recent press reports indicate that Mitsubishi Heavy Industries and the Japan Atomic Energy Agency plan to cooperate with Terra Power, the nuclear company of Microsoft founder Bill Gates, to build the Natrium advanced SMR in Wyoming.[48] Russia's invasion of Ukraine and subsequent rise in natural gas prices has also renewed interest in Japan about reopening some nuclear power plants, while also stirring nuclear safety and security concerns.

[45] Kane, Chen, and Miles A. Pomper, "Reactor Race: South Korea's Nuclear Export Successes and Challenges," *On Korea*, 2014, p. 63, https://keia.org/publication/reactor-race-south-koreas-nuclear-export-successes-and-challenges/

[46] ANS Nuclear Cafe, Nuclear Newswire, March 15, 2022. https://www.ans.org/news/article-3760/election-of-pronuclear-yoon-boosts-south-koreas-nuclear-tech-stocks/

[47] "Japan's JGC Invests in NuScale Power ," *World Nuclear News*, Accessed May 26, 2022, https://world-nuclear-news.org/Articles/Japans-JGC-invests-in-NuScale-Power

[48] "Japan to Help Build Bill Gates' High-Tech Nuclear Reactor in Wyoming -Yomiuri," *Reuters*, January 1, 2022. https://www.reuters.com/markets/commodities/japan-help-build-bill-gates-high-tech-nuclear-reactor-wyoming-yomiuri-2022-01-01/

India

Despite first launching its nuclear program half a century ago, India has not been a significant nuclear exporter. Much of the Indian nuclear complex has been devoted to its nuclear weapons, a prioritization exemplified by New Delhi's decision to conduct its first nuclear weapons test (mislabeled a "peaceful nuclear explosion" in 1974) with fuel and a reactor from the United States and Canada, cutting it off from most international commerce for three decades. India's nuclear establishment routinely promised that nuclear energy would power the country's development, but it never emerged as a significant source of energy. India began courting foreign suppliers at the turn of this century given the poor performance of its own reactors.

The India government has aspired to export for decades, particularly after the US-India civil nuclear cooperation agreement was concluded in the 2005-2008 timeframe. Chinese opposition, however, has helped block India's membership in the NSG, viewed by many as a prerequisite to exports. In the meantime, Indian nuclear officials have bandied about potential sales to countries such as Thailand, Cambodia, and Kazakhstan.

India hopes that it will have better luck in the SMR export market, in part because its traditional heavy water reactors based on Canadian technology produce far less power than traditional reactors, only about 220 MWe.

India has also shown success in building small Pressurized Water Reactors (PWR) of around 82.5 MWe for propelling submarines. Under the Advanced Technology Vessel project, six nuclear powered submarines are planned for construction to bolster India's nuclear triad, and such reactors could help power FNPPs and other SMRs.

Given India longstanding military cooperation with Russia, it could also choose to engage in joint ventures with Moscow. Rosatom has expressed interest in collaborating with Indian companies not only for the construction of large nuclear power plants, but also for joint development of medium- and small-sized nuclear power reactors, including floating nuclear reactors.[49]

India's key target countries for nuclear exports in the Indo-Pacific are Bangladesh, Cambodia, and Thailand.

Potential Customer Countries

The following list only includes those regional states considered to have a plausible possibility of purchasing nuclear power plants. As a result, countries such as Brunei or Laos are not listed.

Bangladesh

Given that Russia is already building two VVER-1200 reactors at the Rooppur NPP site 160 km northwest of Dhaka, with highly subsidized financing, it can be expected to have the inside track for any future nuclear construction in the country, absent Indian exports. In March 2018, Bangladesh, Russia, and India signed a three-way Memorandum of Understanding for cooperation on nuclear power including India's participation in the construction of Rooppur.[50]

Cambodia

Cambodia's primary emphasis has been on increasing electricity from hydropower, already its main source of energy. The Cambodian government reports that only 22.5% of Cambodian households have grid electricity, though 60% are in urban areas. The state-owned enterprise Electricité du Cambodge hopes to provide electricity to all villages by 2020 and to 70% of all rural households by 2030. Cambodia relies chiefly on hydropower, coal, and imported electricity to attempt to meet demand. However, given close economic and political relations with China (its largest trade and investment partner), and deteriorating ones with the United States,[51] Beijing could be expected to have the upper hand should Phnom Penh turn to SMRs further cementing those ties. Other suppliers hoping to make inroads – Russia and India – will likely be at a strong disadvantage.

[49] Dipanjan Roy Chaudhury, "Rosatom Expresses Interest in Teaming up with India to Produce Small and Medium Sized Reactors - The Economic Times," *The Economic Times*, Accessed May 26, 2022, https://economictimes.indiatimes.com/industry/energy/power/rosatom-expresses-interest-in-teaming-up-with-india-to-produce-small-and-medium-sized-reactors/articleshow/71964743.cms?from=mdr

[50] Steve Thomas, "Russia's Nuclear Export Programme," *Energy Policy*, vol. 121, 2018, pp. 236-47.

[51] H.E. Dr. Kin Phea, "Cambodia-China Relations in the New Decade," Konrad Adenauer Stiftung, May 26, 2020, https://www.kas.de/en/web/kambodscha/single-title/-/content/cambodia-china-relations-in-the-new-decade-2#:~:text=In%202006%2C%20the%20two%20countries,Shared%20Future"%20in%20April%202019

Indonesia

As one of the longtime leaders of the Non-Aligned Movement and one of the world's most populous countries, Indonesia has long been adept at playing outside powers against each other, be it the United States and the Soviet Union during the Cold War or Beijing and Washington today. The United States is Indonesia's key security partner, but economic ties with China are strong. Moreover, Indonesia has long had a highly active nuclear research community. Suppliers are salivating at the vast scale of the Indonesian market and noting projections that it will enjoy the third highest projected growth in electricity demand of any country in the world.[52]

As a result, Indonesia probably has more freedom of choice than almost any other regional actor when it comes to nuclear power, and it has made use of its relative autonomy. It has flirted with all the major suppliers for potential direct sales or cooperation in developing its own experimental reactors. Capturing the Indonesian nuclear market would be considered a geopolitical prize for any supplier. Should Jakarta opt for nuclear power, however, Indonesia's stubborn independence may lead it to develop the reactors itself or diversify its suppliers.

Malaysia

It appears that after Fukushima, Malaysia, a major oil and gas producer, has lost interest in nuclear power. Malaysia previously had some interest in South Korea's SMR, but interest seems to have faded.[53] Geopolitically, Malaysia enjoys strong security ties with the United States, but China is its major trading partner and therefore Beijing has significant influence as well.

Myanmar

Russia has long had the inside track with Myanmar (Burma) thanks to a decades-old Rosatom plan for the construction of a nuclear reactor. Myanmar's ruling military regime also has ideological reasons to partner with the Putin government given both share opposition to (perceived or real) attempts by the West to export democracy under the guise of "color revolutions." In the context of this broader rivalry between Russia and the West, Russia is seeking to establish closer ties with various authoritarian regimes around the world, while the European Union and the United States have backed away from Myanmar, including opposing sanctions after the 2021 military coup.

The military regime has also restored the close relationship it had with China before the ill-fated democratic transition. Like Russia, China shares the Myanmar government opposition to foreign interference and insistence on untrammeled sovereignty. China is already involved in several major projects in Myanmar through the BRI. China almost has a complete domination of the electricity market in Myanmar in both the renewable and non-renewable energy sectors with a variety of hydropower and coal projects which they are building and operating. China will be investing $2.57 billion in a liquefied natural gas project at Mee Laung Gyaing, one of the largest electricity projects in the country, and is also expected to be the main shareholder.[54] As a result, should Myanmar reignite nuclear ambitions, the competition for nuclear sales could challenge the growing entente between Moscow and Beijing

The Philippines

The Philippines has long considered reviving the Bataan conventional light water reactor built under the Ferdinand Marcos regime. Completed in 1984, the 623-megawatt (MWe) Bataan Nuclear Power Plant (BNPP) located in Luzon, was never loaded with fuel, or operated, and was mothballed in 1986 due to post-Chernobyl political concerns and safety issues. There have been several attempts to win political support for reviving the plant, such as during power crises in the 1990s and the skyrocketing of oil prices in 2007. The government has also considered converting it into a natural gas-fired power plant, but it seemed impractical, and the plant has been maintained without being operated. In 2010, Korea Electric Power Corporation (KEPCO) submitted a study indicating that it would take $1 billion to rehabilitate the BNPP.[55] Another South Korea-Philippines study in 2017 estimated the cost at $1-3 billion, while

[52] Jacob Kincer, "Who in ASEAN Is Ready for Nuclear Power?" *Energy For Growth*, February 16, 2021, https://www.energyforgrowth.org/memo/who-in-asean-is-ready-for-nuclear-power/

[53] Dharamender Singh "KL and Seoul to Work Together on Nuclear Energy" *The Star*, December 11, 2010.

[54] Sumanthi Samsani, "Understanding the relations between Myanmar and China," *ORF*, April 26, 2021. https://www.orfonline.org/expert-speak/understanding-the-relations-between-myanmar-and-china/

[55] "Turning Back to Bataan?" *Nuclear Engineering International*, accessed May 31, 2022, https://www.neimagazine.com/features/featureturning-back-to-bataan-/

Rosatom experts gave a $3-4 billion estimate in the same year.[56]

In February, President Rodrigo Duterte signed an executive order directing that nuclear power be included in the national energy mix, and that an interagency panel be set up to reopen BNPP,
The recent election of Marcos's son Ferdinand Jr. "Bongbong" to succeed Duterte has provided further momentum, as he has pledged to open the plant. [57]

The Philippines has discussed SMR technology with both South Korea and Russia. South Korean experts conducted a pre-feasibility study for an SMR site in 2019, and the same year Manila signed an agreement with Rosatom to assess the feasibility of a small SMR, floating or on land, and probably using Russian RITM-200 reactors. In January 2022, the Philippines has upgraded its cooperation with Russia by signing a joint plan to assess the feasibility of an SMR project.[58] Russia, South Korea, or the United States would be the most likely vendors of SMRs if Manila chose to go with the smaller reactors rather than reopening the BNPP, given that Manila continues to fight with Beijing over territorial disputes in the East China Sea.

Sri Lanka

In August 2017, Sri Lanka's installed electricity generation capacity was 4043 MWe, with most energy coming from fossil fuels and hydropower. The option of a 600 MWe nuclear plant is included in some long-term energy plans but there is no sign Colombo will choose this option, particularly given the urgent political and economic crisis that recently has shaken the island state. A more likely source of power is India, where a 500 MW HVDC transmission link is being considered in collaboration with the Power Grid Corporation of India Ltd. The country, moreover, currently generates little solar or wind power and would have significant capacity to increase their share of electricity generation.

Relations with Beijing had been close since China was one of the few countries to come forward to support Sri Lanka in its final fight against the Liberation Tigers of Tamil Eelam (LTTE) in 2008-2009. While other actors, such as the United States and European Union, were critical of the Sri Lankan Army's conduct during the final stages of the Sri Lankan Civil War, Beijing provided millions of dollars' worth of sophisticated weapons, as well as six F-7 fighter jets to the Sri Lankan Air Force. Moreover, Beijing shielded Sri Lanka from US resolutions at the United Nations Security Council, which accused Sri Lanka under then President (and now Prime Minister) Percy Mahinda Rajapaksa of human rights violations during the final offensive against the LTTE.[59] In 2019, China gifted a warship to Sri Lanka, the latest sign of its deepening military cooperation with the strategically located island nation in the Indian Ocean.[60] China also provided an estimated $13 billion of infrastructure investment to Sri Lanka from 2006 to 2020, including billions of dollars in loans for Sri Lankan infrastructure, including a new port at Hambantota, a new container terminal in Colombo, a new international airport, a coal-fired power plant and multiple highways. Many of these loans were racked up during Rajapaksa's presidency. In 2017, when Sri Lanka could no longer afford the debt repayments Beijing took over Hambantota on a 99-year lease and wrote off a debt of $1.1 billion. That action has spurred resentment in Sri Lanka and ties between the two countries have become more strained.[61]

The United States, meanwhile, is a major export destination for Sri Lankan products. In any case, there is little near-term possibility of a Sri Lankan nuclear energy program.

Thailand

Thailand has toyed with the possibility of nuclear power for decades but has not moved forward. For example, in 2010, Bangkok approved a Power Development Plan 2010-30 that envisaged five 1000 MWe units starting up over 2020-28. Were Thailand

[56] "Is Nuclear Energy Coming to the Philippines?" *The ASEAN Post*, March 12, 2018, https://theaseanpost.com/article/nuclear-energy-coming-philippines
[57] Faulder, "Asia's Nuclear Power Dilemma."
[58] "Rosatom Signs Agreements in Dubai after Presenting its SMRs," *Nuclear Engineering International*, January 24, 2022, https://www.neimagazine.com/news/newsrosatom-signs-agreements-in-dubai-after-presenting-its-smrs-9422191
[59] Saurabh Singh, "China's Strategic Relations with Sri Lanka," *South Asian Voices*, last modified July 15, 2020, https://southasianvoices.org/chinas-strategic-relations-with-sri-lanka/
[60] "China Gifts Warship to Sri Lanka," *The Economic Times*, last modified July 17, 2019, https://economictimes.indiatimes.com/news/defence/china-gifts-warship-to-sri-lanka/articleshow/70255526.cms?utm_source=contentofinterest&utm_medium=text&utm_campaign
[61] Meera Srinivasan, "A Perception Shift in Relations Between Sri Lanka and China?" *The Hindu*, last modified July 9, 2021, https://www.thehindu.com/news/international/news-analysis-a-perception-shift-in-relations-between-sri-lanka-and-china/article35240800.ece

to move ahead with acquiring nuclear power plants, China would likely have the best shot. Ratchaburi Electricity Generating Holding – Thailand's largest private power company – agreed in December 2015 to take a 10% stake in the two Hualong One reactors being built as Phase II of CGN's Fangchenggang nuclear power plant in China's Guangxi province.[62] Despite this cooperation, any nuclear deal with China would not be expected to shake close US-Thai security relations: Thailand was designated a major non-NATO US ally nearly two decades ago.

Vietnam

A decade ago, Vietnam looked like it would be the first country in Southeast Asia with a nuclear power plant. It had signed deals with Russia and Japan to build plants and was contemplating an additional deal with South Korea. But in 2016 its National Assembly voted to abandon those plans, after officials cited lower demand forecasts, rising costs, and safety concerns.[63] There is no indication that Vietnamese policymakers have changed their mind. Were Vietnam to begin considering nuclear power again, Russia and Japan would have the best chance to win a contract. Vietnam also enjoys an increasingly close relationship with the United States, while it continues to spar with China over territorial disputes and has concluded a nuclear cooperation agreement with Washington, which could provide US companies an opening should Vietnam reconsider nuclear power.

Assessment and Implications

SMR and FNPP technological development is still far too inchoate to come to firm conclusions about the degree to which it might affect country's geopolitical interests. A single operating Russian FNPP does not make a commercially viable industry. It will take the better part of this decade to test the technical feasibility of these systems. That also leaves out the most difficult challenge when it comes to nuclear power: commercialization. If history is any guide, current hopes for the SMR and FNPP market will far outpace future nuclear deployments because nuclear power will continue to be uncompetitive commercially in most electricity generation scenarios, especially given continued drops in the price of alternative technology and storage and growth in exports of liquified natural gas (spurred even faster by the Ukraine crisis). The long timeframes from either building traditional nuclear plants or having operational, licensed SMRs is likely to encourage countries to pursue other options.

In any case, all evidence is that potential new customers in South and Southeast Asia are in no hurry to purchase this technology or nuclear power more generally given high commercial rates. They have taken few concrete steps to develop a domestic nuclear energy industry. As one expert noted:

[T]he theoretical market for nuclear power is meaningless and overplayed. What really matters is whether projects are 'real'…'Real' is a function of the jurisdiction within which the project is located, and that jurisdiction will be judged by the readiness of its nuclear infrastructure. If the country is not ready, as measured by the IAEA Milestones,[64] the project will not proceed, and it certainly will not be financed."[65]

With sufficient subsidies or absence of commercial imperatives, some marginal low- and middle-income customers (i.e., Bangladesh) may be convinced to purchase plants from Russia or China. The Philippines might also finally operate the BNPP plant and South Korea and Japan complete or reopen previously planned NPPs. But given OECD rules, such subsidies are not an option for the United States, South Korea, and Japan. Still those countries' technological and regulatory leadership will likely continue to have an advantage in most existing foreign markets. The exceptions would include former Soviet Republics, China, and Russia's existing allies (such as Pakistan for China), and autocratic fellow travelers, such as Myanmar and Cambodia. Should SMRs live up to their hype, they are likely to prove a double-edged sword in terms of finance,

[62] "China, Thailand Agree to Nuclear Energy Cooperation," *World Nuclear News*, accessed May 31, 2022, https://www.world-nuclear-news.org/NP-China-Thailand-agree-to-nuclear-energy-cooperation-0504174.html

[63] Mai Nguyen and Ho B. Minh, "Vietnam Abandons Plan for First Nuclear Power Plants," *Reuters*, last modified November 22, 2016, https://www.reuters.com/article/us-vietnam-politics-nuclearpower/vietnam-abandons-plan-for-first-nuclear-power-plants-idUSKBN13H0VO

[64] The IAEA Milestones Approach is a series of benchmarks with which the International Atomic Energy Agency aims to help Member States understand the commitments and obligations and human, regulatory, and concrete infrastructure associated with developing a nuclear power program and the decades-long commitment involved to prepare for operating their first plant. See: https://www.iaea.org/topics/infrastructure-development/milestones-approach

[65] Paul Murphy, *A Global View of the Nuclear Industry in 2022: The Need for Collaboration*, Global American Business Institute, January 12, 2022.

making such subsides easier to bear for Moscow or Beijing, but also perhaps less necessary.

It also appears unlikely that SMR sales in Southeast Asia would allow any supplier to reap significant geopolitical gains because of their somewhat risky nature nuclear sales tend to reflect and reinforce existing geopolitical relations rather than shift them, although the United States and its allies in the near future can be expected to see denying Russia export earnings from nuclear sales as a key geopolitical or geoeconomic ties, and Southeast Asian countries may seek to leverage this conflict to their benefit. Even in the most unaligned country and greatest regional geopolitical prize (Indonesia), there is no certainty that even a nuclear decision to rely on one of the major global powers (Russia, China, or the United States) would shift relations rooted more deeply in security or commercial ties. Moreover, Indonesia is careful to preserve its autonomy and may look for ways to limit any outside influence, either by diversifying suppliers, building its own or relying on a second-tier power, such as South Korea.

To the degree that Washington seeks to help US SMR manufacturers gain new markets, Indonesia should be a top priority given its massive need for new electricity sources, while the Philippines, Thailand, and Vietnam should be pursued if they take steps towards acquiring nuclear power. While not an SMR, US technical nuclear safety assistance to the Philippines to ensure that it only opens BNPP after a thorough consideration of safety concerns would be particularly welcome.

For the United States, while SMR sales would be welcome, Washington has many other tools in its arsenal to sway nuclear nonproliferation, safety, and security governance in the region, including its global economic leadership and leadership in international institutions, such as the IAEA. To the degree to which that power has receded amid a rising autocratic wave, selling a few SMRs and FNPPs to marginal economic states is not likely to shift allegiances.

It is also not clear how much the United States, with an already limited nuclear export industry, should focus on trying to compete and expand the nuclear market as opposed to seeking to limit any nuclear expansion to states with solid finances and governance. The United States has strong companies in other low-carbon technologies as well as in liquefied natural gas and could provide these much faster and more competitively than any future SMRs or FNPPs. US policymakers should be cautious before devoting limited resources to what may well prove a weak tool in the important battle for geopolitical influence in South and Southeast Asia.

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