NNWI
New Nuclear Watch Institute

SCALLING SUCCESS

Navigating the Future of Small Modular Reactors in Competitive Global Low-Carbon Energy Markets

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CONTENT

EXECUTIVE SUMMARY

ALTHOUGH THE CONCEPT OF SMALL MODULAR REACTORS (SMR) HAS BEEN GAINING TRACTION ACROSS THE WORLD FOR QUITE A WHILE, THE OVERALL PROGRESS IN THE SECTOR OVER THE LAST 10-15 YEARS HAS BEEN MODEST.

Whilst evidence is mounting that SMRs as part of the global nuclear fleet are vital for achieving net-zero by the middle of the century, the emerging SMR sector is facing a complex interplay of technological, economic, and geopolitical factors that influence, and to some extent constrain, the technology adoption and scalability.

The world's first SMR-based facility, Russia's floating nuclear power plant Akademik Lomonosov, launched in 2020 and deployed in Chukotka remains, so far, the only project that has reached the stage of commercial operation. The recent (in in November 2023) cancellation of NuScale's pilot project in Utah underscores the challenges faced by SMR vendors.

The inherent advantages of SMRs – size, modularisation, and flexibility – are also their vulnerabilities. Their smaller size and modular nature promise faster, cost-effective construction and adaptability to various grid types, especially in emerging markets and remote locations. However, these benefits are accompanied by higher relative electricity costs per unit of installed capacity, while uncertainties in demand, along with regulatory and political risks, create a 'chicken-and-egg' situation for the modular factory manufacturing and scaling that are prerequisites for cost reduction.

30-35%

Although the global SMR fleet is projected to expand at an impressive 30-35% CAGR over the next two decades from the present low base, the overall market growth potential for SMRs between 2035 and 2050 is likely to stay in the region of 20-25% CAGR due to supply-side constrains, competition with other technologies and market fragmentation.

While optimistic forecasts suggest that the global SMR fleet could reach approximately 350 Gigawatts-electric (GWe) by 2050, representing up to 40% of the world's total installed nuclear capacity, our base-case scenario estimates it to be more realistically in the region of 150-170 GWe.

This report segments the market into off-grid energy supply, on-grid power generation, advanced co-generation, and transport applications, each with distinct challenges and opportunities.

We anticipate across the above segments the first wave of SMR deployments to occur around 2030-2035, predominantly featuring light water generation III+ designs. Those projects are likely to face delays averaging 1-3 years, along with significant cost overruns compared to initial schedules and estimates.

Advanced (generation IV) SMRs, despite ambitious targets, are likely to encounter more substantial delays due to more complex licensing, supply chain and fuel supply issues. While some demonstration units may still come online by 2030-2035, full-scale First-Of-A-Kind (FOAK) deployment and subsequent series factory manufacturing are more likely to materialize closer to 2040.

Over a hundred SMR designs have been earlier reported to be in various stages of development in at least 12 countries of the world (first of all: United States, China, Russia, South Korea, Argentina, United Kingdom, France, Canada, Sweden, Japan, India, and South Africa), although more than half of them has been cancelled, shelved, or put on hold. Currently, the UN's IAEA estimates that up 70 designs are in development.

SMR deployment is occurring in a highly competitive landscape, facing challenges both from within the sector among different SMR designs and externally from alternative low-carbon energy sources and large reactor segments. We find that rapid scaling is crucial for successful projects to leverage the economies of modularisation and series deployment, thus reducing costs, in a limited and fragmented market which is going to be dominated by first movers.

We find that non-technology factors such as low-cost capital availability, subsidised demand, shorter supply chain lead times and licensing timeframes are as critical, if not more so, than technology innovations in enhanced safety and performance. In many cases, learning curves, scaling, and lower cost of capital result in a more significant reduction in the final cost of a unit of electricity than savings derived from innovation-driven technology improvements.

This report identifies and assesses the top 25 SMR projects that, due to a combination of external business and internal technological performance drivers, are more likely to be deployed and secure a significant market share by mid-century. If current trends persist, it is likely that more than half of the global SMR installed capacity by 2050 will be concentrated in 6 to 8 first-mover designs.

The Russian RITM reactor family, capitalising on government support and an integrated 'plant-as-a-service' business model, including spent fuel and waste management, is set to dominate the off-grid segment of the global SMR market, becoming the most common installation worldwide. The Chinese ACP100 or Linglong One is projected to follow, capturing about 15% of the global SMR fleet by installed capacity. Despite recent setbacks, NuScale's VOYGR is likely to secure 5-10% of the world's installed SMR capacity in 2050. Amongst advanced reactors, which are set to be deployed in series around 2040s, the US XE-100 appears to have the highest chances to capture the largest market share of 7% of global installed capacity.

To keep OECD vendors competitive, governments should consider augmenting their supply-side support with robust demand-side boosters. These boosters should directly target viable areas of SMRs' application, such as replacing baseload coal-fired power plants and diesel off-grid generation, through specific support mechanisms like feed-in tariffs, contracts for difference, power purchase agreements and so on.

Efforts should be strengthened to streamline licensing and prevent licensing 'bottlenecks' and extend export finance options. OECD stakeholders should foster competitive global alliances enabling SMR developers to offer integrated 'plant-as-a-service', 'one stop shop' options matching the Russian value proposition.

SMR DEPLOYMENT IN THE CONTEXT OF ENERGY TRANSITION

OVERVIEW

THE INTEREST IN SMALL MODULAR REACTORS HAS BEEN PROMPTED BY SIGNIFICANT DIFFICULTIES

associated with conventional, GW-sized reactor projects (mainly EDF's experience with EPR projects in France and Finland and Westinghouse Electric Company's deployment of AP1000 in the United States) and the trend of grid decentralisation associated with a higher share of variable renewable energy adding to load volatility.

The idea of SMR as a substitute for bigger nuclear plants and an alternative to carbon-intensive sources of dispatchable power generation and heat supply is based on the following considerations:

- the factory fabrication of modules and a simpler assembly of prefabricated modules on site as opposed to in situ construction enables the developer to reduce construction risks (first of all, delays and cost overruns almost inevitable for bigger construction projects) and timing;
- modular composition of the plant gives more flexibility for load-following as some modules could be shut down altogether for the periods of low demand or oversupply caused by wind and solar generation;
- suitability for remote regions, islands and territories with less developed grids;
- lower unit of investment and lower investment per unit of capacity;
- higher flexibility of siting: less land use, simple infrastructure, less need for access to water;
- co-generation options thanks to closer proximity to energy users.

It is argued that the cost benefits of the serial, in-factory production of modular components for SMRs and a 'learning curve' may more than offset the loss of scale economies that results from reduced power output, thus leading to a lower levelised cost of electricity (LCOE) than achieved by GW NPPs.

MIT estimates that modularization could reduce construction time and costs by about 20 percent, and similarly to the modularisation process in comparable sectors (such as submarines, chemical plants, offshore oil and gas platforms, etc.) could lead to a reduction of about one-third in the total ownership costs[1].

AT THE SAME TIME THE MODULARISATION AND 'LEARNING CURVE' EFFECTS ARE NEITHER FAST NOR CERTAIN.

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[1] **See:** https://www.pnnl.gov/sites/default/files/media/file/PNNL%20report_Techno-economic%20assessment%20for%20Gen%20III%2B%20SMR%20Deployments%20in%20the%20PNW_April%202021.pdf

Figure 1 below illustrates three scenarios of expected cost reductions, given three potential learning rates: 5% (conservative), 7% (base-case), and 15% (high-case). These reductions are calculated from the current estimate of US$7,500 per kW of installed capacity, factoring in the number of repeated deployments.

The scenarios are plotted against two horizontal lines:

the first one represents an average overnight construction costs per kW for currently deployable large reactors ($5,500)[2] while the other illustrates a capacity factor adjusted, projected cost per kW for a hybrid, utility-scale renewable energy installation backed by sufficient battery energy storage in 2035[3].

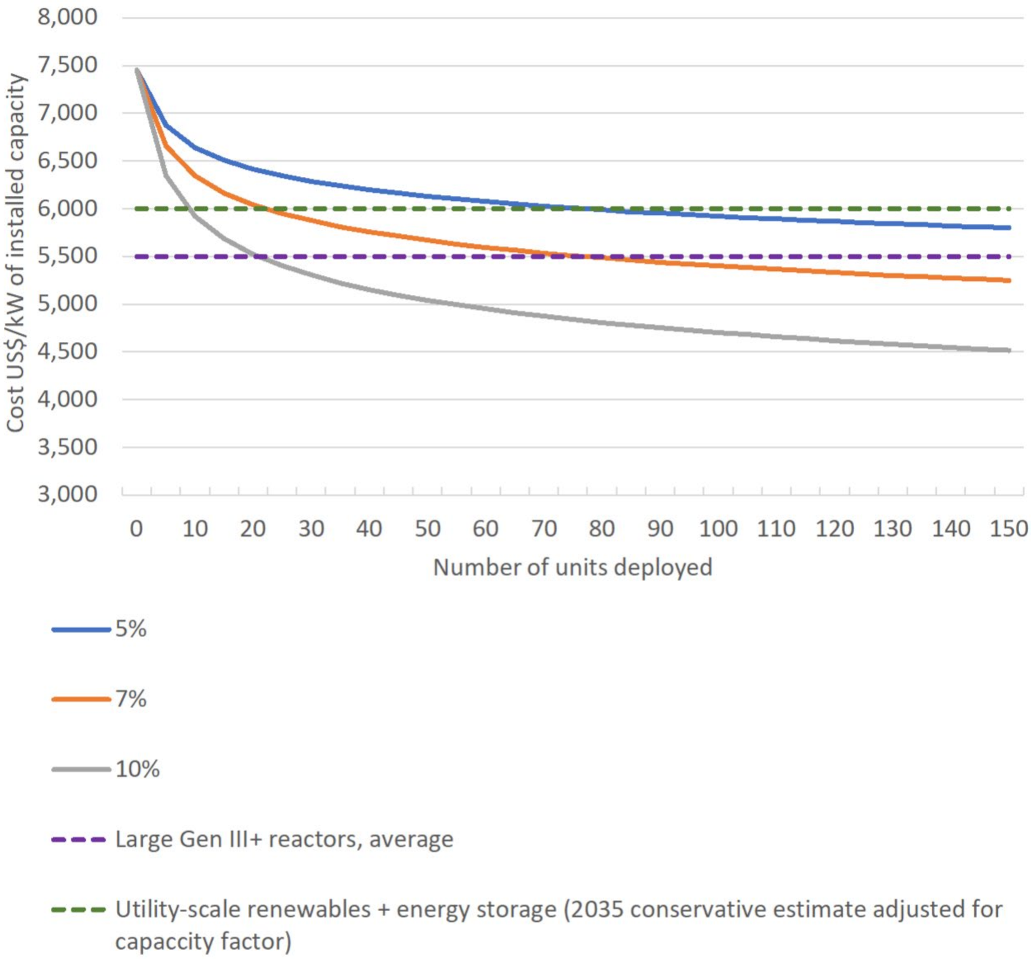

Figure 1

SMR learning curve (7%, 10% and 15% learning rates)

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[2] admittedly, this figure doesn't factor in recent post-COVID producer price inflation and is likely to be higher in the coming years, but at the same time the amount of $7,500 for an average SMR project is also based on older estimates, so the proportion should hold in real terms.

[3] **See:** https://atb.nrel.gov/electricity/2023/utility-scale_pv-plus-battery

AS CAN BE SEEN FROM THE MODEL, EVEN IN THE BEST-CASE SCENARIO OF A 10% LEARNING RATE, PRICE PARITY WITH GENERATION III+ LARGE REACTORS IS NOT REACHED UNTIL AFTER AT LEAST 20 REPEATED DEPLOYMENTS.

80-90 repeated

The base-case scenario suggests that this could be achieved after 80-90 repeated deployments. This is close to the assessment of the UK government which estimates that "given an expected SMR learning rate of between 6.5% and 8%, SMRs could become cost competitive against large nuclear after 5-8 GWe of global deployment of a single design[4] or after about 50-100 power units/modules depending on their size. Given the limited size of the global market it implies significant 'first-mover' competitive advantages while 'lagging behind' in terms of the timeline of deployment and expansion may render even more advanced designs uneconomic.

50–100 SMRs of each design has to be deployed before costs come down to be fully competitive.

Moreover, successful modularisation hinges on a predictable demand for standardized units, which ensures a reasonable level of capacity utilisation at the module manufacturing facility. For efficient and scalable factory production, design modifications should be minimal. However, achieving this in the nuclear sector presents peculiar challenges not observed in other sectors used for benchmarking the modularisation effects. Order backlogs in the new nuclear build sector are vulnerable to fluctuating public sentiment towards nuclear energy, legal and advocacy resistance by anti-nuclear groups, as well as changing market conditions and geopolitical turbulence. Additionally, regulatory requirements not only vary significantly from country to country, but they are often site-specific, complicating the standardisation process.

This set of factors leads to a 'chicken-and-egg' dilemma: the demand for nuclear projects is constrained by the high costs associated with first-of-a-kind (FOAK) projects.

Yet, the essential cost reduction achievable through modularisation cannot materialise without stable demand for repeated 50-100 deployments.

Furthermore, on-grid SMR applications face growing competition from alternative dispatchable electricity sources and grid balancing solutions. Advances in sodium-ion and other battery technologies[5] suggest that the average cost per MWh of stationary energy storage could fall below $150 as early as the early 2030s[6]. This reduction makes the combination of intermittent renewables with such storage solutions increasingly economical for many grids. Similarly, according to Lazard[7], the declining costs of geothermal energy are now translating into $60-80 per MWh for the levelised cost of electricity, further intensifying the competitive pressure. These trends indicate a shifting landscape in the energy sector, where the cost-effectiveness and rapid scalability of renewables and storage technologies could challenge the economic viability of many on-grid SMR projects.

On the global stage, there is a mismatch between the presence of nuclear infrastructure in countries with operational nuclear fleets but limited energy consumption growth, and the need for dispatchable low-carbon generation (and/or carbon-intensive baseload capacity replacement) to meet net-zero targets in countries without nuclear infrastructure. Countries with the highest dependence on coal and electricity supply shortages, where the economic fundamentals for SMRs appear particularly strong, often lack nuclear infrastructure. This includes the absence of relevant legislation, regulators, and experienced operators.

Furthermore, public opinion in many of these countries makes it almost impossible for their governments to advocate for new nuclear builds, whether they involve SMRs or large reactor facilities.

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[4] **See:** https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/665197/TEA_Project_1_Vol_1_-_Comprehensive_Analysis_and_Assessment_SMRs.pdf

[5] **See:** https://www.technologyreview.com/2023/05/09/1072738/this-abundant-material-could-unlock-cheaper-batteries-for-evs/ , https://www.powerengineeringint.com/energy-storage/global-energy-storage-market-to-hit-1twh-by-2030/

[6] **See:** PNNL, MIT, Techno-economic Assessment for Generation III+ Small Modular Reactor Deployments in the Pacific Northwest, 2021 (cited above)

[7] **See:** 2023 Levelized Cost Of Energy+, Lazard, April 2023, https://www.lazard.com/research-insights/2023-levelized-cost-of-energyplus/

STATE SUPPORT MECHANISMS

As detailed in the section on potential market size estimates, we project the buildout of 150-160 GWe of SMR capacity worldwide by 2050 in our base-case scenario. Achieving this will necessitate an investment of approximately US$800-900 billion over the next 25 years, based on 2023 price levels. The majority of the necessary investment decisions must be made before SMR technologies achieve a scale of deployment at which their economic viability becomes self-sustaining, driven solely by market forces. In the early stages, state support and subsidies are crucial for the growth trajectory of the sector and pivotal for enabling it to reach the stage of full commercialisation.

Based on our analysis of the drivers of SMR viability and demand-side dynamics, we estimate that, in the base-case scenario, the global SMR sector will need to receive approximately US$150 billion in state aid and subsidies to sustain the projected growth pace. This amounts to roughly $6 billion per year over the next 25 years, in 2023 US dollars.

US$150 billion

TOTAL INVESTMENT

US $800-900 BILLION BY 2050 IN THE WORLD. OF WHICH $150 BILLION IN STATE SUPPORT OF $6 BILLION PER YEAR.

To put it into perspective, over the course of 15 years, the renewable energy sector has secured a total of over 2.5 trillion US dollars (as of 2023) in state support, with solar alone receiving about $70-100 billion in subsidies every year from the governments of the world's biggest economies.

Back in 2008 in the EU the level of subsidies on solar power amounted for €496 per MWh of generated electricity in 2008, the figure has which halved in 10 years[8].

Meanwhile, according to the OECD's International Energy Agency (IEA), despite the global decarbonisation agenda and net-zero pledges, the amount spent on fossil fuel subsidies worldwide reached a record high of over US$1 trillion in 2022 alone[9]. About US$ 60-70 billion is spent in G20 countries every year on subsidies to coal, including those channelled through 'capacity mechanisms' designed to ensure the security of electricity supply by maintaining a necessary level of available dispatchable power generation in the grid[10].

Redirecting a small fraction of fossil fuel subsidies to the SMR sector is unlikely to adversely affect the availability of funds for renewable energy expansion in any way. Instead, it would complement the rising share of renewables in the grid, ensuring the resilience of the electricity system and security of supply.

The availability of state support for both the supply and demand sides of potential SMR markets will play a decisive role in determining the prospects of SMR deployment in any specific market over the next 15-20 years.

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[8] https://trinomics.eu/wp-content/uploads/2020/11/Final-Report-Energy-Subsidies.pdf

[9] https://www.iea.org/topics/energy-subsidies#

[10] https://priceofoil.org/content/uploads/2019/06/g20-coal-subsidies-2019.pdf

The types of present and potential state support for SMR development could be grouped in the following categories:

Direct funding

(grants or alternative schemes of subsidies) of R&D and indirect incentives for private R&D spending;

Support for the infrastructure,
from the regulatory reference system to supply chain localisation, and sites availability;

Tax credits,
tax deductions and tax expenditures for vendors, operators and energy users (customers),

Demand-side subsidies,
income and price support mechanisms, including the market risk mitigation mechanisms (Feed-in Tariffs, Power Purchase Agreements (PPAs) and Contract-for-Difference schemes (CfDs) ensuring the revenues at a specific price regardless of the market conditions,

The cost of capital reduction
mechanisms ranging from the direct equity involvement by the state or state-owned enterprises in SMR deployment to state guaranties for debt financing and export credit facilities by sovereign funds, state-owned banks or development finance institutions (DFIs).

UNITED STATES

In terms of direct R&D funding the USA has indeed long been one of the global leaders.

In 2012 the US Department of Energy launched a 6-year US$ half-a-billion program[11], granting both mPower and NuScale over US$200M each[12]. Combined with indirect incentives this helped to attract private sector investment in advanced reactors of over $1.3 billion from about 50 private companies promoting a wide range of technologies, “including fast-spectrum reactors, molten salt reactors, high temperature reactors, fusion technologies, hybrid energy solutions, and others”[13].

Recently, the U.S. nuclear sector, particularly SMR developers, has received a significant demand-side boost from a series of legislations passed in the United States in 2021-2022. Collectively, the Inflation Reduction Act (IRA, 2022), Infrastructure Investment and Jobs Act (2021), and the Department of Energy (DOE) programs under the Energy Act of (2020) have provided over US$6 billion in public subsidies for various aspects of the nuclear energy sector, including uranium supply, operating nuclear capacity, SMR reactors, and new reactor designs.

This funding underscores the government’s commitment to supporting the entire nuclear energy ecosystem, from fuel supply to reactor innovation.

The United States has been the first in the world to begin actively encouraging the conversion of retired and aging coal-fired power plants into sites for SMRs. The IRA offers a tax credit of 30% for constructing zero-emission advanced nuclear power plants launched from 2025, with an additional 10% for installing SMRs at retired coal plant sites. Furthermore, using domestic content in these projects adds another 10% credit. A Department of Energy study has identified a significant number of former coal plant sites as suitable locations for SMRs, potentially adding substantial clean energy capacity to the grid.

To boost US SMR exports, the Biden-Harris administration launched the Foundational Infrastructure for the Responsible Use of Small Modular Reactor Technology (FIRST) program[14] in 2021.

This program aims to provide ‘capacity-building support to partner countries as they develop their nuclear energy programs to support clean energy goals under the highest international standards for nuclear safety, security, and nonproliferation.’ Initially, the program had a budget of just US$5.3 million, but it is expected to receive increased funding for initiatives like the coal-to-nuclear conversion Project Phoenix (discussed further in the EU subsection). In 2023 the US also launched the Nuclear Expediting the Energy Transition (NEXT) One Stop Shop for SMR Support to help countries approaching SMR deployment to develop necessary regulatory and investment frameworks.

In a recent development, the Export-Import Bank of the United States (EXIM) has committed to supporting the global deployment of U.S. Small Modular Reactor (SMR) systems and components. This commitment was announced at the 2023 United Nations Climate Change Conference (COP28) in Dubai in December 2023 and featured in the White House’s fact sheet for the summit[15]. EXIM’s SMR support program aim to enhance the competitiveness of U.S. SMR exporters, offering extended repayment terms, substantial financing for U.S. export contracts (up to 85% of value), and up to 40-50% local cost support, and includes a significant feature where it subsidises interest costs before the plant becomes operational. It also includes collaborative financing options with other OECD Export Credit Agencies[16]. These measures, including pre-construction technical service financing and the Make More in America Initiative, demonstrate a significant step towards doubling down on state support efforts to promote the US SMR technologies globally.

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[11] https://www.nrc.gov/docs/ML1431/ML14310A125.pdf

[12] http://www.nnl.co.uk/media/1627/smr-feasibility-study-december-2014.pdf

[13] https://www.trade.gov/topmarkets/pdf/Civil_and_Nuclear_Top_Markets_Report_2017.pdf

[14] https://www.state.gov/program-to-create-pathways-to-safe-and-secure-nuclear-energy-included-in-biden-harris-administrations-bold-plans-to-address-the-climate-crisis/

[15] https://www.whitehouse.gov/briefing-room/statements-releases/2023/12/02/fact-sheet-biden-harris-administration-leverages-historic-u-s-climate-leadership-at-home-and-abroad-to-urge-countries-to-accelerate-global-climate-action-at-u-n-climate-conference-cop28/

[16] https://www.exim.gov/policies/small-modular-reactor-financing

RUSSIA

Russia has not disclosed specific figures allocated exclusively to the development of its SMR sector. It is also challenging to estimate the value contribution of the Soviet research legacy and Rosatom's ongoing classified defence contracts for the Russian Navy, including nuclear submarines.

However, based on official information from the Russian government regarding overall support for Russian nuclear energy, over 10 years from 2012 to 2022, Russia has spent more than 1 trillion Rubles (approximately US$ 21.7 billion at the weighted average exchange rate) and continues to spend between US$1-1.5 billion annually[17].

US$1-1.5 billion

Additionally, the Russian government provides Rosatom with comprehensive support in terms of export finance facilities and international advocacy. The Russian foreign ministry actively promotes Rosatom's products and services through its diplomatic channels, proposing framework intergovernmental agreements to countries for the peaceful use of atomic energy. Once Rosatom identifies a business opportunity, it conducts a tailored feasibility study, designing a finance scheme that suits the needs of the importing country and the specific profile of each project. The Russian government then offers export finance facilities at attractive interest rates, either as an intergovernmental loan or a credit line through a Russian development finance institution, significantly reducing the cost of capital.

Not surprisingly, leveraging this support, Rosatom has, over the last decade, cemented its leadership position in the global nuclear industry, specifically in new nuclear build exports and uranium products markets.

According to the International Atomic Energy Agency (IAEA) database, as of December 2023, Rosatom is building six times as many reactors for export (four times as much in terms of electric capacity) as all its competitors combined. Out of the total 60 GWe (58 reactors) currently under construction worldwide, 39% is based on Russian designs. In the new nuclear build export market, which accounts for 25 GWe out of the total 60 GWe, the Russian share is 81% and 86% by total capacity and the number of reactors, respectively. Rosatom operates uranium enrichment facilities with a total capacity of 27.7 million SWU/yr, almost half of the world's total of 60.2 million, and supplies about one-third of the global nuclear power fleet's needs. Rosatom is currently the only commercial supplier of High Assay Low Enriched Uranium (HALEU) in the world, a type of fissile material critical for manufacturing fuel for the majority of advanced Generation IV reactors.

Thanks to comprehensive state support, including funds allocated to the Arctic and the Northern Sea Route development program for a new nuclear icebreakers fleet and SMR-based floating nuclear power plants, Rosatom was the first in the world to launch a pilot SMR facility, FNPP Akademik Lomonosov in Pevek (Chukotka). Russia has now effectively reached the stage of series SMR manufacturing with its RITM-200 technology. This technology, used with minor modifications in marine nuclear propulsion applications (such as icebreakers), is also utilized in both floating and onshore power stations.

CHINA

The overall state support for the nuclear sector in China is vast. China employs a range of mechanisms to meet its ambitious domestic and export nuclear energy deployment targets, from direct R&D funding to soft loans[18], state-directed domestic demand-boosting policies, and export finance[19].

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[17] https://rosatom.ru/upload/iblock/8b3/8b3e406a7cb52d075c63a131b8b55fcb.pdf

[18] https://carnegieendowment.org/files/Hibbs_ChinaNuclear_Final.pdf

[19] https://www.energypolicy.columbia.edu/wp-content/uploads/2022/08/NuclearFinance-CGEP_Report_111022-1.pdf

140 GWe

Domestically, China aims to add over 140 GWe of nuclear capacity to the grid by 2035, which would quadruple the size of its current fleet. This effort implies building reactors at a scale of 9-10 GWe per year, requiring an investment of approximately $440 billion in new nuclear builds.

According to experts close to the Chinese nuclear industry, the export potential for both large reactors and SMRs is estimated at around US$140-150 billion[20], implying the construction of 25-30 GWe of capacity abroad.

While specific official figures are scarce, the significance of the nuclear industry is underscored by its inclusion as a national priority in China's 'Five-Year Plans'[21]. The fact that small nuclear reactors, alongside other advanced reactor technologies such as high-temperature reactors and fast reactors, are featured in these plans as top priority indicates the high level of importance the state places on the development and deployment of SMRs.

The scale of China's export finance support can be illustrated by the conditions of a US$ 6.7 billion loan to Argentina for the construction of Hualong One, the flagship Chinese large reactor design. The agreed interest rate was 4.5%, with repayment terms of 20 years, while the market yields of Argentina's US-dollar-denominated sovereign debt of comparable maturity were about 30-35%. These conditions represent a net present value of US$4.5-5.2 billion in subsidized cost of capital over 20 years. It is important to note that China, unlike the US, France, or other OECD countries, is not bound by OECD export finance standards. Consequently, the gap between market interest rates and its export finance options can be as wide as necessary to make the deal attractive to the buyer.

Similarly to Russia, China does not publicly disclose the full extent of its state support for SMR R&D expenses, but estimates suggest they amount to at least several hundred US$ millions, not including corporate funding from CNNC and CGN. China has selected its ACP-100 Linglong One (玲龙), which translates from Chinese as 'Nimble Dragon', as its flagship SMR design for both domestic use and exports. The first demonstration unit is currently scheduled to begin operations in 2026. However, assuming the highly likely delays associated with the First-Of-A-Kind (FOAK), we conservatively expect the project to be fully operational by 2027[22].

Despite this, China is on track to become the first country in the world to launch a land-based SMR power plant. A modification of the ACP-100 is also designed for floating nuclear power plant applications. China is reportedly considering deploying these in significant numbers in various locations, including the South China Sea23. Although the controversial plans for the contested areas have been recently put on hold due to security concerns24 in the event of potential hostilities, the program could be resumed as China continues to build up its military presence in the region.

Estimating the scale of potential demand-side subsidies for domestic buildouts and exports in China is challenging. However, considering the magnitude of the country's nuclear ambitions, we estimate that, over the next 15 years, China may allocate as much as US$25-35 billion for deploying the fleet of Linglong One reactors, both domestically and internationally. This allocation includes mechanisms for reducing the cost of capital, which would be critically important for higher credit risk countries like Turkey and South Africa.

Alongside Russia, China is expected to become one of the most active players in the global SMR export market.

EUROPEAN UNION AND THE UK

In Europe, a fully articulated, large-scale SMR support program exists only in the UK.

However, despite a pledge to commit about £250 million (approximately US$315 million) back in 2015, substantial support began only recently. Before the pandemic, the UK government had allocated no more than £30 million (US$40 million), with the majority of the funds going to developers of advanced or innovative technologies whose commercialisation horizon extends well beyond 2030[25].

However, in 2020 the UK government adopted the Ten Point Plan for a Green Industrial Revolution and the 2020 Energy White Paper which have highlighted the importance of developing nuclear energy, including SMRs. Under this plan, the government announced the Advanced Nuclear Fund, with an allocation of up to £385 million (approximately US$500 million) million. This fund includes up to £215 (US$270) million for SMRs to develop domestic smaller-scale power plant technology designs and up to £170 (US$215) million for a research and development program aimed at delivering an Advanced Modular Reactor (AMR) demonstration by the early 2030s.

US$500 million

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[20] https://www.bloomberg.com/news/features/2021-11-02/china-climate-goals-hinge-on-440-billion-nuclear-power-plan-to-rival-u-s?leadSource=uverify%20wall
[21] http://zfxxgk.nea.gov.cn/1310540453_16488637054861n.pdf
[22] https://www.cnr.cn/hn/tp/20231102/t20231102_526472798.shtml
[23] https://time.com/5370092/south-china-sea-nuclear-power/
[24] https://www.scmp.com/news/china/science/article/3222289/china-suspends-plan-build-floating-nuclear-reactors-south-china-sea
[25] http://euanmearns.com/who-killed-the-small-modular-reactor-programme/

According to the UK government website[26], the UK is working on key policy and market enablers, including finalising regulatory access, siting, and financing for SMRs deployment to as part of their commitment to boost nuclear capacity to 24 GW by 2050.

This plan includes a government-run competition for SMR development, in which Rolls-Royce's led consortium is widely seen to be the frontrunner. The government has also established the Great British Nuclear body to select and support promising SMR technologies.

The EU-level support for SMRs has been hindered by internal divisions among member-states over their attitudes towards nuclear energy in general. The debate has intensified recently regarding the classification of nuclear energy as 'green' or sustainable in the EU taxonomy. Countries like Germany, which is phasing out nuclear energy altogether, Luxembourg, Portugal, Denmark, and Austria have expressed opposition to classifying nuclear energy as a climate-friendly power source. On the other hand, France, Poland, Hungary, and the Czech Republic advocate for the inclusion of nuclear power plants and nuclear waste storage facilities in the 'green' classification. France, leading this group, has announced plans to build new nuclear reactors to reduce carbon emissions and to promote energy independence.

In November 2023, the European Commission announced the creation of an Industrial Alliance dedicated to SMRs during the European Nuclear Energy Forum in Bratislava, Slovakia. According to NuclearEurope[27], a Brussels-based trade association behind the initiative, the EU SMR Industrial Alliance focuses on accelerating the deployment of SMR technologies and ensuring a strong EU supply chain, including a skilled workforce. The Alliance aims to incentivize the market for SMRs, explore financing options, strengthen the nuclear industry's capabilities (including education and training), and support innovation, research, and development.

The EU SMR support program is likely to be revolving about the French NUWARD project, a 300-400 MWe design developed by the consortium of the French Alternative Energies and Atomic Energy Commission (CEA), EDF, Naval Group, and TechnicAtome.

In February 2022, as part of the France 2030 plan, the French government announced that it would allocate $1.1 billion (€1 billion) of public funding to the Nuward SMR design.

This funding underscores the government's ambition to see an SMR prototype by early 2030s, contributing to France's goal of adding 25GW of new nuclear generation by 2050. Prior to NUWARD, the French state support for SMRs was at best very limited. The government provided funding to the EDF-led Flexblue concept, a 50-250 MWe underwater PWR design, with just about €20 million. The project was discontinued in 2016.

Sweden has been funding the SEALER (Swedish Advanced Lead Reactor) project, a 55 MWe lead-cooled reactor, through VINNOVA (The Swedish Innovation Agency) since 1996. The developer, LeadCold, recently renamed Blykalla, along with its consortium partners, has recently received a SEK 99 million (US$ 9.5 million) grant from the Swedish Energy Agency. This grant is for building a 2.5 MWt non-nuclear prototype at Oskarshamn and aims at constructing a full-scale demonstration unit in the early 2030s. Although the project boasts promising features, such as a 10–30-year operating period without refueling and reduced capital costs, the lead-coolant technology is relatively niche. We do not expect its wide international expansion without a significant export push, which Sweden alone might not be able to provide.

It should be also noted that the EU has significant restrictions on state aid in member states. In most of the cases state aid for nuclear faces inquiries by the European Commission which causes delays and most certainly – challenges in the EU courts from anti-nuclear countries such as Austria, which could push back deployment schedules for years. This, combined with the scarcity of funds and varying public support for nuclear subsidies, leads to potential problems with subsidising new nuclear build in the EU and undermining the export prospects of European SMR designs.

The EU countries of Central and Eastern Europe countries, and especially Czech Republic, Poland, Slovakia and Romania, are actively exploring deployment of SMRs to replace their massive coal power generation fleet with a low-carbon source of baseload. With limited resources available in terms of their own financial support, they are working closely with the US government, which has pledged it support for energy transition in the region. In particular, through Project Phoenix, launched by US Special Presidential Envoy for Climate John Kerry at the COP27 climate summit in Egypt in 2022, Czech Republic, Poland and Slovakia were selected to receive a share of $US 8-million support for coal-to-small modular reactor (SMR) feasibility studies.

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[26] https://www.gov.uk/government/publications/advanced-nuclear-technologies/advanced-nuclear-technologies

[27] https://www.nucleareurope.eu/press-release/european-commission-announces-creation-of-small-modular-reactor-alliance/

REST OF THE WORLD

Besides the US, UK, Russia, China, and the EU, there are four additional countries—Argentina, Canada, South Korea, and the Persian Gulf nations (specifically the Kingdom of Saudi Arabia and the United Arab Emirates)—that are most active in exploring and supporting the development and deployment of SMRs.

In Canada, state support for Small Modular Reactors (SMRs) is a key component of the nation's strategy to develop non-emitting forms of energy and bolster its nuclear capabilities.

In early 2023, Canada unveiled the "Enabling Small Modular Reactors Program," allocating CAD 29.6 million (USD 21.8 million) in funding over a four-year period. This initiative aims to support the development of supply chains for Small Modular Reactor (SMR) manufacturing, enhance fuel supply and security, and facilitate research in the realm of safe SMR waste management solutions. The Canadian government has approved up to CA$74 million (US$ 55 million) in federal funding for SMR development in Saskatchewan, led by SaskPower. This funding will support pre-engineering work, technical and environmental assessments, regulatory studies, and community and Indigenous engagement. SaskPower has selected the GE-Hitachi's BWRX-300 for potential deployment in Saskatchewan in the mid-2030s[28].

The Canadian Nuclear Safety Commission (CNSC) has a formal collaborative relationship with the US Nuclear Regulatory Commission (NRC) on advanced reactor and SMR technologies, focussed in particular on licensing the BWRX-300 design.

Although Argentina was initially one of the first-movers in the SMR market with its CAREM technology, the country's economic challenges have hampered its prospects for deployment and international expansion. The newly elected, climate-sceptic President Javier Milei, who pledged to scrap state funding for research and innovation, is expected to suspend previously announced new nuclear build plants, including the Hualong One deal with China, the future of the CAREM 25 demonstration unit, which is in the final stages of completion, remain uncertain[29].

South Korea, one of the other first-movers and in collaboration with Gulf states Saudi Arabia and the UAE, developed the SMART (System-integrated Modular Advanced Reactor), an up to 100 MWe PWR reactor. In 2012, it was the world's first fully licensed SMR. The Korea Atomic Energy Research Institute initially planned to complete its demonstration unit by 2017, but the project was shelved by former anti-nuclear President Moon Jae-in's administration (2017-2022). The design is now expected to be upgraded and re-licensed, as the new Korean administration seeks to revitalise the nuclear sector and relaunch its SMR export program[30]. Additionally, a KEPCO-led group of companies has developed a new 60 MWe IPWR design, BANDI-60, for floating nuclear power plants, while Samsung Heavy Industries (SHI) announced in January 2023 that it had completed the conceptual design for the CMSR Power Barge, a floating nuclear power plant based on compact molten salt reactors[31].

In summer 2023 South Korea announced a new public-private alliance aimed at the acceleration of SMR deployment[32]. While the outstanding technological and business capabilities of the Korean nuclear sector suggest that both the SMART and BANDI-60 designs are likely to secure their market share, the lack of state support and the legacy of Moon's 'nuclear pause' could delay Korea's SMR plans. Consequently, the main market for these technologies is expected to remain within the Middle East region, at least until 2040.

CONCLUSION

State support for the development and deployment of SMR designs is crucial, especially in the early stages of global SMR buildout.

We estimate the total monetary value of such aid to be around US$ 150 billion, encompassing demand incentives, price support, and interest rate/cost of capital subsidies. This need could be primarily met through policy changes, such as reallocating funds from fossil fuel subsidies.

The United States, Russia, and China have emerged as global leaders in state support for the SMR sector. The US combines direct R&D funding with substantial investments in a deployment framework and tax incentives. Russia's advanced SMR deployment program, with projects in the Arctic and Siberia, along with robust export support mechanisms, gives Rosatom a competitive edge. China, with its significant state investment and ambitious domestic and export goals, is also a key player.

However, the US and other OECD countries, traditionally focusing on R&D funding, are now expanding their support mechanisms to include a wider range of deployment enablers. This represents a significant shift in their approach to SMRs. Yet, in terms of export support, these countries face limitations as OECD members, restricted in their ability to subsidize interest rates. This is not the case for Russia and China, giving them a distinct advantage in offering more competitive financing terms. The cost of capital is crucial for the economic viability of SMRs, and this ability to offer better financing terms positions Russia and China advantageously in the global SMR market, potentially shaping the future landscape of nuclear energy technology exports.

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[28] https://world-nuclear-news.org/Articles/Federal-funds-announced-for-Saskatchewan-SMR-proje
[29] https://www.forbesargentina.com/money/por-buen-momento-comprar-acciones-at-t-n44562
[30] https://neutronbytes.com/2020/01/18/south-koreas-smart-smr-gets-new-life/
[31] https://www.world-nuclear-news.org/Articles/ABS-approves-Korean-SMR-power-barge-design
[32] https://www.ans.org/news/article-5170/south-korea-launches-publicprivate-smr-alliance/

VIABILITY DRIVERS: SMRS AND ENERGY SYSTEMS

In this section of the report, an analysis will be made of the likely competitive position of SMR technology at the initial stage of their commercial and technological readiness (assumed to be between 2030 and 2035).

We begin with a 'generic' SMR technology – using the baseline assumptions and the model put forward by the UK Government in the Small Modular Reactor Techno-Economic Assessment.

Then, we assess the competitiveness of SMRs applications relative to alternative dispatchable on-grid and off-grid energy solutions.

GENERIC SMR MODEL: METHODOLOGY AND COST ASSUMPTIONS

As noted above, the technical and economic parameters (see Table 1 below) are taken from a report conducted by the UK government[33]. The set below – the 'generic' SMR – is the result of a synthesis of anonymised vendor submissions that were collected for an earlier section of SMR projects for government support.

Table 1

Parameter	Unit	Value	Unit	Value
Capacity	MW	300		
Construction Cost	2010£/kW	4750	2023US$/kW	7500
Fixed O&M	2010£/kW/yr	130	2023US$/kW/y	280
Variable O&M	2010£/MWh	4.6	2023US$/MWh	10.2
Fuel Cost	2010£/MWh	5	2023US$/MWh	10.9
Lifetime	Yr	50		
Construction Period	Yr	3		
Capacity Factor	%	85		

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[33] **See page 24**
https://www.gov.uk/government/publications/advanced-nuclear-technologies/advanced-nuclear-technologies

US$148/MWh

Based on the above assumptions, the simplified levelised cost of electricity (disregarding tax considerations which could vary from country to country, subsidies, possible revenues produced derived from co-generation etc) by the generic SMR (at a cost of capital of 8%) would equal US$148/MWh, about half of which is accounted for by construction costs (as is the case with 'traditional' large nuclear power plants).

As is the case for large nuclear power plants, the levelised electricity cost of an SMR is heavily dependent on two variables: the overnight construction cost and the (weighted average) cost of capital. The determination of these two values will determine the eventual competitiveness of SMR technology to a large extent. Indeed, much of the attraction of SMRs is the result of their supposed ability to reduce these two cost drivers; in-factory, series production of modular units – and the congruent opportunity to exploit 'learning-by-doing' – is said to reduce the former and the smaller figure of total capital investment required – widening the pool of potential investors – to construct an SMR may improve financing terms.

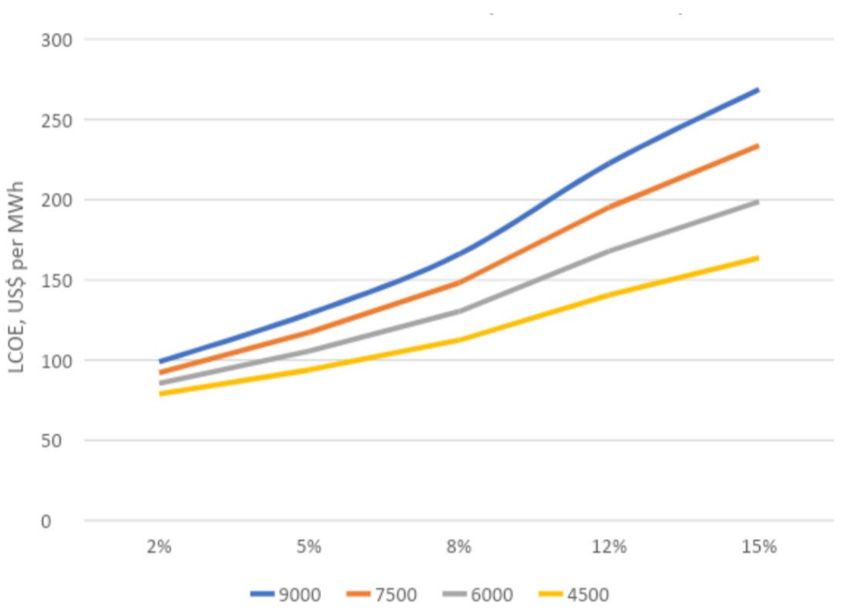

Figure 2

'Generic' SMR LCOE sensitivity to Cost of Capital

As shown in the chart on Figure 2 above, the primary driver behind the final cost of a unit of electricity for SMRs is the cost of capital.

Any increase in the cost of capital or discount rate amplifies the effect of increasing or decreasing the overnight construction cost.

Other factors, such as improved fuel efficiency or extended intervals between refuellings (resulting in reduced fuel costs per unit of generated electricity and a higher capacity factor), lower operational costs, and longer operational life, have a very limited impact on the Levelized Cost of Electricity (LCOE). For instance, even halving or doubling the fuel cost leads to a mere 3-8% change in the cost per unit of electricity, which is less than the impact of changing the discount rate by 1%.

It should be noted that innovation-driven cost savings are most likely to pertain to the cost of equipment, specifically the prefabricated modules, and to a much lesser extent, if at all, the cost of setting up the facility.

This includes expenses such as site licensing, site development and civil works, construction materials, transportation, and site security. Even for the most simplified 'plug-in' designs, these setup costs could account for as much as one-third of the upfront capital expenditure[34].

Moreover, for smaller installations with lower capacity, the proportion of such costs could be even higher. For example, physical security rules, including perimeter barriers for the site and facility buildings designed to withstand the impact of a large commercial aircraft, still apply to SMR sites just as they do to larger nuclear power stations[35].

Table 2

US$ per kW	2%	5%	8%	12%	15%
9000	98.90	128.97	166.01	222.56	268.82
7500	92.20	117.26	148.13	195.25	233.80
6000	85.50	105.55	130.24	167.94	198.78
4500	78.80	93.84	112.36	140.63	163.76

As indicated in Table 2 above, the best-case scenario for a generic SMR — achieving an LCOE below US$90 per MWh — is feasible only if the overnight construction costs are below US$6,000 per kWe of installed capacity, and the project has a discount rate of just 2%. This rate is currently below the so-called 'risk-free' rate, namely, the long-term yield of U.S. Treasuries, and thus could only be achieved through subsidies. At the industry average cost of capital for electric utility companies in industrially developed countries, which is 8%, even a substantial reduction in overnight construction costs to US$4,500 per kWe would still result in an LCOE firmly above $100 per MWh.

For private energy or industrial firms potentially operating SMRs in emerging markets, where country and business risks are higher, the cost of capital is likely to be closer to 15%. This means that the LCOE would range between US$150 and $300 per MWh.

SUCH AN ECONOMIC PROFILE IMPOSES CONSTRAINTS ON THE POTENTIAL CONDITIONS UNDER WHICH SMRS COULD BE DEPLOYED IN A COMPETITIVE ENERGY TRANSITION ENVIRONMENT.

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[34] https://www.world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/small-nuclear-power-reactors.aspx

[35] https://www.nrc.gov/docs/ML1104/ML110460434.pdf

APPLICATIONS

THE POTENTIAL GLOBAL MARKET FOR SMALL MODULAR REACTORS (SMRS) PRESENTS A MULTIFACETED LANDSCAPE, DISTINGUISHED BY POTENTIAL APPLICATIONS, EACH WITH ITS OWN MARKET SIZE, COMPETITIVE DYNAMICS, AND VIABILITY DRIVERS.

This segmentationincludes:

On-grid Applications

Primarily focusing on replacing carbon-intensive baseload generation, such as coal-fired plants, this segment addresses the need for cleaner, more sustainable energy mix within the existing grid infrastructure in the context of energy transition. This segment could also utilise some basic co-generation features such as district heating and seawater desalination.

Off-grid Applications

Targeting remote locations and communities not connected to the central grid, SMRs in this segment offer a reliable power source for areas where grid extension is impractical or cost-prohibitive.

Advanced Co-generation

This segment encompasses applications like process heat, typically above 400 °C (752 °F), for industrial use and new energy applications, such as hydrogen production, where SMRs can provide both electricity and heat, meeting diverse energy needs in a single integrated solution.

Transport Applications

Encompassing uses in the maritime (such as icebreakers and nuclear propulsion vessels) transport sector, and potentially in future space applications.

ON-GIRD

The primary driver of demand for on-grid SMRs applications is mainly driven by the need to replace baseload capacity that has historically been provided by carbon-intensive generation (especially coal-fired power plants).

In broad terms, this transition is necessitated by the increasingly acute threat that climate change poses to humanity and has been given policy clout in the largest world economies through the introduction of carbon-pricing mechanisms, such as the European Union's Emission Trading Scheme (ETS) and a multitude of national initiatives, including carbon emission taxes, mandatory coal phase-outs etc. Of equal importance is the current (and likely near- to mid-term) absence of the long-term industrial scale energy storage solutions that would enable intermittent renewable energy sources – solar and wind – to provide baseload, dispatchable electricity capabilities while maintaining system reliability and security.

As such, a key determinant of actual SMR demand will be its cost-effectiveness in providing baseload, dispatchable electricity, and heat compared to alternatives. Over 70 countries have committed to phasing out coal or stopping the development of new unabated coal power plants, representing 20% of global coal-fired generation.

70 countries

However, less than half have set specific target dates in their national plans, primarily in Europe and advanced economies.

Given the abundant low-cost coal supplies worldwide, investing in new coal assets is a possibility and indeed is underway in many markets.

According to the IEA[36], 'unabated' coal-fired new build power plants, under prevailing market conditions and without carbon pricing, would have an LCOE of US$55-75 at a market cost-of-capital discount rate of 8-10%. For SMRs to reach this level, a subsidized discount rate of 2-3% and construction costs below $3,000 per kWe are required, exceeding most aggressive cost reduction projections. However, with CCUS, coal generation's LCOE increases dramatically to US$100-120 per MWh, a level also reached with carbon pricing above $70 per metric ton of CO2 emissions.

In the near to medium term, it appears that SMR demand will be concentrated in countries implementing explicit coal phase-outs.

It is important to consider SMRs' competitive position relative to gas-fired power plants (CCGTs), currently leading the debate on baseload replacement. Gas-fired electricity is more cost-effective due to lower construction costs, lower carbon intensity (especially with CCUS), and higher fuel costs.

Comparatively, SMRs fare slightly better against gas-fired generation over a wider range of finance rates or construction costs. Without carbon pricing but including the cost of hedging for volatile natural gas prices, LCOE for a new gas-fired plant operating predominantly in load-following mode (60-70% average capacity factor) would be US$65-85 per MWh at an 8-10% discount rate. A CCUS-equipped gas plant working at an average capacity factor of 40% to back up variable renewable generation would have an LCOE of US$110-130 per MWh. The same holds for a CCGT plant without CCUS but at a level of effective carbon pricing above US$ 80-90 per metric ton of CO$_2$.

Additionally, in on-grid applications, SMRs compete with other low-carbon dispatchable energy sources such as large nuclear power plants and geothermal sources. Focusing solely on electricity generation (excluding district heating co-generation), the economic viability of SMRs is further challenged by alternatives like enhanced grid interconnections and utility-scale energy storage, which, albeit only partially, address some grid balancing needs.

For larger countries in the early to middle stages of industrial development, where energy intensity remains high, GW-size nuclear power plants offer a value proposition difficult for SMRs to match. A 4-6 GWe multi-unit nuclear power plant, built outside the OECD countries at an 8-10% discount rate, would have an average LCOE of US$50-70 per MWh, a level challenging for most SMR designs. At a 2-3% subsidized discount rate, typical for major infrastructure projects, such a large power plant could achieve an LCOE of just US$30-50[37].

Geothermal energy sources, where available, could be the source of electricity and heat at LCOE of US$50-70 per MWh, with potential cost reduction to as low as US$40 per MWh[38].

It would be a considerable factor of competition for the western part of Americas, especially the United States, parts of Southeast Europe and the Middle East and Southeast Asia. In regions with abundant wind and solar irradiation, falling prices for battery energy storage and improved grid interconnections could lead to a reduced demand for baseload dispatchable generation. For instance, the National Renewable Energy Laboratory (NREL) of the U.S. Department of Energy predicts that a utility-scale solar PV installation backed by battery energy storage could achieve an LCOE of US$45-65 per MWh between 2030 and 2050[39].

However, when considering alternative options such as energy storage and grid interconnections, it is important to remember that they cannot replace thermal plants, like coal, fuel oil, and natural gas, in supplying district heating. With current natural gas prices ranging between US$2.5 and US$8 per MMBtu, the cost of gas-fired heating is estimated to be US$2-7.5 per gigajoule (GJ). According to estimates from the School of International and Public Affairs (SIPA) at Columbia University[40], switching to electric resistance heating powered by the grid could more than triple the cost to US$11-26/GJ.

If powered solely by renewables, the cost for electric heating could rise to US$40-65 per GJ.

IN COMPARISON, THE COST OF HEATING FROM AN SMR IS ESTIMATED TO BE IN THE RANGE OF US$5.5-7.5/GJ.

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[36] https://www.iea.org/reports/projected-costs-of-generating-electricity-2020

[37] https://world-nuclear.org/information-library/economic-aspects/economics-of-nuclear-power.aspx

[38] https://atb.nrel.gov/electricity/2023/geothermal

[39] https://atb.nrel.gov/electricity/2023/utility-scale_pv-plus-battery

[40] https://www.globalccsinstitute.com/wp-content/uploads/2020/06/JF_LowCarbonHeat-CGEP_Report-20191002-2.pdf

Based on the considerations above, and assuming an achievable LCOE range for SMRs of US$70-100/MWh, we can identify the key parameters of the markets for on-grid SMR applications. These include:

- Countries with aggressive climate targets, high carbon pricing, coal phase-out plans, and a significant size of aging coal fleet;
- Countries and regions where large nuclear power plants are not feasible due to grid size or configuration, among other considerations;
- Regions with limited renewable energy options, particularly geothermal, due to climatic conditions, but with demand for baseload electricity and district heating.

140 GWe

We estimate the size of this potential segment to be 50-60 GWe under the base-case scenario, with major regional markets including the United States, Canada, Northern Europe (including the Nordic countries and the United Kingdom), and Central and Eastern Europe. Under a high-case scenario, assuming more radical climate policies, the potential market size could reach 100-120 GWe.

This segment is expected to be dominated by PWR-based technologies, mainly developed in the United States, the UK, and France, with first-movers such as VOYGR (NuScale) and BWRX-300 (GE-Hitachi) potentially sharing about one-third of the market.

OFF-GRID AND MINI-GRIDS

The segment of off-grid application of SMRs presents a significant deployment potential, particularly for remote communities and natural resource extraction sites currently reliant on costly and carbon-intensive and heavily polluting diesel power generation. As per the International Finance Corporation (IFC), the global installed capacity of off-grid diesel generators is estimated to be about 150 GW, with the total cost of electricity starting from $400 per MWh. 15-20 GW of off-grid and mini-grid power installations are estimated to burn fuel oil.

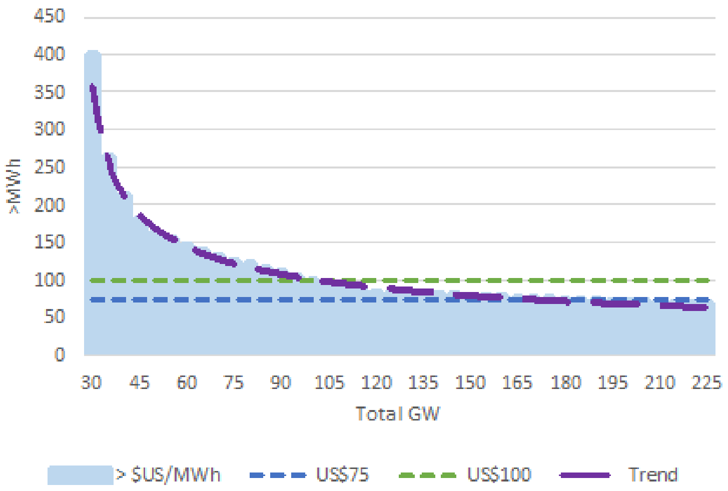
Even without carbon pricing or other policy restrictions the use of fossil fuels in many of such remote locations is extremely expensive due to logistical challenges.

The total installed hybrid renewables-battery solutions capacity used as an alternative to diesel and other fossil fuels generation for off-grid generation and mini-grids, has been growing over the last years to reach 12.5 GW globally in 2022[41]. About 3.5GW of them, according to Wood Mackenzie are deployed to power mining sites[42].

However, in many locations the use of renewable energy is limited due to climatic and terrain features with lower capacity factors translating into higher LCOE. This leaves to smaller (from 20 to 150 MWe) and micro (less than 20 MWe) reactors a significant market size.

Figure 3

Estimated total off grid capacity (<150 MW each, globally) by maximum electricity price in 2030



Taking into account the anticipated growth in the mining sector, it is estimated that by 2050, the off-grid SMR market could account for 60-70 GWe of total installed capacity. Key deployment areas are likely to include the Arctic region, China, the Middle East, select African regions, and remote island territories.

We expect this segment to be dominated by Russian technologies, including the RITM family in both land-based and floating applications, as well as Shelf-M. Chinese designs, mainly the ACP100 in both on-shore and off-shore versions, are also likely to feature prominently, along with a significant presence of South Korean technologies, such as SMART and BANDI-60.

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[41] https://www.irena.org/News/pressreleases/2023/Mar/Record-9-point-6-Percentage-Growth-in-Renewables-Achieved-Despite-Energy-Crisis
[42] https://www.woodmac.com/press-releases/off-grid-energy-key-to-power-growth-in-emerging-markets/

ADVANCED CO-GENERATION

THE ADVANCED CO-GENERATION SEGMENT ENCOMPASSES APPLICATIONS OF SMR TECHNOLOGIES WHERE POWER GENERATION IS NOT THE SOLE (OR PRIMARY) VALUE DRIVER OF THE ENERGY ASSET.

Among advanced reactor designs currently at relatively advanced stages of development, there are two main potential co-generation functions:

1. **high-temperature process heat for industrial use; and**
2. **recycling of spent nuclear fuel from conventional nuclear reactors.**

INDUSTRIAL PROCESS HEAT

While evolutionary Generation III and III+ light water reactors can produce steam at temperatures of about 260-330°C, advanced reactors with different moderators and coolants can achieve higher output temperatures of about 500-800°C.

Lower temperature heat is utilised in basic co-generation options like district heating and seawater desalination. In contrast, higher temperatures enable use in industrial sectors such as ammonia production, methanol synthesis, steam methane reforming for hydrogen production, and petrochemical processes.

Although it is estimated to be the most economic option compared to other low-carbon sources such as electrical resistance or 'green' hydrogen, replacing process heat from fossil fuels with that of advanced small modular reactors (SMRs) in industrial assets is a complex and challenging process. These assets typically operate for decades, with typical capital stock turnover ranging between 20-50 years. Implementing alternative heat sources requires compatibility with energy-using facilities, which entails at least partial redesign and capital expenditure. The viability of such changes depends on factors like mass transfer limits, space requirements, modification degree, and cost.

Economic considerations, including upfront capital needs, and potential engineering challenges in adapting equipment will play a critical role in the practicality of applying SMR technologies in existing facilities, often rendering them impractical until the end of the operational life of industrial assets. Along with supply-side constraints such as likely licensing delays, construction delays of demonstration units, and cost overruns, these factors will limit the growth of this sector in the coming decades. Considering the rate of capital asset replacement in relevant industries and the pressure from expected decarbonization policies, our base-case scenario estimates that such applications will realistically be limited to 20-25 GWe by 2050 and will require substantial direct and indirect subsidies.

We expect that over two thirds of this total capacity would be installed in North America (first and foremost the United States, but also Canada) with some experimental (but of limited scale) applications also installed in China, South Korea, Russia, United Kingdom, and Northern Europe.

CLOSING NUCLEAR FUEL CYCLE

Closing the nuclear fuel cycle, which involves recycling spent fuel and burning waste, is crucial for the sustainable and efficient development of nuclear energy. Advanced reactor designs focused on this goal address several key challenges: reducing radioactive waste, enhancing resource utilisation, and minimising environmental impact.

Innovations in reactor technology, mainly in the segment of fast-neutron reactors, are being developed to improve efficiency of the use of conventional nuclear fuel and burn materials left in the fuel used in conventional reactors (mixed oxide or MOX, WATSS[43], and REMIX[44] recycled fuel technologies). These technologies not only expand the rates of energy capacity utilisation of nuclear fuel but also reduce the volume and toxicity of radioactive waste.

The economics of 'waste-to-energy' SMRs differ from other nuclear power generation installations. Instead of paying for fuel feedstock, these reactors should receive a 'gate fee' for consuming materials that would otherwise not be recycled.

The size of this 'gate fee', or negative fuel cost, can be estimated by comparing the costs of reprocessing spent fuel with those of long-term storage and disposal. Currently, this amount is relatively modest: in 2010 US dollars, the levelized cost of storage per kilogram of heavy metal content was US$100-200[45], which in 2023 prices equates to approximately US$200-300, while the cost of fuel reprocessing through the conventional PUREX (Plutonium and Uranium Recovery by EXtraction) method is about ten times higher.

This high reprocessing cost also negates the value of saving of about 30% of natural uranium otherwise needed. Moreover, as the PUREX process entails separation of plutonium, the technology is associated with nuclear proliferation risks and currently implemented in just 2 countries in the world (France and Russia) with a long-delayed facility in Japan becoming operational in 2024[46].

Not surprisingly, under the current market conditions, out of 7-11,000[47] tons of spent fuel generated annually in the world only less than one third is reprocessed. Reprocessing spent fuel from Pressurized Heavy Water Reactors (PHWRs), like the CANDU type, is considered not economically viable due to their minimal content of U-235 and Pu, which are usually around 0.2% and 0.4%, respectively[48]. In at same time, a standard CANDU reactor produces approximately 140 metric tons of heavy metal (MTHM) annually, which is about seven times higher than the output of a light water reactor.

However, as the world increasingly relies on nuclear energy to meet net-zero targets, with an expected doubling of global nuclear capacity by 2050, the issue of mounting volumes of spent fuel left in long term storage leads to more public scrutiny and pressure on governments and nuclear operating utilities. Such accumulation confronts limited storage capacities. The construction of new storage facilities or the export of spent fuel is met with public resistance, largely due to a common misconception that equates spent nuclear fuel with nuclear waste. In response, national and local authorities are increasingly likely to discourage nuclear operators from choosing the long-term storage option effectively making it more expensive.

A notable example is a tax on spent nuclear fuel storage in Spain, introduced in 2013, and the legislative initiative in New York State, where a law effective from January 1, 2021, has classified spent fuel pools and dry cask storage systems as taxable real property. Such measures are seen as incentives for utilities to close the fuel cycle[49].

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[43] **Waste To Stable Salt, see** https://www.world-nuclear-news.org/Articles/Moltex-announces-waste-recycling-breakthrough

[44] https://world-nuclear.org/information-library/nuclear-fuel-cycle/fuel-recycling/processing-of-used-nuclear-fuel.aspx

[45] https://fissilematerials.org/library/ipfm-spent-fuel-overview-june-2011.pdf

[46] https://japannews.yomiuri.co.jp/original/perspectives/20230622-117266/

[47] **Holdsworth AF, Eccles H, Sharrad CA, George K. Spent Nuclear Fuel—Waste or Resource? The Potential of Strategic Materials Recovery during Recycle for Sustainability and Advanced Waste Management. Waste. 2023; 1(1):249-263.** https://doi.org/10.3390/waste1010016

[48] https://world-nuclear.org/information-library/nuclear-fuel-cycle/fuel-recycling/processing-of-used-nuclear-fuel.aspx

[49] **See also:** https://www.researchgate.net/publication/276378222_Impact_of_the_Taxes_on_Used_Nuclear_Fuel_on_the_Fuel_Cycle_Economics_in_Spain

However, we do not expect this process to be rapid as encouraging recycling and closing the fuel cycle will likely necessitate significant state support and policy adjustments. Inevitable for innovative technologies licensing and implementation difficulties would hinder the progress and cause significant delays which would push potential scaling back to early 2040s.

Prominent designs in this sector include Rosatom's BREST-OD-300, OKLO's Aurora, and Moltex's SSR-Wasteburner. All three aim to address the issue of high reprocessing costs by circumventing PUREX technology and avoiding plutonium separation. The Russian BREST reactor will utilise mixed uranium-plutonium nitrides as fissile materials for its fuel. In contrast, Aurora and SSR-Wasteburner, designed for recycling spent fuel, rely on innovative pyroprocessing, anticipated to be more efficient and economically viable.

Pyroprocessing facilities' potential compactness allows for on-site location, adjacent to advanced 'wasteburning' SMRs, potentially reducing transportation costs and facilitating repeated recycling. This concept aligns with the SMR model of smaller, distributed units across multiple locations. Regarding the BREST-OD-300, it remains unclear whether Rosatom will maintain the project within the SMR range or opt for larger reactors using the same technology.

We project that by 2050, this segment could reach about 5 GWe of installed capacity in our base-case scenario, potentially up to 20 GWe in a high-case scenario. The majority of these installations are expected in North America (the United States and Canada), and possibly in the United Kingdom, Romania, and South Korea.

Approximately 1 GWe of SMRs based on the closed fuel cycle principle is likely to be operational in Russia by 2035. However, it is uncertain whether the SMR concept will be central to Russia's strategy for closing the fuel cycle.

1 GWe of SMRs

TRANSPORT APPLICATIONS

THE SMRS' APPLICATIONS IN THE TRANSPORT SECTOR, MAINLY IN MARITIME TRANSPORT, REPRESENTS A NICHE SEGMENT.

Historically, nuclear propulsion has been primarily utilised in military vessels, with notable examples including submarines and aircraft carriers. However, its civilian applications have been limited, with some exceptions like Russian nuclear-powered icebreakers.

In the commercial sector, the idea of nuclear propulsion for cargo ships has surfaced occasionally, but it has not seen widespread adoption. This limited application is primarily due to high upfront costs, stringent safety regulations, and public perception concerns. Nonetheless, nuclear propulsion offers distinct advantages such as significantly reduced greenhouse gas emissions and extended operational range without refuelling[50].

Despite these advantages, the International Energy Agency (IEA) projects that the future of low-carbon maritime shipping will likely be dominated by green ammonia, hydrogen, electricity, and biofuels propulsion. This projection is based on current technological trends, economic viability, and regulatory landscapes. Consequently, the application of SMRs in maritime shipping, including nuclear-powered icebreakers and potential nuclear propulsion cargo vessels, is expected to remain a specialised area. By 2050, this segment, excluding military applications, is unlikely to exceed 2-3 (base-case) to 10 (high-case scenario) GWe of total capacity. The segment is likely to be dominated by the Russian designs and, in high-case scenario also some innovative microreactors based on the molten salt technology[51].

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[50] https://horizons.lr.org/december-2022/nuclear-ships

[51] https://www.offshore-energy.biz/major-breakthrough-in-molten-salt-reactor-tech-for-maritime-use/

GLOBAL MARKET DYNAMICS

ESTIMATES AND UNCERTAINTIES

In this chapter, we analyse the global market potential for Small Modular Reactors (SMRs) and the dynamics of the global buildout to 2050.

Existing forecasts very dramatically in their estimates of the market potential and the pace of deployment with extreme variations occur not only between different sources and analysts but also within the same forecast under different scenarios. Estimates of the world's total installed SMR capacity for 2050 range from as low as 28 GWe (in Idaho National Laboratory's 2021 analysis) to as high as 375 GWe (in 2018 McKinsey & Company estimate further used by NEA OECD).

6–10 GWe

AVERAGE FORECASTS FOR 2035 HAVE COME DOWN SIGNIFICANTLY FROM EARLIER PREDICTIONS OF 65–75 GWE, MADE SOMEWHAT TEN YEARS AGO, TO CURRENTLY 6–10 GWE.

Table 3 SMR deployment potential, GWe

Source	Year of forecast	2035	2040	2050
NEA (low case)	2016	0.9		
NEA (hight case)	2016	21		375
Bloomberg NEF	2021			
NNL UK	2014	75		
NuScale	2017	65		
UxC (mid case)	2013		22	
UxC (low case)	2013		9	
Idaho National Laboratory	2021	6	9	28

These discrepancies underscore the complexities and uncertainties surrounding the development of the SMR sector. A wide range of factors, from macroeconomic variables such as GDP growth and interest rates and technological advancements, to the vicissitudes of public sentiment towards nuclear energy and geopolitical shifts, influence viability of designs and specific projects as well as the prospects of the sector as a whole.

Our own forecast is based on a combination of a top-down analysis, focusing on global decarbonisation needs and the expected share of nuclear energy in the global energy mix under various scenarios, and a bottom-up assessment. The latter involves evaluating the deployment likelihood of the specific SMRs applications discussed earlier in this report across 60 countries using a decision-tree methodology.

Probability weights for this analysis are derived from historical data in comparable sectors, expert estimates, and simulations, adjusted for non-statistical factors such as public opinion and geopolitical issues.

THE COUNTRIES IN OUR ANALYSIS CAN BE GROUPED INTO FIVE MAIN CATEGORIES:

1. **‘closed’** home markets of key SMR vendors (countries where the import of foreign nuclear technologies is restricted and foreign ownership of nuclear facilities is either prohibited or highly unlikely): Russia and France;

2. **open’ and ‘relatively open’** home markets of notable SMR vendors (countries where indigenous nuclear technologies are preferred and localisation is prioritised, yet import and foreign ownership are still possible): Argentina, Canada, China, South Korea, Sweden, the United Kingdom, and the United States;

3. **countries** currently either already operating nuclear power generating facilities or expected to start within 1-2 years, with a potential market niche for SMR applications: countries such as Romania, Czech Republic, Finland, India, Turkey etc.

4. **countries** with no operational nuclear facilities but having nuclear energy featured in their long-term energy plans and actively exploring nuclear new build options, with a potential market niche for SMR applications: countries such as Estonia, Poland, Myanmar, Indonesia etc;

5. **countries** with some strong fundamental potential demand for SMR applications (energy deficit, lack of affordable alternatives, etc.) and no articulated anti-nuclear public opinion, but without existing nuclear infrastructure and specific plans (examples include Nigeria, Sudan, Shri Lanka etc).

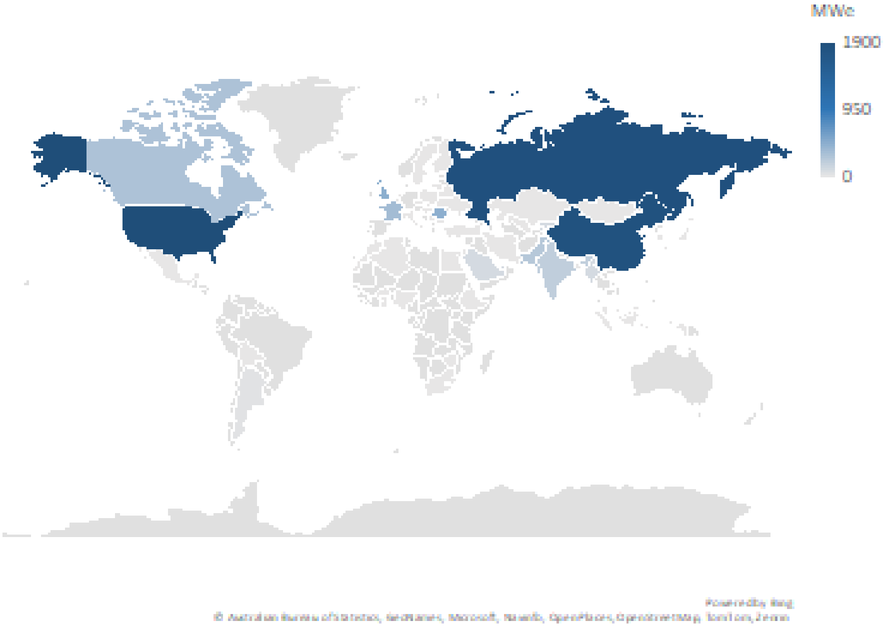
We expect the likelihood of reaching the fundamental demand potential and the pace of deployment to vary significantly from group to group and along with other indicators affect the timeline of potential deployment.

In the beginning of 2030s, we expect the first wave of SMR deployment in the world (dominated by the light water reactor technologies) to take place in group 1 and 2 countries and partially group 3.

We expect 80-90% of the world installed capacity to be deployed in the vendors' home markets with only 10-20% remaining part to be export projects (group 2 and 3). Geographically, the United States, Russia and China would comprise two thirds of the world's total in 2035, each holding 20-25% of the global market share.

Figure 4

SMR deployment landscape in 2030s



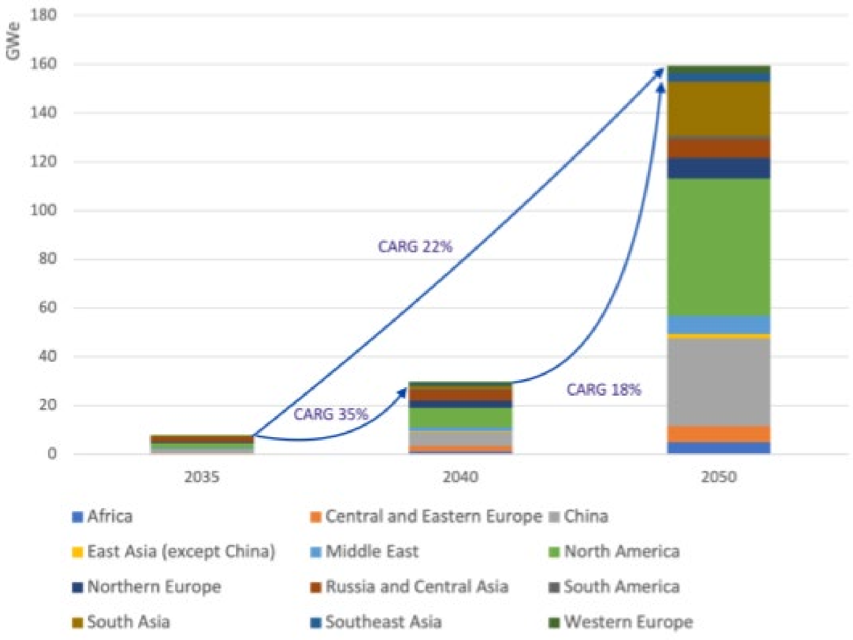
At the second stage, around 2035 and beyond, we project a rapid growth of the export market in countries in group 3 and 4, with approximately 9-11 GWe of export projects of the same 'first-mover' designs with the export share in the new build reaching 40% (or 25-30% of the world's total installed capacity by 2040).

FINALLY, AFTER 2040

we expect the third stage to bring a rapid scaling of deployment of advanced SMRs in groups 1 and 2, while light water SMRs would fill the markets of groups 3, 4 and 5. The share of export in the global new build market would remain fluctuating around 40%.

Figure 5

SMRs by Total Installed Capacity (base-case scenario)



Although the fundamental potential demand for SMRs in the growing global energy mix, mainly driven by the net-zero policies agenda, could be as high as 350-400 GWe of global installed capacity by 2050, market growth is expected to be constrained by the variety of both demand-side and supply-side factors.

In our high-case scenario, the global installed capacity by 2050 is still unlikely to reach this level of fundamental potential, more realistically being around 300 GWe. In this scenario, post-2040, SMRs would be deployed in over 60 countries, playing a crucial role in phasing out unabated coal, powering off-grid facilities and mini-grid 'energy islands', and in closing the nuclear fuel cycle.

In our low-case scenario, expected growth would effectively stall by the end of the 2030s due to a series of relatively unsuccessful rollouts of advanced SMR technologies. These technologies, in this scenario, would prove to be not competitive enough compared with the best available technology alternatives, including larger (600-1200 MWe) nuclear reactors, innovative CCUS technologies that significantly reduce the costs of carbon capture and disposal, or breakthroughs in energy storage, 'green' hydrogen for industrial and residential heating, and so on. The buildout of SMRs could potentially face further challenges from macroeconomic factors, such as slowing global economic growth and higher interest rates.

Additionally, geopolitical instability and major military conflicts in regions with significant deployment potential could also hold back SMR plans, as well as hypothetical high-impact, very low probability 'black swan' events, which might significantly influence public sentiment towards nuclear energy.

Under this scenario, the global SMR fleet would comprise only 25-30 GWe installations, primarily located in 15-20 countries from groups 1, 2, and 3.

MARKET FRAGMENTATION

REGULATORY FRAGMENTATION

Despite ongoing efforts to harmonise nuclear energy regulations, nuclear safety and security requirements still vary considerably across countries.

This variance necessitates design modifications to adhere to specific national regulations, thereby complicating the licensing process for export-oriented projects. The need for tailored modifications not only extends the overall duration of licensing but also significantly increases costs (up to 30%[52] of engineering, procurement and construction costs in case of conventional nuclear plants)[53], undermines the economies of series deployment, and dilutes the benefits of standardisation, one of the key 'selling points' of SMRs.

Several prominent international nuclear organisations have recently launched special SMR-related initiatives to address this issue. The members of the International Nuclear Regulators' Association (INRA), which brings together nuclear regulators from Canada, France, Germany, Japan, South Korea, Spain, Sweden, the UK, and the USA, have agreed to share regulatory evaluations and resources. The UN's International Atomic Energy Agency (IAEA), as part of its Nuclear Harmonization and Standardization Initiative (NHSI), has launched the Regulatory Track to increase regulatory collaboration with a special focus on SMRs and established a Platform on SMRs, a 'one-stop-shop' for IAEA member states interested in the development and deployment of the SMR technology[54].

SPECIAL INITIATIVES

The OECD's Nuclear Energy Agency (NEA) is facilitating the development of international frameworks and common standards by organising expert workshops on the topic, developing decision-support tools, and conducting targeted research.

Harmonisation, however, is likely to be a complex and time-intensive endeavour and would not remove all the differences. The reluctance of national regulators to compromise their regulatory independence and sovereignty is likely to remain a major obstacle. Indeed, in the INRA statement on SMR collaboration in May 2023, the members noted "the potential challenges and practical hurdles facing timely pursuit of an international pre-licensing process" and stressed that "independent, national regulatory reviews should not be replaced by an international approach[55]."

The level of harmonisation and international cooperation achieved in the civil aviation industry is often suggested as a potential model for the SMR sector. For instance, the Chicago convention on International Civil Aviation, signed in 1944, sets out the principle of mutual recognition of safety certificates by all (now 193) signatory states. Even something remotely resembling such a mechanism would be extremely difficult to replicate for the nuclear industry.

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[52] **OECD/NEA (2020), Unlocking Reductions in the Construction Costs of Nuclear: A Practical Guide for Stakeholders, OECD Publishing, Paris,** https://doi.org/10.1787/33ba86e1-en

[53] **Rohunsingh Sam, Tristano Sainati, Bruce Hanson, Robert Kay, Licensing small modular reactors: A state-of-the-art review of the challenges and barriers, Progress in Nuclear Energy, Volume 164, 2023**, https://doi.org/10.1016/j.pnucene.2023.104859 , https://www.sciencedirect.com/science/article/pii/S0149197023002949

[54] https://www.iaea.org/services/key-programmes/smr-platforms-nhsi#:~:text=The%20NHSI%20is%20a%20complementary,and%20the%20NHSI%20Industry%20Track.

[55] https://world-nuclear-news.org/Articles/Regulators-support-international-collaboration-on

Firstly, unlike aviation, where safety standards are relatively independent and globally uniform, nuclear safety regulations are intricately linked to specific national legislative frameworks concerning environmental and safety standards, which significantly vary from country to country.

The public perception of nuclear risks and the associated lack of trust would make necessary changes in respective national environmental legislations politically challenging. Secondly, nuclear technologies, unlike those in civil aviation, are closely intertwined with the issues of national security and non-proliferation, where the interests and priorities of countries diverge. Finally, SMR designs, and particularly advanced SMR designs, are based on a wide variety of disparate technologies, some still in developmental stages. Historically, national nuclear engineering schools, scientific communities, and consequently regulators, have had varying degrees of familiarity with these technologies. This has been influenced by the availability of utilised materials, specific energy needs, and strategic national priorities. Finding a common ground in this context presents a formidable challenge.

Foreign policy considerations matter too. The absence of key players like Russia and China in the organisations in tackling the issues of harmonisation, such as INRA and NEA OECD is also noteworthy, especially considering the fact that they are the only countries currently operating SMRs and their significant projected share in the SMR market.

It appears more probable that over the next two decades, national regulators will form several closer regulatory alliances of various sizes, sometimes based on bilateral agreements such as the US-Canada nuclear regulatory partnership, featuring some degree of mutual recognition of SMR licensing and SMR factory certification. These alliances are likely to form around the largest potential SMR exporters: the US and Canada, Russia, and China. Additionally, there's the prospect of a European alliance, leveraging EU-based institutional assets like the Western European Nuclear Regulators Association (WENRA) and The European Nuclear Safety Regulators Group (ENSREG).

While such alliances may partially mitigate some aspects of regulatory fragmentation within their groups, cross-group SMR export is expected to remain hindered by the lack of universal harmonisation.

GEOPOLITICAL FRAGMENTATION

THE ROLLOUT OF SMR TECHNOLOGIES IS TAKING PLACE AGAINST THE BACKDROP OF A SEA CHANGE IN GLOBAL GEOPOLITICAL FORTUNES.

Post-Cold War, the global nuclear industry experienced around 20 years of unparalleled globalisation. Amid hopes for a new nuclear renaissance, U.S. and French nuclear vendors formed partnerships with Chinese firms, which financed and hosted the home markets[56]. Similarly, Chinese nuclear companies became integral to the global supply chains of Western vendors. Russia emerged as a key supplier of enriched uranium to the U.S., providing up to 20% of its needs[57], and formed alliances with European firms such as Siemens, GE-Alstom, and Rolls-Royce, complementing Russian nuclear steam supply systems with Western IT solutions, turbine technologies, and other critical plant components. About half of the EU's new nuclear build (planned and under construction) was based on Russian VVER reactor technology, offering prospects of billions of euros in revenues for EU-based supply chain partners. In 2013, Rosatom even inked a memorandum of understanding with the UK government about the prospects of a Russian-designed nuclear power plant in the UK[58].

However, the tide of globalisation appears to have turned. The Russian full-scale invasion of Ukraine in February 2022 triggered a systematic effort by the EU, U.S., and UK to cut all kinds of cooperation with Russia, including in the nuclear sector.

[56] https://spectrum.ieee.org/a-double-first-in-china-for-advanced-nuclear-reactors
[57] https://www.centrusenergy.com/who-we-are/history/megatons-to-megawatts/
[58] https://world-nuclear-news.org/Articles/Companies-join-forces-to-bring-VVER-to-UK
[59] https://www.reuters.com/world/europe/finnish-group-ditches-russian-built-nuclear-plant-plan-2022-05-02/

Concurrently, following a series of trade disputes, suspicions of cyberespionage, and malign geopolitical scheming, China is no longer seen in North America and Europe as a dependable partner but rather as a rival.

OECD governments and nuclear firms alike are actively seeking to minimise their reliance on Russian and Chinese markets, finance, and supplies. Notable examples include Finland's cancellation of Rosatom's VVER-1200 Hanhikivi project[59] and the UK effectively shelving the Chinese Hualong One plan for Bradwell B, despite its prior licensing by UK regulators[60].

A December 2023 announcement by the United States, Canada, France, Japan, and the United Kingdom – the pro-nuclear majority of the Group of Seven (G7) collectively dubbed the 'Sapporo 5' after the G7 meeting in Japan earlier this year – about their effort to break up from Russian nuclear fuel supplies marks a notable instance too. At COP28 in Dubai, the group pledged to commit 'at least $4.2 billion' in government-led and private investment to expand their uranium enrichment capacitie[61]s. This investment aims to increase both the quantity of Separative Work Units (SWUs) per year and the production of High-Assay Low-Enriched Uranium (HALEU) in "like-minded nations", which is currently commercially produced only by Rosatom and critical for the future operation of most advanced SMR designs.

These shifts are set to lead to an increasing fragmentation of the potential SMR market, dividing the potential export geographies into at least two, but more likely three or four zones of "geopolitical gravity."

The first one is expected to bring together OECD countries and 'like-minded nations' (a formula referring to liberal democracies and resembling the Cold War concept of the 'Free World'). Unless a more articulated nuclear alliance between Russia and China is formed in the context of the recent geopolitical shift, or even a broader one as part of the BRICS cooperation formula (which is less likely), we expect the Russian and the Chinese zones to expand separately, overlapping in some parts of the world such as, first of all, Africa, and Latin America. Both Russia and China are likely to capitalise on anti-colonial sentiment in the Global South to bolster their influence in emerging markets.

This division is projected to have a profound impact on the competition landscape and potential market size for specific SMR projects depending on the country of origin. The OECD-based SMR vendors are expected to be predominantly competing against each other and advanced alternative low-carbon energy solutions in the markets of the 'like-minded nations': developed countries and their closest geopolitical allies. In contrast, Russia and China, effectively cut off from the OECD markets, are expected be aggressively scaling up their SMR foothold in middle- and low-income countries, offering more affordable solutions backed by generous financing schemes that reduce the cost of capital and, subsequently, the final cost per kilowatt-hour.

It is also worth noting that unlike many OECD vendors, Rosatom has a back-end fuel-cycle management scheme where used fuel which had been fabricated in Russia for a Russian reactor and from Russian uranium materials could be taken back to Russia for storage and reprocessing[62]. This option effectively frees the SMR importer or host country from the need to handle spent fuel and radioactive waste, which is very attractive for newcomer countries devoid of developed nuclear infrastructure. Additionally, Rosatom is uniquely positioned in the context of SMR deployment as a conglomerate featuring its own mining businesses. Originally focused primarily on natural uranium extraction, Rosatom is now expanding its portfolio of minerals into a broad range of metals critical to energy transition such as lithium, copper, and zinc, as well as mining rare earth metals and gold[63]. Taking on minerals' deposits in emerging markets, Rosatom would be able to deploy and operate Russian SMRs to power their own off-grid operations. Finally, according to the World Nuclear Association, among the countries from groups 4 and 5 in our classification, Russia has the highest number of counterparties of signed intergovernmental agreements on cooperation in the field of 'the peaceful use of atomic energy', three times as many as all other potential SMR exporting countries combined[64], which creates a necessary diplomatic framework for prospective new build projects.

In this new geopolitical context, SMR offers are also likely to be bundled into complex 'cooperation' packages with broader foreign policy, security, and trade agendas. They would include the provision of technologies, resources, and commodities (such as energy commodities, metals and other critical materials, and food), intergovernmental loans and international aid, and even military cooperation, for instance, the supply of ammunition and intelligence sharing.

The renewed global geopolitical divide, reflecting, in particular, the diverging strategic interests of major powers, is set to influence the choices and alliances formed in the SMR sector in almost equally strong way as the global push for energy transition.

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[60] https://neutronbytes.com/2021/07/26/uk-govt-said-ready-to-cut-china-out-of-its-nuclear-plans/
[61] https://www.energy.gov/articles/cop28-us-canada-france-japan-and-uk-announce-plans-mobilize-42-billion-reliable-global
[62] https://fissilematerials.org/library/ipfm-spent-fuel-overview-june-2011.pdf
[63] https://www.ifri.org/sites/default/files/atoms/files/vidal_russiaminingstrategy_2023.pdf
[64] https://world-nuclear.org/information-library/country-profiles/others/emerging-nuclear-energy-countries.aspx

SUPPLY-SIDE ANALYSIS

OVERVIEW

OVER A 70 SMR DESIGNS ARE NOW IN VARIOUS STAGES OF DEVELOPMENT IN AT LEAST 18 COUNTRIES OF THE WORLD, FIRST OF ALL: UNITED STATES, CHINA, RUSSIA, SOUTH KOREA, ARGENTINA, UNITED KINGDOM, FRANCE, CANADA, SWEDEN, JAPAN, INDIA AND SOUTH AFRICA.

Those designs vary dramatically in:

- **Output capacity, size**
- **Technology (coolant/moderator)**
- **Core temperature**
- **Potential applications**
- **Stage of development**
- **Available investment, stage and expected pace of development.**

THE SMR PROJECTS COULD BE GROUPED INTO THREE MAIN CATEGORIES:

1. FIRST-MOVERS

these are designs that are either already operational or in the final stages of development, with feasible prospects for a reference/ demonstration plant becoming operational by or around 2030.

Unlike other designs at a comparable stage, these projects have their First-Of-A-Kind (FOAK) units either under construction or 'firmly planned' at specific sites with advanced licensing stages. Mainly, these are (with just two exceptions: the already operational Chinese Generation IV high-temperature reactor - HTR-PM, and the boiling water reactor BWRX-300 developed by GE-Hitachi) evolutionary Integral Pressurised Water Reactors (IPWRs), essentially PWRs reduced in size and redesigned to integrate key NSSS components into a single pressure vessel. This group includes: VOYGR (NuScale, US), RITM-200 (Rosatom, Russia), ACP100 Linglong One (CNNC, NPIC, China), and CAREM (CNEA, Argentina). Additionally, there is the stand-alone Russian Generation IV project BREST-OD-300, currently under construction and expected to be operational around 2030. This project is designed to recycle spent nuclear fuel from other reactors and burn nuclear waste. However, we do not expect either HTR-PM or BREST-OD-300 to enter the series deployment stage before the 2040s, as they are primarily demonstration projects, and work on more commercialized designs based on their technologies is still underway. The prospects of CAREM securing the necessary backing to move onto the next stage are also unclear. Therefore, we expect that the first wave of series deployment will be dominated by just four first-movers: RITM-200, ACP100 Linglong One, VOYGR, and BWRX-300. Shelf-M is expected to be a first-mover in the segment of microreactors (less than 20 MWe) and would not compete with the rest of the group.

2. LATER 'EVOLUTIONARY'

designs, which at somewhat earlier stages of development, or those paused/R&D significantly cut over the previous years, with some deployment prospects between 2030 and 2035, realistically closer to 2035 and beyond.

The group includes PWR-type projects: UK SMR (Rolls-Royce, UK), NUWARD (EDF, France), SMART (KAERI, South Korea), BANDI-60 (KEPCO, South Korea), SMR-300 (Holtec, US) and AP300 (Westinghouse, US). Although some of the technologies look promising, in particular in the baseload replacement segment of the market, delays with entering the markets and securing an order book sufficient for series manufacturing of the modules reduces their market prospects.

3. INNOVATIVE OR ADVANCED DESIGNS

based on technologies other than water-cooled thermal reactors (including sodium-, gas- and lead-cooled fast reactors, very high- temperature reactors, molten-salt reactors, supercritical water-cooled reactors, very small, sealed reactors or 'nuclear batteries', and nuclear fusion concepts).

Regardless of the current stage of their development, it is highly unlikely that any of those designs would be able to secure a noticeable market share before 2035-2040.

However, some of the designs in this group might later prove very successful and disruptive to the market, offering new advanced ways of co-generation, 'natural' safety features and significant savings on fuel-cycle efficiency.

Among the most notable designs, which have secured sizable public and private financial backing, include two fuel-cycle closing reactors SSR-Wasteburner (Moltex Energy, UK-Canada; Stable Salt Reactor) and Aurora, a fast neutron heatpipe microreactor, designed by OKLO, a start-up backed by Sam Altman (CEO of OpenAI, the developer of ChatGPT). There is also PRISM, a 300 MWe sodium-cooled fast reactor design (GE-Hitachi, US), sharing the same, "waste-to-watts" model, yet after more than ten years since GE-Hitachi started marketing the design it appears to have been shelved with parts of the connect applied to the project of ARC-100 and Natrium (see below). There is a standalone ST40 fusion reactor concept developing by Tokamak Energy (UK), which recently announced a significant progress in this breakthrough area[65]. The process heat application segment is targeted by ARC-100 sodium-cooled reactor (US-Canada), Hermes, a high-temperature salt-cooled reactor developed by Kairos Power (US), and Natrium, a sodium-cooled fast reactor developing by Bill Gates's TerraPower. IMSR (Integral Molten Salt Reactor) by Terrestrial Energy (Canada) is another advanced design based on the molten salt technology. There is also a very high temperature reactor XE-100, developed by X-energy (US) and two 5MW microreactors: gas cooled MMR (Ultra Safe Nuclear, US) and heatpipe fast eVinci (Westinghouse Electric Company, US). There are also two lead-cooled fast reactor designs: SVBR-100 (Rosatom, Russia) and SEALER, developing by Blykalla (previously: LeadCold Nuclear Inc, a spin-off the Royal Institute of Technology (KTH) in Stockholm). Notably, such designs as GE-Hitachi PRISM and SEALER haven't been selected for the UK funding. However, they are being licensed in Canada.

DEPLOYMENT TIMING

MOST OF THE REACTOR VENDORS MENTIONED ABOVE, INCLUDING THOSE DEVELOPING ADVANCED, NEXT GENERATION REACTORS, HAVE ANNOUNCED VERY AMBITIOUS COST TARGETS AND DEPLOYMENT TIMELINES.

For instance, GE-Hitachi claims that BWRX-300 enables save to up to 60% of capital cost per MW "when compared with other typical water-cooled SMR and large nuclear designs in the market"[66] (<$2,250 USD/kWe for nth-of-a-kind) and is "deployable globally as early as 2029[67]."

However, historically, almost all ex-ante cost and timeline targets in engineering innovation, both nuclear and non-nuclear, have tended to underestimate, sometimes dramatically, the required resources, as many practical implementation constraints remain unknown until deployment is attempted. Moreover, some key cost and duration drivers, such as labour market constrains, local supply chain readiness and quality construction materials costs and availability, usually vary significantly from country to country and from location to location. When modelled,[68] It appears that SMRs have construction risk profiles relatively similar to larger reactors, with the likelihood of delays for first-of-a-kind (FOAK) installations being around the median of 30-35% (compared to initial schedules), and as high as 60-120% in some cases.

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[65] https://world-nuclear-news.org/Articles/Tokamak-Energy-achieves-crucial-plasma-temperature

[66] https://aris.iaea.org/PDF/BWRX-300_2020.pdf

[67] https://www.gevernova.com/nuclear/carbon-free-power/bwrx-300-small-modular-reactor

[68] **W. Robb Stewart, Koroush Shirvan, Construction schedule and cost risk for large and small light water reactors, Nuclear Engineering and Design, Volume 407, 2023**

Importantly, the above figures do not include licensing delays, which are likely for almost all projects but are significantly more probable for advanced designs.

Historically, regulators have taken more time to review designs of a new generation or innovative technology compared to more conventional or subsequent designs of the same generation. For instance, in the UK, it took 10 years to license the AP-1000 reactor designed by Westinghouse Electric. The French EPR, the next reactor of the same generation, was reviewed and licensed in 6 years, while the UK modification of the Chinese Hualong One (HPR1000) took only 5 years. Licensing of innovative designs beyond light water reactor (LWR) technologies is likely to take longer and may be associated with more requests for design alterations.

There is also a challenge, which some analysts identify as 'regulators' capability gap[69].' In many developed countries, particularly in Europe, there has been minimal new nuclear construction in recent decades. This lack of activity has led to an erosion of regulatory expertise and capabilities. Moreover, in most countries regulators have been predominantly exposed exclusively to the pressurised water reactor (PWR) designs and may simply lack experts who are adequately familiar with the nuances of other innovative reactor technologies. As the nuclear industry pivots towards advanced reactors, which often incorporate novel technologies and materials, this expertise gap poses a significant challenge which is likely to take many years to properly address.

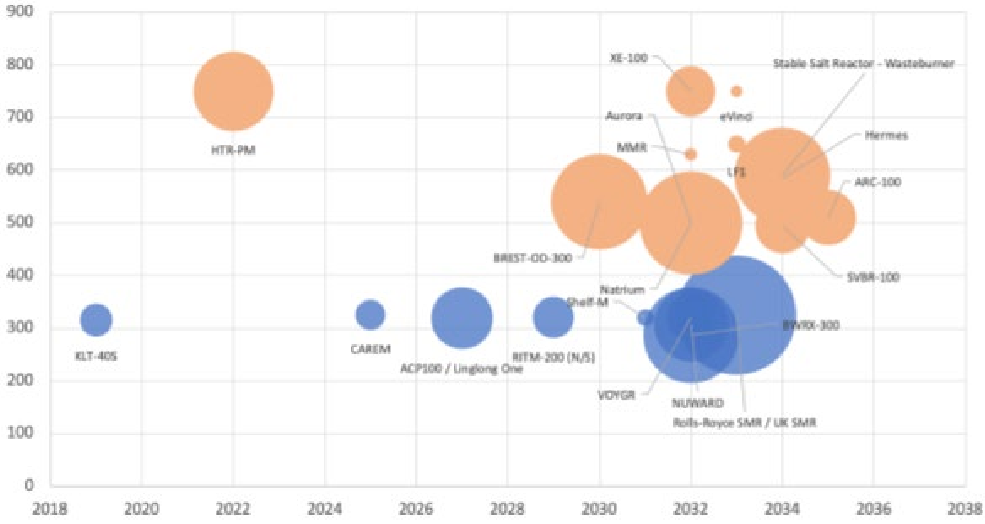
Another issue is the anticipated surge in regulators' workload expected around 2030 and in the early 2030s. As a multitude of advanced reactor designs progress towards the final stages of development and licensing, regulatory bodies are likely to face a significant influx of materials they need to thoroughly review, including design alterations for reactors which have already had been assessed. This could lead to 'reviewing bottlenecks', as regulators struggle to process a large volume of complex documentation often pertained to very niche issues of specific novel technologies. This bottleneck could cause further delays, affecting the overall pace of SMR deployment.

In Figure 6 below, we have plotted the designs with substantial financial backing that are at the relatively latest stages of development, in terms of their most likely (base-case scenario) timing of deployment.

To ensure comparability, the indicated year refers to the start of commercial operation or the first-of-a-kind (FOAK) installation in a planned series (allowing for alterations for specific applications and plant configurations, but with reactors of the same basic technical characteristics and capacity, i.e., the timing of smaller-scale prototypes is not included). The expected years of deployment normally differ from those projected by the developers, factoring in the expected delays explained above. The vertical axis shows the design outlet temperature, which is defining for its suitability for co-generation applications, while the size of the circles represents the reactor capacity. Evolutionary light water reactors are plotted in blue, and advanced reactors are plotted in orange.

Figure 6

First waves of SMRs deployment



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[69] **Rohunsingh et all, 2023:** https://www.sciencedirect.com/science/article/pii/S0149197023002949?via%3Dihub

COMPETITION CLUSTERS

As SMR designs vary in terms of their suitability for different applications and geographies, considering factors such as size, capacity, outlet temperature, the need for water resources in the proximity, and seismic profile,

and given the expected significant market fragmentation, we propose a matrix of competition clusters to assess the potential impact of competition on the viability of specific technologies and projects.

Each cluster is anticipated to have its own potential market size, which we assume, for simplicity, aligns with our base-case scenario projections for 2050. Some designs, due to their versatility, could compete in multiple clusters simultaneously, while others may only compete with similar projects within a single cluster.

MARKET SIZE

TO ACCOUNT FOR GEOGRAPHICAL FRAGMENTATION, WE HAVE, AGAIN FOR SIMPLICITY, DIVIDED ALL POTENTIAL DEPLOYMENT LOCATIONS INTO TWO MAJOR GROUPS.

The first group includes the Sapporo-5, other pro-nuclear OECD countries (excluding Turkey), and non-OECD emerging markets leaning towards closer nuclear cooperation with the US and its allies, such as Ghana, the Philippines, Thailand, and Ukraine. The second group comprises non-OECD pro-nuclear countries that tend to lean geopolitically towards Russia (e.g., Belarus, Central Asian countries, Myanmar, Sri Lanka), China (e.g., Pakistan and some Belt and Road Initiative participants), or both (e.g., Algeria, Ethiopia, Turkey, Iran). In many 'neutral' countries of this group, which remain technically open to hosting OECD designs, China and Russia are expected to use their geopolitical influence to support their vendors' export efforts to a degree difficult for any OECD country to match. Notably, within this group, China and Russia are not only the largest exporters but also expected to have their own substantial shares of the projected global SMR fleet, the markets which are effectively closed to OECD developers.

While full-fledged sanctions against Rosatom and potentially Chinese nuclear firms remain a possibility, especially post-2030 when the Sapporo-5 group is expected to have decoupled their nuclear fuel supply chain from the Russian enrichment capacities, their impact on the SMR export market is unlikely to be material compared to the current restrictions' regime. SMR new build projects are less exposed to sanctions risks as the supply chains for new Russian and Chinese SMR designs are highly unlikely to feature any critical components manufactured in potentially sanction-imposing countries.

Additionally, financing such projects, partly due to the smaller scale of required finance, could be managed bypassing the dollar and euro currency systems.

Table 4

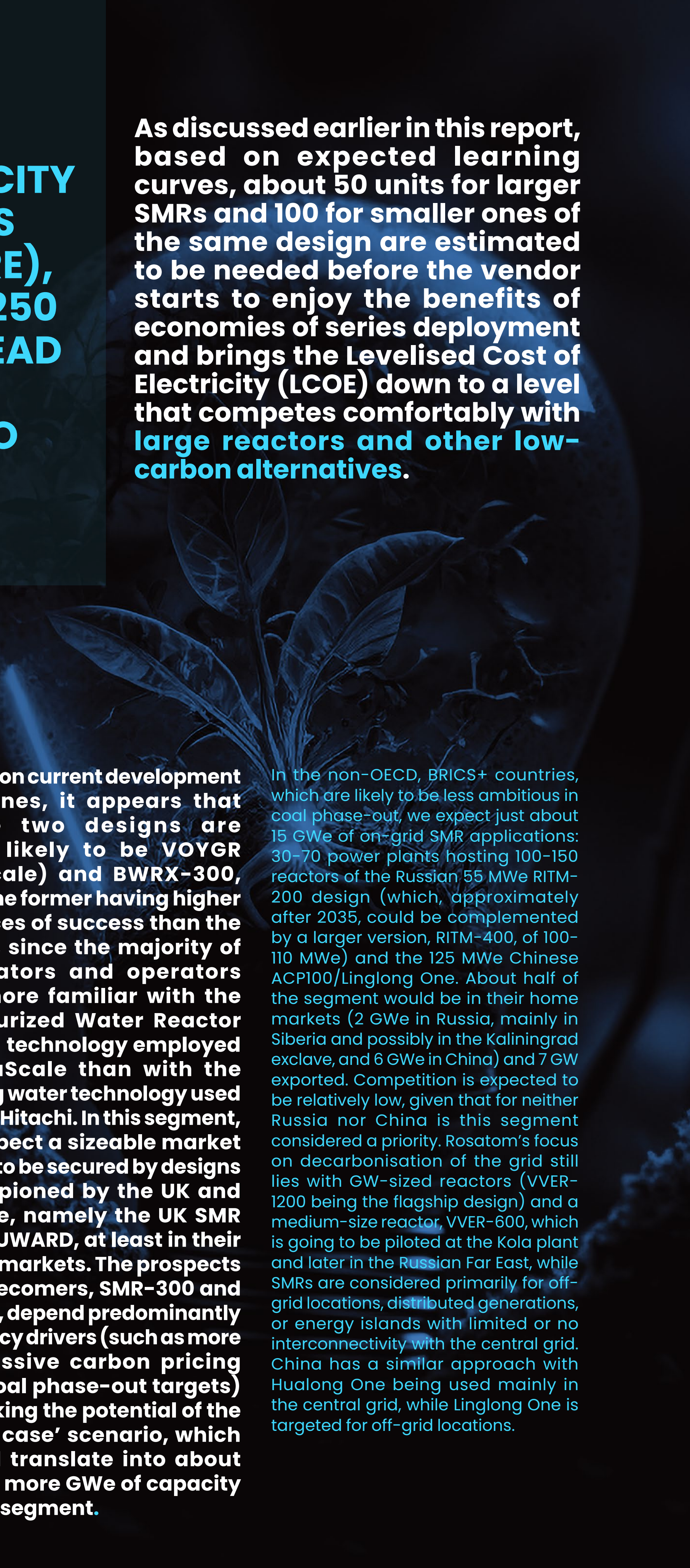
	Sapporo 5 + allies (OECD+)		BRICS + non-OECD Russia's and China's allies	
Applications:		GWe/ [Units]		GWe/ [Units]
On-grid [>200 MWe]	BWRX-300, VOYGR (NuScale), UK SMR, NUWARD, SMART, SMR-300 (Holtec), AP300 (WEC), CAREM	40 [150-250]	RITM-200 (+RITM-400 post 2035) ACP100/ Linglong One	15 [100-150]
Off-grid (larger industrial), distributed grid [>10MWe, <200 MWe]	VOYGR (NuScale), NUWARD, CAREM, SMART	10 [50-150]	RITM-200 ACP100/ Linglong One	40 [400-500]
Off-grid (smaller industrial), mini-grids (remote communities), [<10MWe]	MMR eVinci BWXT(1-5MWe)	2 [450-500]	Shelf-M (Rosatom) Mobile MMR-1MWe (Rosatom)	3 [250-350]
Floating/underwater	NuScale-Prodigy VOYGR(m) BANDI-60	5 [50-150]	RITM-200 (+RITM-400 post 2035) ACPR50S Shelf-M (Rosatom)	10 [150-250]
Advanced co-generation - process heat [>10 MWe]	ARC-100, Hermes, SEALER-55, Natrium, XE-100, Aurora (15 and 15MWe Powerhouses), Terrestrial Energy's IMSR	17 [100- 200]	BREST-OD-300 SVBR-100 HTR-PM	6 [30-40]
Advanced co-generation - process heat [<10 MWe]	Aurora, MMR, eVinci BWXT(1-5MWe) Xe-Mobile	2 [450-600]	LF1 (China) SVBR-10 Mobile MMR-1MWe (Rosatom)	1 [50-150]
Closing fuel cycle/ 'waste-to-energy'	Stable Salt Reactor – Wasteburner, PRISM (GE-Hitachi) Aurora (OKLO)	4	BREST-300	1 [1-4]
Transport	BWXT-DRACO	<1	RITM-200 (+RITM-400 post 2035)	3 [30-50]
Off-grid (larger industrial), distributed grid [>10MWe, <200 MWe]	BWXT(1-5MWe), Xe-Mobile, Mitsubishi's MHI mobile microreactor	<1	Mobile MMR-1MWe (Rosatom)	1
Total		»80		»80

ON-GRID APPLICATIONS WITH BASIC OPTIONAL CO-GENERATION

As shown in Table 4 (above), despite a significant potential market size (40 GWe, or about 10% of the world's total installed nuclear capacity in operation in 2023), the segment of on-grid applications (coal replacement, basic co-generation: district heating/seawater desalination) in OECD+ countries appears to be one of the most contested, with at least 8 evolutionary designs vying for space.

DUE TO THE LARGER AVERAGE UNIT CAPACITY (HALF OF THE DESIGNS ARE 300MWE OR MORE), NO MORE THAN 200-250 REACTOR UNITS, SPREAD OVER ABOUT 60-100 SITES, WOULD FIT INTO THIS SEGMENT.

As discussed earlier in this report, based on expected learning curves, about 50 units for larger SMRs and 100 for smaller ones of the same design are estimated to be needed before the vendor starts to enjoy the benefits of economies of series deployment and brings the Levelised Cost of Electricity (LCOE) down to a level that competes comfortably with large reactors and other low-carbon alternatives.



This suggests that the most likely market structure for this segment is an oligopoly, with two first-movers controlling about half of the market.

Based on current development timelines, it appears that these two designs are most likely to be VOYGR (NuScale) and BWRX-300, with the former having higher chances of success than the latter, since the majority of regulators and operators are more familiar with the Pressurized Water Reactor (PWR) technology employed by NuScale than with the boiling water technology used by GE-Hitachi. In this segment, we expect a sizeable market share to be secured by designs championed by the UK and France, namely the UK SMR and NUWARD, at least in their home markets. The prospects for latecomers, SMR-300 and AP300, depend predominantly on policy drivers (such as more aggressive carbon pricing and coal phase-out targets) unlocking the potential of the 'high-case' scenario, which would translate into about 30-40 more GWe of capacity in this segment.

In the non-OECD, BRICS+ countries, which are likely to be less ambitious in coal phase-out, we expect just about 15 GWe of on-grid SMR applications: 30-70 power plants hosting 100-150 reactors of the Russian 55 MWe RITM-200 design (which, approximately after 2035, could be complemented by a larger version, RITM-400, of 100-110 MWe) and the 125 MWe Chinese ACP100/Linglong One. About half of the segment would be in their home markets (2 GWe in Russia, mainly in Siberia and possibly in the Kaliningrad exclave, and 6 GWe in China) and 7 GW exported. Competition is expected to be relatively low, given that for neither Russia nor China is this segment considered a priority. Rosatom's focus on decarbonisation of the grid still lies with GW-sized reactors (VVER-1200 being the flagship design) and a medium-size reactor, VVER-600, which is going to be piloted at the Kola plant and later in the Russian Far East, while SMRs are considered primarily for off-grid locations, distributed generations, or energy islands with limited or no interconnectivity with the central grid. China has a similar approach with Hualong One being used mainly in the central grid, while Linglong One is targeted for off-grid locations.

OFF-GRID APPLICATIONS

For off-grid industrial applications (with optional basic co-generation, no process heat), distributed and mini-grid solutions for remote communities, islands, etc., we divide the segment into six clusters, three in each of the geopolitical groups:

larger industrial applications and energy islands (from 10 MWe to 200 MWe demand), such as mining sites for larger mineral deposits, smaller industrial applications and mini/microgrids (up to 10 MWe), and floating/underwater power plants for coastal locations.

In the larger off-grid applications segment in the OECD+ markets, just four designs are competing for the demand of 10 GWe (50-150 reactors), with only one full-fledged first-mover, VOYGR (NuScale), the Argentinian CAREM, which is unlikely to secure significant export finance backing, and two later designs: the South Korean SMART and French NUWARD. The level of competition is expected to be moderate, with VOYGR (NuScale) securing up to half of the market, followed by SMART (deployed predominantly in the Middle East), NUWARD (French overseas territories and some exports) and Aurora's larger powerhouses (15 MWe and 50 MWe, see the subsection "Closing fuel cycle" below).

In contrast, in the non-OECD, BRICS+ part of the world, we expect this kind of applications to be one of the largest, envisaging about 40 GWe of capacity additions contested by only two vendors:

40 GWE

For remote industrial sites and mini-grids with a size of 10 MWe and less (2 GWe of expected additions in the OECD+ part, and 3 GWe in the non-OECD Russia/China zone), competition is expected to be moderate. MMR (Ultra Safe Nuclear, US) and eVinci (Westinghouse Electric Company) would be relative first-movers in the OECD segment (realistically, closer to the mid-2030s), followed later by BWXT's (US) high-temperature gas-cooled microreactor BANR – Terrestrial Micro RX (1-5 MWe)[70] in stationary and mobile versions and X-Energy's Xe-Mobile 2-7 MWe microreactor[71].

In the non-OECD part, Rosatom is expected to have a monopoly with two designs: the 10 MWe Shelf-M, which is expected to be first deployed in Siberia in the early 2030s[72], and a mobile gas-cooled microreactor (1 MWe), unlikely to be ready for commercial deployment earlier than the late 2030s.

Finally, in the floating and underwater segment with 15 GWe globally (5 GWe in OECD+ and 10 GWe in non-OECD Russia-China+), there will be four main designs competing for up to 400 reactor units globally, spread over 50-150 sites. RITM-200S (also RITM-400S post-2035) would be the first movers, followed by the Chinese ACP100S and/or ACPR50S designed for floating power plants and the Russian Shelf-M. In the OECD part, we expect the South Korean BANDI-60 and NuScale's adaptation of its VOYGR design for barge-mounted installations (a project being developed in conjunction with Prodigy Clean Energy) to be the main market participants, benefiting from the low saturation of the segment.

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[70] https://www.bwxt.com/what-we-do/advanced-technologies/terrestrial-micro-rx

[71] https://x-energy.com/reactors/xe-mobile

[72] https://www.world-nuclear-news.org/Articles/Shelf-M-project-being-developed-for-Sovinoye-gold

ADVANCED CO-GENERATION

We expect a relatively high level of competition in the higher-capacity (>10 MWe) segment, 15-20 GWe in OECD+, contested by ARC-100, Hermes, SEALER-55, Natrium, Terrestrial Energy's IMSR, OKLO Aurora's powerhouses (15 MWe and 50 MWe)[73] and XE-100.

X-Energy's XE-100 is set to be among the first movers, benefiting from competitive advantages such as a higher outlet temperature (750°C compared to the average of 500°C), enabling versatile process heat applications, and its own fuel cycle supply capacities based on the proprietary innovative TRISO technology supported by the US Government. We estimate the firm to deploy about 100 reactors by 2050, achieving significant economies of scale and taking over more than half of the estimated size of the market segment.

Natrium, a 345 MWe molten salt TerraPower's project backed by Bill Gates, is expected to become the second-largest incumbent in this segment, with 2-3 GWe of installed capacity (about 7-8 commissioned commercial reactors) by 2050.

Although the first Natrium installation in Kemmerer, Wyoming (US) is announced to become operational by 2030, given the complexity of its molten salt technology (unlike XE-100's gas-cooled high temperature technology, with 3 reactors currently operating in Japan and China, no molten salt reactors have been built since 1969, when the Molten Salt Reactor Experiment was shut down after just three months of operation), the licensing process is likely to face delays. Combined with first-of-a-kind construction risks and fuel-cycle uncertainties, it is likely that the project will be at least 2-3 years behind schedule, with the Wyoming site beginning to generate electricity in 2032-2033.

Since the reactor incorporates features of a heat storage facility and a process heat generating plant, it is expected to benefit from enhanced manoeuvrability and higher electricity prices during peak times. However, the economics of the project may still prove challenging. Its pilot plant in Wyoming is estimated to cost US$4 billion for a single unit 345 MWe plant (or about US$11,600 per kWe), approximately 55% higher than the pilot XE-100 project, estimated at US$2.4 billion for a four-unit 320 MWe plant (or about US$7,500 per kWe). Both figures are ex ante estimates, with no allowance for unexpected delays and cost overruns. While TerraPower insists it will achieve a 75% cost reduction at the series deployment stage with an overnight construction cost between $2,800/KW and $3,000/KW, applying historically relevant learning rates does not support this projection.

Terrestrial Energy's Integral Molten Salt Reactor (IMSR) has a high potential to be used in replacing smaller coal power plans. Utilising the molten salt technology as well, it's almost half the size of Natrium (400 MWth and 195 MWe of electricity) and also has heat storage capacity, which makes it possible to operate in load following co-generation mode. IMSR operates at higher temperatures (up to 700°C) which makes it particularly suitable as a source of process heat to a broader range of industrial applications. IMSR has been selected for the REPOWER program, an international initiative launched in 2021 by TerraPraxis, a non-for-profit organisation, in partnership with Microsoft, the MIT, Bryden Wood, Schneider Electric and others, to support conversion of existing coal-fired power plants into SMR and geothermal sites[74].

The IMSR has passed stage 2 of the pre-licensing licensing review in Canada. The US Department of Energy (DOE) awarded Terrestrial Energy a grant to support the licensing of the IMSR in the United States. Importantly, unlike Natrium, which relies on HALEU, IMSR is the only advanced reactor which is designed to use standard assay low enrichment uranium (LEU). This significantly reduces the risks of delays associated with HALEU availability and security of supply. In base-case scenario, we expect the design to pass the first-of-a-kind stage around 2033 and secure over 2GWe of capacity by 2050 with about 10-12 units in Canada, the United States and UK.

We expect all other designs in this segment combined to secure no more than 2-3 GWe of installed capacity by 2050, with just 15-25 units in operation. Much like with the competition in the on-grid basic co-generation segment, their upside potential significantly improves in the high-case scenario with more aggressive climate policies and broader state support in the OECD markets.

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[73] **for detailed description see the section "Closing fuel cycle" below.**

[74] https://world-nuclear-news.org/Articles/Terrestrial-joins-TerraPraxis-coal-to-nuclear-init

30-40 POWER UNITS

In the non-OECD cluster, we expect nomore than 30-40 power units with a total installed capacity of 6 GWe to be completed by 2050. Non-OECD countries are more likely to delay complete decarbonisation of their heavy industries, and the advanced reactor designs currently under development are not expected to play the same role in supplying process heat to industrial sites as in the OECD part of the world.

The outlet temperature range of the economically feasible and potentially deployable projects would still fall short of the needs of a broad range of energy users (in sectors such as steelmaking, glass, and cement manufacturing, etc.), so, with advanced co-generation still an economically viable option, the main economic rationale behind the deployment of advanced reactors would be increasing energy efficiency, reducing the volume of spent fuel and waste, and enabling energy supplies to regions with limited water resources. As both the Russian RITM-200 and Chinese Linglong One are PWRs, they rely on water availability for cooling, limiting their potential deployment in areas with a very dry climate and scarce water resources. In contrast, designs like the Russian BREST-OD-300 (currently under construction), SVBR-100, and the Chinese HTR-PM (operational since 2022) do not need water and could be potentially deployed even in the middle of a desert, as they use lead, a lead-bismuth eutectic (LBE) alloy, and helium, respectively, as their coolants.

In the mini-grids and smaller applications (<10 MWe) subsegment, competition is expected to be moderate. In the OECD+ cluster, the main competitors are expected to be OKLO's Aurora, MMR (Ultra Safe Nuclear), eVinci (Westinghouse), BWXT's microreactor (1-5MWe), and Xe-Mobile (X-energy). Apart from Aurora, a closing-fuel-cycle type of reactor, other microreactors, according to the Nuclear Energy Institute's (NEI) analysis, are expected to have First-Of-A-Kind (FOAK) stationary low-capacity installations with overnight capital costs in the range of US$10,000-20,000 per kWe, translating into an LCOE range of $140 to $410/MWh, which, along with the learning curve, would go down to $90-$330/MWh after the 50th unit in series deployment. The NEI study didn't consider mobile applications, which are likely to be more expensive.

For instance, BWXT's mobile microreactor, funded by the US Ministry of Defense as part of Project Pele, is being developed for $300 million. It hasn't been disclosed how much of the funding is allocated to R&D and design and how much directly to manufacturing and installation. Assuming half of the amount is spent on manufacturing for a 5 MWe capacity, the FOAC capital cost for such mobile applications would be in the region of US$30,000/kWe and higher for lower capacity mobile applications.

We expect the frontrunners of the competition in this segment to include the US Department of Defence-supported BWXT's Microreactor design, selected for demonstration in June 2022 and expected to be completed as early as 2024, X-energy's XE-mobile, selected for engineering design in September 2023, and Oklo's Aurora, tentatively chosen for Eielson Air Force Base in Alaska in September 2023.

With up to 600 units to be deployed by 2050, this market size will be sufficient to accommodate scaling up of all three designs with significant upside potential.

The non-OECD designs include Rosatom's SVBR-10 (a micro, 10 MWe version of SVBR-100, described above), LF1, also 10 MWe, a thorium-based molten salt reactor design expected to be deployed in the mid-2030s, and Rosatom's mobile microreactor, expected to be based on Russian space and defence microreactor technologies.

We don't expect these designs to be deployed at a significant scale. Up to 2050, due to higher costs compared with bigger alternatives, they would remain niche products with up to 150 reactors of all three designs deployed by 2050 (1 GWe).

CLOSING FUEL CYCLE

WE EXPECT THIS SEGMENT TO REACH THE TOTAL OF 5 GWE OF INSTALLED CAPACITY, ENCOMPASSING 3-4 GWE IN THE OECD+ SEGMENT AND 1 GWE IN RUSSIA AND CHINA. THERE IS LIMITED COMPETITION.

We also expect that, unlike in other competition clusters, the Canadian “waste-to-energy” design SSR-Wasteburner, if the pilot installations are successful, has a potential of broader deployment across countries other than OECD+, which have used or still using heavy water reactors.

The design, along with its smaller competitor, OKLO’s Aurora, stands out for its use of a special kind of recycled spent nuclear fuel, which enables on-site reprocessing of fuel through pyroprocessing.

Pyroprocessing is a method for reprocessing spent nuclear fuel that differs from conventional aqueous methods.

It involves the electrochemical treatment of spent fuel in a molten salt medium, enabling the separation of useful fissile materials from waste products, while, as was noted earlier in this report, avoiding plutonium separation. This alternative to PUREX and other conventional reprocessing technologies is particularly beneficial for recycling spent fuel from heavy water reactors with lower content of uranium, which made it practically uneconomic to recycle.

Initially, GE-Hitachi proposed the technology for its PRISM concept, intended to be the first ‘waste-burner’ project in the category of advanced reactors. However, the vendors have not managed to secure customers and funding for a demonstration unit, and the project appears to have been shelved. According to the GE-Hitachi website, “the PRISM reactor concept is currently being put into practice in two reactors: the Natrium reactor in Wyoming and the ARC-100 in Canada.”SSR-Wasteburner’s developer, Moltex Energy, claims that its technology offers a significant reduction in overnight construction costs compared with light and heavy water reactors, thanks mainly to the absence of pressurised reactor components and expensive safety features arising from the use of water as a coolant and moderator.

In 2016, it estimated that in a multi-unit installation, the cost per kWe of installed capacity would be between US$2,000 (in North America) and $2,900 (in the UK) – between US$2,500 and $3,700 in $2023. However, it should be noted that this estimate is based on a conceptual, not a final detailed design approved by a regulator. We expect the capital cost to rise significantly, at least to parity with non-OECD evolutionary designs, yet the “waste-to-watts” business model would still make it an appealing option for sites with heavy-water reactors and CANDU-type legacy spent fuel. We estimate that the design is relatively unlikely to be licensed before the early 2030s, with the pilot installation in New Brunswick (Canada) coming online closer to 2035. In the following 15 years, we expect 6-10 units to come online in Canada, Romania, India, and other PHWR operating countries.

OKLO’s Aurora, which is said to also use pyroprocessing to recycle spent fuel from other reactors, targets a number of use cases with a product line including a 1.5MWe single microreactor installation (the first demonstration unit) and two options of “powerhouses”: 15 MWe and 50 MWe. In its 2023 investor presentation, OKLO says that it targets an LCOE of US$40 to $90 per MWh. The 1.5 MWe FOAK microinstallation is estimated to cost $10 million to build ($6,667 per kWe), while a 15 MWe powerhouse FOAK would cost US$34 million without fuel cost and US$69 million including the initial fuel load ($4,600 per kWe). For a NOAK 50 MWe powerhouse, overnight installation costs are expected to go down to as low as $2,320 per kWe, including the initial fuel load.

With a target electricity price of US$90-$105, the company expects its powerhouses to achieve a full payback in 4-8 years.

Notably, unlike many other nuclear vendors, OKLO is betting on a business model similar to that pioneered by Russia's Rosatom for some of its export projects. Instead of delivering reactors under EPC contracts or licensing the design out (like NuScale does), OKLO plans to use a "turn-key", "build-own-operate", reactor-as-a-service model. Its customers, which are said to be data centres, military units and installations, factories, etc., are not expected to buy or operate reactors; they would be paying for stable, low-carbon energy supply at a fixed competitive price.

Although OKLO plans to start building Aurora reactors and powerhouses from 2027, immediately after completing its microreactor demonstration unit, the transition from a microreactor to 15-50 MWe powerhouses is likely to be more complex than anticipated, taking into account potential regulatory risks and so on. We expect that the scaling stage of the project will be achieved later, closer to the mid-2030s, with costs, both capital and operating, being significantly higher than initial estimates. Nevertheless, by 2050, OKLO plausibly could operate 40-60 (1 GWe) Aurora powerhouses running on recycled spent fuel.

The approaches to closing the nuclear fuel cycle vary significantly between Russia (also France and China) on one hand, and the US and Canada on the other.

The "waste-to-energy" SMR designs in the US and Canada, such as the SSR-Wasteburner and Aurora, suggest a move towards more decentralized, on-site reprocessing solutions (possibly due to a combination of limited resources and lack of political consensus to enforce expensive MOX recycling schemes), aligning with the smaller scale and flexibility of SMR deployments. In contrast, Russia follows a strategy of centralized reprocessing, focusing on the development of new generation reactors, both thermal and fast, compatible with MOX and REMIX fuels produced at large facilities.

BREST-OD-300 is not a "wasteburner" in the way SSR is. Although its mixed uranium-plutonium nitride fuel contains actinides from spent LWR fuel, its principal added value is not in recycling them: being a fast "breeder" reactor, it generates as much plutonium isotopes as it burns as a source of energy, with the only "consumable" part being uranium-238 – which could be replenished from depleted uranium without a need for enrichment.

Since manufacturing mixed fuel is synergistically interlinked with that of MOX and REMIX, logistically clustering fast breeders together with centralized spent fuel reprocessing facilities makes more economic sense than decentralisation. Although the success of BREST-OD-300 and Rosatom's Proryv ("Breakthrough") project would have a ground-breaking effect for closing the nuclear fuel cycle, it would not automatically mean series deployment of the BREST design. Given the logic of centralization, it is more likely that the technology would migrate to a higher capacity segment of 600 MWe or more.

TRANSPORT AND OTHER

We do not expect all other applications (including nuclear propulsion in maritime transport and in space, mobile emergency energy supply – disaster relief applications, military, government and so on) to exceed 4-5 GWe in 2050.

The vast majority of nuclear marine propulsion operating capacity would come from the newly built Russian icebreakers and potentially SMR-powered cargo vessels. They are likely to use RITM-200 (and later RITM-400) designs. There will be also some space propulsion projects, in the US, Russia and possibly China. The US part could be illustrated by the DRACO—the Demonstration Rocket for Agile Cislunar Operations - program for which BWXT was selected to manufacture the custom space-bound reactor in July 2023.

Mobile microreactors for disaster relief, government and defence use will be represented by BWXT(1-5MWe), Xe-Mobile, Mitsubishi's MHI mobile microreactor and Rosatom's mobile microreactor in a highly fragmented market.

MARKET PROJECTIONS AND PROJECTS' VIABILITY

Our analysis suggests that the viability of Small Modular Reactor (SMR) projects hinges more on economic and business considerations (such as the cost of capital, access to market segments and the degree of competition) than purely technological efficiency factors.

The following key parameters are instrumental in determining the success and scalability of SMR ventures:

Time to First-Of-A-Kind (FOAK) Unit

The timeframe for getting the first unit operational is crucial. An earlier start provides a significant advantage in terms of scaling up the technology and capturing a sufficient market share. This early market entry is essential for achieving economies of series deployment and benefiting from the learning curve, which in turn can lead to cost reductions and technological refinements.

Supply Chain Control

Success in the SMR sector is closely linked to the extent of control a company has over its supply chain, encompassing both reactor manufacturing and the fuel cycle. Firms that have a greater degree of control over these aspects are more likely to navigate market uncertainties and maintain consistent quality and cost efficiency.

Availability of Capital, in particular

- Low cost of capital (it directly impacts the Levelised Cost of Electricity (LCOE) and the pricing of cogeneration products and services. A lower discount rate makes the project more financially attractive and competitive).

- Access to capital (it is also vital for scaling up the project beyond the demonstration phase, especially in the face of demand uncertainties and fluctuating costs. Adequate funding ensures that projects can swiftly transition from initial demonstration to wider commercial deployment).

Domestic Market Support and Export Assistance

Domestic Market Support and Export Assistance: Government incentives such as feed-in tariffs (FIT), matching private investment, power purchase agreements (PPA), and contracts for difference (CfD) can provide critical support in the home market. Additionally, government-backed export support can secure a stable demand pipeline during the crucial phase of scaling up.

Market Size and Competition

The potential market size, considering the target segments and geographical market fragmentation, is a key factor. Moreover, the level of competition within these markets significantly influences the prospects of any SMR project.

"Turn-Key" Operations and Innovative Business Models

The availability of "plant-as-a-service" or BOO (build-own-operate) models, where vendors offer comprehensive life-cycle management of the plant, can be a game-changer. This approach, which includes fresh fuel supply and spent fuel management in exchange for long-term energy supply contracts, can greatly enhance the attractiveness of SMR projects. Additionally, when SMR vendors are part of or backed by larger conglomerates involved in energy-intensive industries, innovative arrangements such as "product sharing" or "energy-for-equity" deals can emerge. In such cases, electricity supply from an SMR-based plant is compensated with an interest in the project, which can be particularly appealing in sectors like mining.

BASED ON THE ABOVE PARAMETERS, WE HAVE IDENTIFIED 25 MOST VIABLE (AT PRESENT) PROJECTS AND DIVIDED THEM INTO FIVE GROUPS IN TERMS OF THEIR POTENTIAL MARKET POWER AND VIABILITY:

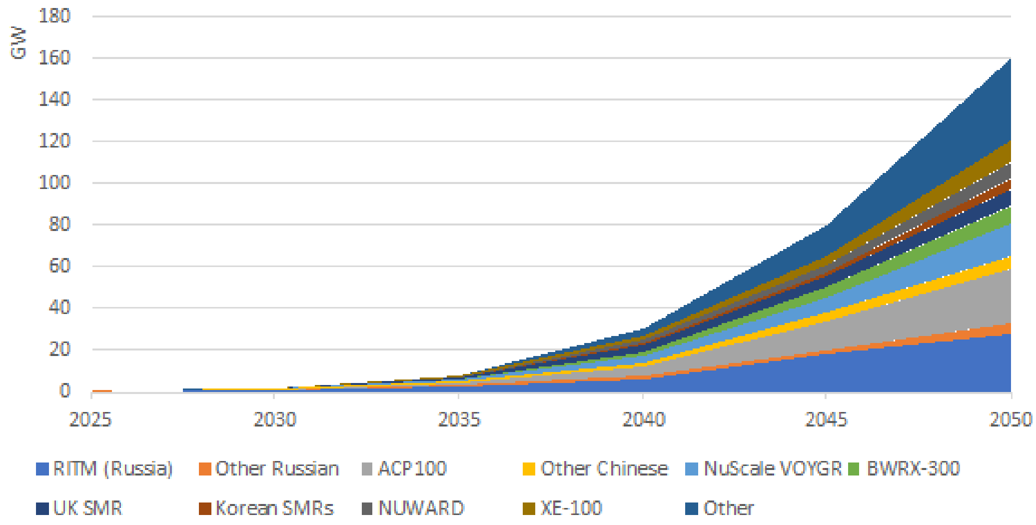
Table 5

First-movers and front-runners, the biggest expected market share in 2050	RITM-200, ACP-100/Linglong One, NuScale VOYGR, BWRX-300, XE-100
High viability, strong backing 'latecomers'	Natrium, NUWARD, UK-SMR, SVBR-100
Niche projects	SVBR-10, BANDI-60, Shelf-M, BWXT Micro, Xe-Mobile, HTR-PM, MMR
High risk potential disrupters	Aurora, SSR-Wasteburner, TE IMSR
Other viable with significant projected market share	SMART, ARC-100, Hermes, ACPR50S, eVinci, LF1

The most likely deployment dynamics under the base-case scenario is illustrated in the chart below (Figure 7).

Figure 7

Projected global SMR fleet by reactor designs



RITM-200N

Rosatom's RITM series, including RITM-200 for transport, RITM-200S for floating, RITM-200N for onshore plants (and possibly RITM-400 in the future[75]) is expected to capture about 17-18% of the global fleet's capacity by 2050.

As of 2023, Rosatom has already manufactured eight RITM reactors for icebreakers, with six more being manufactured for a floating plant (powering Baimskaya mine) and an onshore plant in Yakutia, Russia[76]. The target electricity price is US$70-80 per MWh[77], competitive for remote off-grid locations in the Arctic and Siberia. By 2030, Rosatom is expected to have 16 operational RITM reactors with about 900 MWe of capacity (about half of the world's total). Leveraging its first-mover advantage, the RITM-200 is the first design expected to reach series manufacturing, reducing costs through the learning curve and bringing the target price down to about US$50-60 by the mid-2030s. This effectively means price parity with unsubsidised coal power generation and existing large nuclear plants. Rosatom is also set to benefit from a virtually "closed" supply chain for its SMR, critical for rapid scaling in the face of supply chain imbalances.

The Chinese ACP100/Linglong One, including ACP100S designed for floating nuclear power plants, is expected to follow closely, capturing 15-16% of the global fleet. The Linglong One is set to be the first onshore SMR in commercial operation from 2026-2027. Benefiting from lower cost manufacturing capabilities, this design is expected to be deployed widely in China and among its closest trade partners and allies within the Belt and Road initiative. Additionally, China is likely to promote the deployment of its SMRs by Chinese mining companies operating in Africa.

Russian and Chinese designs, including smaller, micro, and advanced SMRs, would collectively account for about 40% of the global fleet.

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[75] https://www.nucnet.org/news/rosatom-signs-agreement-to-explore-small-reactors-for-industrial-region-in-siberia-11-2-2023

[76] https://www.vedomosti.ru/business/articles/2023/08/27/992087-rosatom-vibral-ploschadki-dlya-pyati-malih-aes
See also: https://ria.ru/20231113/energokompleksy-1909037802.html

[77] https://www.kommersant.ru/doc/5681632

NuScale's VOYGR (US), despite recent setbacks, is projected to secure around a tenth of the global installed capacity by 2050 (including it's floating power plants modification of VOYGR). NuScale is likely to be the first in the OECD+ to build a commercially operating plant, expanding rapidly into Eastern and Central Europe, aided by European nuclear regulators' familiarity with PWR technology and localisation options. The company has a mature manufacturing ecosystem and has formed a partnership with ENTRA1 as a developer, offering flexible deployment models, including Build-Own-Operate schemes[78].

The XE-100 (US) reactor by X-Energy, with its high-temperature gas-cooled technology, stands poised to capture a significant market share in the global SMR landscape, potentially reaching 7% by 2050. X-Energy's agreement with Energy Northwest to bring multiple XE-100 units to Washington state, with the first module expected online by 2030, envisages up to 12 reactors (960 MWe). Although deployment deadlines may be pushed back, significant support from the U.S. Government positions the XE-100 as one of the first advanced reactors to be fully licensed.

Three evolutionary light water reactor (LWR) designs are projected to each secure about 5% of the market: GE-Hitachi's BWRX-300, NUWARD (France), and UK-SMR (Rolls-Royce-led consortium).

GE-Hitachi's BWRX-300, selected by Ontario Power Generation, is advancing towards a construction permit for a pilot plant at the Darlington nuclear station site. If successful, this would represent the first commercial SMR contract in the US. The vendor and operator plan for the first unit to be operational by early 2029. One strategic advantage of the BWRX-300 is its limited exposure to fuel risks, as the design uses standard BWR fuel assemblies. However, licensing BWR technology in countries without previous BWR experience may be time-consuming, as BWRs have a different operational and safety profile compared to more common PWRs. Operators accustomed to PWRs may find transitioning to BWR technology challenging, requiring changes in operational protocols, safety procedures, maintenance practices, retraining, and infrastructure adjustments. Additionally, due to its size, the BWRX-300 competes in a highly crowded SMR market segment, limiting its expansion potential.

Two projects, the UK-SMR developed by a Rolls-Royce-led consortium and NUWARD developed by EDF via its subsidiary, are PWR-type reactors supported by the UK and French governments, respectively.

SIGNIFICANT DELAYS ARE EXPECTED FOR BOTH PROJECTS, WITH SCALING STAGES ANTICIPATED CLOSER TO THE MID-2030S.

The Rolls-Royce SMR consortium aims for 7.5 GWe capacity in the UK (16 units of 470 MWe capacity). The first unit is planned to be completed in the early 2030s, with up to 10 reactors planned by 2035. The UK government committed £210 million (US$260 million) in 2021, with Rolls Royce and shareholders in the SMR business investing around £280 million. The target cost is £1.8 billion (US$2.25 billion) for nth-of-a-kind (approximately $4,800 per kWe), translating to an LCOE of £40-60/MWh (approximately US$50-75)[79]. The design is expected to receive a generic license from the UK regulator in 2026, with the pilot unit initially planned to be commissioned in 2030[80]. However, the first-of-a-kind UK-SMR unit is likely to be deployed in 2032-2033, making it a relative latecomer among evolutionary PWR designs in a competitive segment. Future UK governments are likely to support the project more aggressively, enabling it to secure a significant portion of the UK market and result in about 8 GW of installed capacity by 2050.

Currently in the basic design phase, NUWARD aims to commence construction of its inaugural unit in France by 2030. The typical NUWARD station would consist of two reactors, each with a capacity of 170 MW, resulting in a total electricity generation capacity of 340 MW, and designed to be partially underground. The commercialisation phase is scheduled to begin in 2025, with detailed design and permit applications set for 2026. We expect the project to face delays with the first pilot installation coming online about the same time later than UK-SMR, close to 2035. However, as the project is benefiting from full support of the French government, which has already committed €500 million (approximately US$550 million) to its development at the early stages, we expect that EDF would be able to build 20-25 NUWARD-based power plants in France, including overseas departments, and for export, resulting in 5% of the global SMR fleet in 2050[81].

US$550 MILLION

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[78] https://www.nuscalepower.com/-/media/nuscale/pdf/investors/2023/investor-presentation.pdf

[79] https://world-nuclear-news.org/Articles/Rolls-Royce-on-track-for-2030-delivery-of-UK-SMR

[80] https://world-nuclear-news.org/Articles/UK-assessment-of-Rolls-Royce-SMR-design-progresses

[81] https://www.edf.fr/en/the-edf-group/producing-a-climate-friendly-energy/nuclear-energy/shaping-the-future-of-nuclear/the-nuwardtm-smr-solution/development-roadmap#:~:text=February%202022,to%20export%20its%20SMR%20model.

CONCLUSIONS AND RECOMMENDATIONS

THE DEPLOYMENT OF SMALL MODULAR REACTORS (SMRS) IS UNFOLDING IN A HIGHLY COMPETITIVE ENVIRONMENT,

marked by both internal competition among various SMR designs and external pressure from alternative low-carbon energy solutions, as well as cost reduction efforts in the segment of large reactors.

The market size for SMR applications of specific categories, therefore, is not unlimited. For successful projects, rapid scaling is essential to capitalise on the economies of modularisation and series deployment, reducing costs as market niches in a fragmented landscape are quickly occupied by first movers. Some next-generation, innovative SMR designs, upon completing the demonstration unit phase, might need to adapt by changing the concept or capacity as the initially planned market niche had already been taken.

Economic factors like low-cost capital availability, subsidised demand, and licensing duration are critical, often outweighing the impact of technology innovations. With deployment timelines being crucial for the SMR market's potential, designs don't necessarily have to be the most innovative, but they must be innovative enough to be fit for purpose. In many cases, cost savings from the learning curve and scale factors are likely to surpass the actual innovation-driven economic improvements.

The initial wave of SMR deployments is expected around 2030, primarily involving Generation III+ light water designs such as the Russian RITM-200, Chinese Linglong One (ACP100), NuScale's VOYGR, and GE-Hitachi's BWRX-300, followed by the UK SMR and French NUWARD. First-Of-A-Kind (FOAK) SMR projects, similarly to FOAK projects with larger reactors, are likely to face on average at least 1–3-year delays compared to their initial schedules and significant cost overruns. These could impede capital raising for scaling and manufacturing capacity expansion.

Advanced, Generation IV SMRs will likely encounter more substantial delays, with regulators less familiar with the technologies and less mature supply chains. Although some demonstration units might come online by 2035, full-fledged FOAK deployment and series factory manufacturing are more likely around 2040.

Government support in OECD countries has primarily focused on supply-side aspects like research grants and R&D funding. This might be insufficient to break the "chicken-and-egg" dilemma of supply-demand imbalances at the stage of moving from demonstration to series manufacturing. Without demand-side subsidies, the competitiveness of OECD vendors might be undermined by slower deployment, leaving promising SMR export markets to Russia and China.

If current trends persist, in the context of regulatory and geopolitical fragmentation, Russian and Chinese designs are poised to dominate nearly with 40% of the global SMR fleet by capacity:

Russia's Rosatom, with pre-selected designs, including Gen III+ PWRs RITM-200 and Shelf-M and Gen IV fast reactor SBVR-100, is set to replicate its success in large reactor exports. Supported by government demand subsidies and export finance, and offering a "plant-as-a-service" model for emerging markets and nuclear newcomers, Rosatom is expected to surpass 7GWe of operational SMR capacity by 2040, dominating off-grid and naval transport applications.

China, set to launch the world's first onshore SMR unit with Linglong One (ACP100), will see this design, along with Hualong One (HPR1000), as a flagship export. Backed by state support, China's SMR designs are expected to comprise 6.5GW by 2040, scaling up to over 30GW by 2050, with export priorities along the Belt and Road Initiative (BRI).

TO COMPETE WITH RUSSIA AND CHINA, OECD COUNTRIES SHOULD CONSIDER EQUIVALENT SUPPORT FOR THEIR SMR PROGRAMS:

1. **Complement supply-side support** with strong demand-side incentives, targeting priority applications like coal-fired power station replacement and diesel generation replacement for larger off-grid customers:
   - Some initiatives recently launched by the US Government, like project Phoenix[82], aimed to support the conversion of coal power plants into SMR sites, or project Pele[83], financing the development of microreactors, should be scaled up and replicated in other OECD countries.
   - Non-governmental initiatives like REPOWER[84] platform, led by TerraPraxis, and facilitating coal-to-SMR conversion projects, should be supported by both national governments and local authorities in charge of the locations of plants.
   - Governments could offer special subsidised tariffs or price support schemes like Contracts for Difference (CfDs) for grid applications, tax credits for diesel replacement, and levies on sales of new large diesel generators when microreactors are commercially available.

2. **Remove all remaining restrictions** on SMR-based clean energy solutions by international development institutions, streamline export finance options, and offer international trade advocacy services.

3. **Encourage nuclear regulators** to collaborate in developing at least partial common standards, with mutual recognition of pre-licensing design and factory certification for SMRs. They should also be encouraged to share knowledge, information, and expert networks, particularly regarding innovative technologies.

4. **Encourage firms** to form competitive global alliances combining vendors, potential international plant operators, and key supply chain partners (including fuel-cycle), capable of competing with Russian and Chinese national champions in the "plant-as-a-service" lifecycle energy solutions segment.

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[82] https://www.state.gov/project-phoenix/
[83] https://www.cto.mil/pele_eis/
[84] https://www.terrapraxis.org/projects/repower

APPENDIXES

LIST OF SMR PROJECTS/ REACTOR DESIGNS

Name	Developer/Vendor	Country
ACP100/Linglong One	CNNC	China
ACPR50S	CGN	China
AP300	Westinghouse Electric Co	United States
ARC100	ARC Clean Technology	Canada
Aurora	OKLO	United States
BANDI-60	KEPCO	South Korea
BREST-OD-300	Rosatom	Russia
BWRX-300	GE-Hitachi	United States
BWXT Micro	BWXT	United States
BWXT-DRACO	BWXT	United States
CAREM	CNEA	Argentina
eVinci	Westinghouse Electric Co	United States
Hermes	Kairos Power	United States
HTR-PM	TUINNET	China
IMSR	Terrestrial Energy	Canada
LF1 (TMSR-LF1)	SINAP	China
Mitsubishi MHI MMR	Mitsubishi MHI	Japan
MMR	Ultra Safe Nuclear	United States
[Mobile MMR-1MWe][85]	Rosatom	Russia
Natrium	TerraPower	United States
VOYGR	NuScale	United States

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[85] No official name, conceptual design based on space and defence reference units

Name	Developer/Vendor	Country
NUWARD	EDF	France
PRISM	GE-Hitachi	United States
RITM-200	Rosatom	Russia
SEALER-55	Blykalla (LeadCold)	Sweden
Shelf-M	Rosatom	Russia
SMART	KAERI	South Korea
SSR-Wasteburner	Moltex Energy	Canada
SMR-300	Holtec International	United States
SVBR-10	Rosatom	Russia
SVBR-100	Rosatom	Russia
UK-SMR	Rolls-Royce	United Kingdom
XE-100	X-Energy	United States
Xe-Mobile	X-Energy	United States

GLOSSARY

BOP	Balance of Plant
BRICS	Brazil, Russia, India, China, South Africa
CAGR	Cumulative Average Growth Rate
CANDU	Canada Deuterium Uranium
CAPEX	Capital Costs
CCUS	Carbon Capture Utilisation and Storage
COP	Conference of Parties
DAC	Design Acceptance Confirmation
ECCS	Emergency Core Cooling System
ETS	European Union's Emission Trading Scheme
FNPP	Floating Nuclear Power Plant
ENSREG	The European Nuclear Safety Regulators Group
EXIM	Export-Import Bank of the United States
FOAK	First-of-a-kind
GDP	Gross Domestic Product
HALEU	High Assay Low Enriched Uranium
IAEA	International Atomic Energy Agency
IEA	International Energy Agency (OECD)
IFC	International Finance Corporation
IMSR	Integral Molten Salt Reactor
INRA	International Nuclear Regulators' Association
LCOE	Levelized Cost of Electricity
HTR-PM	High-temperature gas-cooled reactor pebble-bed module
LEU	Low Enriched Uranium
LoCA	Loss-of-a-coolant accident

LWR	Light-water reactor
MOX	Mixed Oxide Fuel
MTHM	Metric Tons of Heavy Metal
NOAK	Nth-of-a-kind
NPM	NuScale Power Module ™
NPP(s)	Nuclear Power Plant(s)
NRC	Nuclear Regulatory Commission
NREL	National Renewable Energy Laboratory
NSSS	Nuclear Steam Supply System
NHSI	Nuclear Harmonization and Standardization Initiative
OECD	Organisation for Economic Co-operation and Development
PCCS	Passive containment cooling system
PDHR	Passive Decay Heat Removal System
PHRS	Passive hydrogen removal system
PHWR	Pressurised Heavy Water Reactor
PPA	Power Purchase Agreement
PPS	Pre-Project Service
PSA	Probabilistic Safety Assessment
PSAR	Preliminary safety analysis report
PSIS	Passive safety injection system
PRHS	Passive residual heat removal system
PUREX	Plutonium Uranium Reduction Extraction
PV	Photovoltaic cell
PWR	Pressurised Water Reactor
RCPs	Reactant Coolant Pumps

RCS	Reactant coolant system
R&D	Research and Development
REMIX	Regenerated Mixture Fue
RPV	Reactor pressure vessel
SDA	Standard Design Approval
SGs	Steam Generators
SLIS	Small Leak Injection System
SMART	System-integrated modular advanced reactor
SMR	Small Modular Nuclear Reactor
SoDA	Statement of Design Acceptability
SSR	Solid State Reactor
SWU	Separative Work Units
TRL	Technology Readiness Level
vSMR	very Small Modular Nuclear Reactor
WENRA	Western European Nuclear Regulators Association

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