Nuclear Small Modular Reactors: Key Considerations for Deployment

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Nuclear Small Modular Reactors (SMRs): Key Considerations for Deployment

A report by graduate students at the Johns Hopkins School of Advanced International Studies for the **International Energy Forum**

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Preface

This report was authored by students of the Johns Hopkins School of Advanced International Studies as part of a practicum project in the Master of Arts in International Relations degree program. The key findings within the report are formulated independently and do not necessarily reflect the perspectives of either the IEF or Johns Hopkins SAIS. The report aims to maintain neutrality in its analysis. The authors neither endorse nor oppose nuclear small modular reactors (SMR) technology but rather aim to develop an informative decision-making framework

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Acronyms and Abbreviations

Abbreviation	Description
BOO	Build-Own-Operate
CfD	Contract for Difference
CFPP	Carbon Free Power Project
CFR	Code of Federal Regulations
COL	Construction and Operation License
COP	Conference of Parties
CSF	Cost Stabilization Facility
DOE	Department of Energy
ECA	Export Credit Agency
EPC	Engineering, Procurement, and Construction
EXIM	Export-Import Bank (United States)
FIRST	Foundational Infrastructure for Responsible Use of Small Modular Reactor Technology
FOAK	First-of-a-Kind
HALEU	High-Assay Low Enriched Uranium
HTGR	High Temperature Gas Reactor
HWR	Heavy Water Reactor
IAEA	International Atomic Energy Agency
IBNI	International Bank for Nuclear Infrastructure
IEF	International Energy Forum
IRA	Inflation Reduction Act
LACE	Levelized Avoided Cost of Energy
LCOE	Levelized Cost of Electricity
LEU	Low Enriched Uranium
LFSCOE	Levelized Full System Cost of Electricity
LILW	Low and Intermediate Level Waste
LLW	Low-Level Waste
LLC	Limited Liability Company
LPO	Loans Program Office
LWR	Light Water Reactor
MDB	Multilateral Development Bank
MOX	Mixed-oxide fuel
MWe	Megawatt of electricity
MWh	Megawatt hour
NOAK	Nth-of-a-Kind
NPP	Nuclear Power Plant
NPT	Nuclear Non-Proliferation Treaty
NRC	Nuclear Regulatory Commission (United States)
OCC	Overnight Capital Cost
O&M	Operation and Maintenance
PRA	Probabilistic Risk Assessment
PUREX	Plutonium Uranium Extraction

PWR	Pressurized Water Reactor
RAB	Regulated Asset Base
SAIS	School of Advanced International Studies
SMR	Small Modular Reactor
SNF	Spent Nuclear Fuel
SPV	Special Purpose Vehicle
U-235	Uranium 235
UAMPS	Utah Associated Municipal Power Systems
WENRA	Western European Association of Nuclear Regulators

Executive Summary

Overview

Nuclear energy is considered by many as a viable, and even necessary component in a portfolio of options to reduce carbon emissions in the power sector. An emerging part of this discussion is the role and potential of nuclear small modular reactors (SMRs), defined as nuclear reactors with power capacity of up to 300 megawatts of electricity (MWe) per unit, in achieving climate goals and fostering economic development as part of the energy transition.

Much excitement has been generated regarding SMR deployment globally. However, these reactors also pose new considerations when compared to larger, more conventional reactors. Understanding the challenges and opportunities facing SMR deployment can better inform policy makers and stakeholders and aid in their objectives of reaching decarbonization targets.

This report was produced by a graduate student consulting team from Johns Hopkins SAIS on behalf of the IEF. In addition to reviewing available literature, academic studies, and industry-produced reports, the authors also conducted thirty interviews with stakeholders active in the civilian nuclear power and SMR sector. The information gathered from these interviews has informed the report and its key findings.

The report presents nineteen key findings for nations considering SMR deployment, exploring technical considerations, regulation and governance, cost, and financing aspects. It also includes a decision-making framework that can serve as a tool for interested policy makers and stakeholders.

Key Findings

1. **SMR deployment requires a coordinated and sustained effort across governments, industry, and international institutions.** The specific features of civilian nuclear power plants (NPPs) necessitate the full endorsement of host governments, even if projects are led by private sponsors. This requirement hinges on various characteristics of a national government, including its ability to create an enabling environment that makes nuclear power feasible. SMR designers must work early with government and regulatory counterparts who can help facilitate these processes. International dialogue and collaboration should also be initiated at early stages to establish conducive trade relations and successful partnerships for the export of SMR technology.

2. **Countries with substantial vested interests in SMRs are willing to embrace the First-of-a-Kind (FOAK) risk associated with this new technology.** For emerging economies, this could include countries with limited alternatives for firm electricity generation, those facing high electricity costs where SMRs can offer competitive prices, or nations deeply concerned with energy and water security, as well as climate resilience. Countries concerned with nuclear reactor export competitiveness are heavily involved in advancing their own domestic SMR industries. These nations will set the standard for SMR deployment globally.

3. **SMRs offer enhanced flexibility for low-carbon power generation.** A key promise of many SMR designs is modularity, meaning that they can be factory fabricated, transported to the site, assembled, and stacked to reach the desired total energy output. This feature enables more flexibility in deployment locations, allows for better load following in grid systems with higher penetrations of variable renewable resources, and permits incremental growth in output capacity. This is important for smaller grid systems and is a distinct advantage that SMRs have over large NPPs. However, if used for power generation, guidelines from the International Atomic Energy Agency (IAEA) state that SMR units should still be less than ten percent of the total grid capacity to avoid overwhelming the grid. Countries with small grid sizes must carry out grid reinforcements to ensure grid stability.

4. **Nations must consider fuel types when selecting a reactor design, since its availability will impact reactor operations, regulatory requirements, international partnerships, and waste management.** Some SMR designs utilize low enriched uranium (LEU) or mixed-oxide fuels (MOX), which are commonly used in large reactors and is commercially available in numerous countries. Other designs employ more novel fuel types, such as high-assay low-enriched uranium (HALEU) or thorium-based fuels, which offer some advantages in terms of improved waste characteristics and reduced nuclear proliferation risks. However, these fuels are not as widely commercially available.

5. **SMR designs integrate inherent safety features that reduce the risk of accidents and could contribute to greater public acceptance of these reactors as safe and sustainable power generation options.** Advanced SMR designs have inherent safety features, including passive systems that utilize gravity, natural circulation, and material properties rather than active systems or operator intervention. Designs also integrate reactivity control mechanisms and robust containment structures capable of withstanding extreme events. These features enhance safety margins and reduce accident risks, fostering greater public acceptance of SMRs.

6. **The choice of technology partner holds long-term implications for energy security, supply chains, and international partnerships.** SMR technology importing countries must consider the long plant lifecycles of SMRs and establish strong ties with countries integral to its supply chain to ensure continued access to fuel and other essential components.

7. **SMRs pose distinct challenges for existing nuclear waste management processes.** SMRs produce more complicated waste streams, in terms of both composition and volume. This complexity is driven by increased neutron leakage from their smaller reactor cores, which occurs when neutrons escape and interact with surrounding materials, leading to more radioactive material. SMR designs utilize three strategies to mitigate neutron leakage, including enriched fuel, neutron reflectors, or modified coolant types. However, the variety of fuel waste types and diverse coolants presents challenges to waste disposal due to their divergence from established technologies and practices for nuclear waste management. Thus, further research is required to adequately address these challenges.

8. **SMR deployment necessitates adherence to the same international conventions governing nuclear safety, security, safeguards, and liability as large NPPs.** Countries considering civilian nuclear power, including SMRs, must develop a domestic legal framework addressing nuclear safety, security, safeguards, and liability. This framework should adhere to the principles outlined in international conventions. These principles provide essential protections to states, people, and the environment, and assign responsibilities and liabilities in the event of incidents. Given that SMRs present many of the same risks as large NPPs, the existing principles generally apply to SMRs. However, new SMR designs introduce certain ambiguities that require additional attention from countries when establishing nuclear legislation.

9. **An independent regulator is an essential prerequisite to SMR deployment.** Nuclear legislation should establish and determine the functions of an effectively independent regulatory body, which broadly include standard setting, licensing and authorization of nuclear installations, inspection, and enforcement. The independence of the regulatory body is important to avoid influence from individuals or entities advocating for nuclear energy within the government. The regulator is responsible for ensuring that the entire lifecycle of NPPs from reactor design and site selection to construction, operations, waste management, decommissioning, and accident response aligns with the regulatory framework. A reliable and transparent regulator demonstrates strong governmental commitment, engages stakeholders, and provides confidence to investors, vendors, and society for new civilian nuclear power infrastructure.

10. **The smaller size of SMRs does not equate to a simplified regulatory process under existing regulatory frameworks.** SMRs require many of the same enabling environments as traditional NPPs. Establishing nuclear infrastructure and regulatory frameworks can be a long process, often spanning several years. This is especially true for nuclear newcomers who have yet to implement a civilian nuclear power program and will need to comply with relevant international conventions and any other requirements dictated by exporting countries. While there are efforts to harmonize these requirements, it is unlikely that these processes can be significantly shortened or streamlined. Moreover, the novel features of many advanced reactors may extend timelines for authorization by regulators.

11. **While SMRs may introduce complexities into the licensing process, regulatory reforms hold the promise of accelerating SMR deployment at scale.** SMR licensing can be facilitated by improvements to the existing regulatory framework, which focuses on traditional large light water nuclear reactors. Regulators may introduce a more technology-neutral stance that takes a risk-informed, performance-based approach.

12. **When estimating the life-cycle cost of SMRs, four cost drivers should be considered: capital costs, operations and maintenance (O&M) costs, fuel costs, and decommissioning costs.** The life-cycle cost encompasses all the costs incurred over the entire lifespan of the nuclear reactor project for power generation. These costs may vary based

on SMR reactor technology, size, application, and location. In comparison to large reactors, SMRs are expected to have higher costs per unit of output due to a lack of economies of scale in which expenses are spread across higher total output.

13. **Unique characteristics of SMRs, such as modularization, learning effects, shorter construction times, and co-siting economies can potentially reduce costs for SMRs.** Modularization allows for uniform fabrication of reactor components which can be more easily transported and assembled at the installation site. This standardizes and centralizes manufacturing, thus reducing costs. As a result of learning effects, or the efficiency gains achieved due to the accumulation of experience as more units are produced and deployed, costs can further be reduced. SMRs are expected to have a shorter construction time compared to large reactors, thereby reducing financing costs. SMRs also allow for co-siting at pre-existing facilities, enabling cost savings on certain fixed, indivisible costs, such as licensing, insurance, and human resources.

14. **The commonly used cost metric, levelized cost of electricity (LCOE), does not account for grid integration costs and grid flexibility. It is important to look beyond the LCOE to fully evaluate the economic potential of SMRs.** In general, SMRs may require less grid build out, given their potential for portability and co-siting. SMRs may also incur lower additional grid costs compared to variable renewable resources, given their stable and continuous electricity generation, which aligns well with the grid's firm power needs and growing demand for grid resilience.

15. **The lack of definitive data for SMR costs necessitates a thorough and cautious evaluation from investors and policymakers.** There is a considerable degree of uncertainty surrounding SMR costs, particularly for FOAK projects. FOAK projects will incur higher expenses which are expected to decrease with Nth-of-a-Kind (NOAK) production. Until more units are produced and deployed and potential cost benefits of SMRs become a reality, true SMR costs are still unknown.

16. **Governments can provide critical financial support to FOAK SMR projects.** Given the early stage of global SMR deployment, FOAK projects will likely incur higher costs and other project risks. The government is in a unique position to fund demonstration projects, allocate spending through various government programs, or help contain project costs by providing loan guarantees or other tailored loan products.

17. **Demonstration projects play an essential role in understanding cost estimates for specific SMR designs and demonstrating commercial viability.** Most SMRs in operation today are demonstration projects; this is an important step for both SMR designs deployed domestically, as well as for designs destined for export. Demonstration projects are an important indicator to investors and can help establish an orderbook for future projects.

18. **There are many potential financing structures and business models for SMR projects.** SMR projects can be sponsored directly or indirectly by national governments or by private

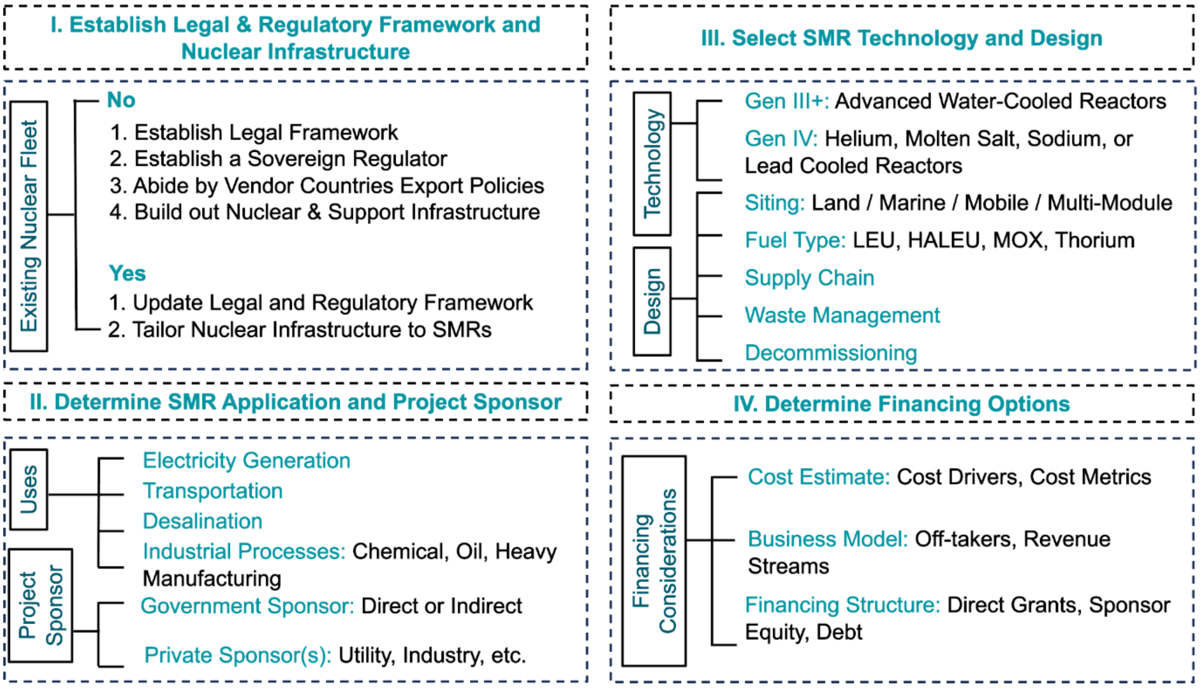
sponsors, including utilities, industrial companies, data centers, or other power off-takers. Projects will likely utilize a blended financing approach, relying on some mix of grants, debt, and equity, however sourced. The specific business model of the project will determine its commercial viability. Projects may have unique power off-takers and revenue streams given the range of applications for SMRs and diverse policy and regulatory landscapes in a host country.

19. **SMR projects will rely on financing from numerous stakeholders and dedicated financial institutions.** If SMRs are exported to other host countries, a wider range of stakeholders could be involved in financing the project. For example, export credit agencies are uniquely positioned to help finance these projects by providing direct loans or loan guarantees to foreign commercial entities. Several countries have sovereign lenders dedicated to nuclear infrastructure investments. Progress is also being made to establish the International Bank for Nuclear Infrastructure, which is still in its fundraising phase at the time of report publication but could play a specific role in early-stage financing and project endorsement.

Summarized Decision-Making Framework for SMR Deployment

The Summarized Decision-Making Framework for SMR Deployment is a tool designed for countries considering pursuing SMR projects (see Figure 1). It is intended to serve as a high-level guide for policy makers and market stakeholders. It highlights the foundational prerequisites for civilian nuclear power programs, such as establishing the legal and regulatory framework and nuclear infrastructure, as well as project-specific considerations such as selecting SMR technology and designs, determining the SMR application, identifying the project sponsor, and exploring financing options, which should be considered in a more holistic way.

Figure 1: Summarized Decision-Making Framework for SMR Deployment



Source: Produced by the authors.

Introduction

Project Background

Nuclear energy is considered by many as a viable, and even necessary component in a portfolio of options to enhance energy security and reduce CO_2 emissions in the power sector. However, reliance on nuclear power has always generated debate. Those in favor argue that clear and specific policy mechanisms can promote greater use of nuclear energy to reduce emissions, provide reliable firm power, and improve energy security. Those opposed are skeptical that nuclear energy can fulfill its promise and overcome existing challenges to its expansion, such as the high capital costs of construction, safety and security concerns, waste disposal issues, and proliferation risks.

An emerging part of this discussion is the role and potential of nuclear SMRs. Advocates claim that the smaller size of these reactors could lower the overall capital costs of construction, reduce construction times due to modularity, feature improved safety mechanisms, reduce waste streams, provide firm power to complement renewable resources on the grid, and could be tailored to meet the needs of smaller or more remote loads, as well as specific industrial uses. Consequently, SMRs could play a key role in achieving climate goals and fostering sustainable economic development as part of the energy transition. However, they also pose challenges related to higher per unit costs, require newer, specific licensing and regulatory regimes compared to those governing conventional reactors, and for nuclear newcomer countries, SMRs necessitate the development of commensurate institutions and human capacity to manage, operate, and regulate the technology.

The International Energy Forum (IEF), which gathers 70 energy ministers from producer and consumer countries, has a broad mandate to examine all energy issues including new technologies that can contribute to the energy transition and help nations meet their net zero commitments. SMRs are one such technology that is offering potential solutions. This report aims to delineate some of these opportunities and challenges facing SMR development and deployment globally. This nascent technology has received significant attention in civilian nuclear energy discussions, serving as a focal point at COP28 and attracting interest as a strategic investment area for infrastructure-exporting countries and potential host nations. Recognizing this significance, this report serves as a tool for interested countries by offering considerations for host countries in terms of regulation and governance, technology, costs, and financing while maintaining a technology-neutral stance.

Methodology

The authors reviewed publicly accessible literature, academic studies, and industry-produced reports, and conducted thirty interviews with stakeholders active in the civilian nuclear power and SMR sector. These interviews took place between September 2023 and April 2024 and engaged experts specializing in international law and governance, policy, regulation, finance, nuclear physics, and waste management. The information gathered from these interviews has been utilized to inform the content of the report but is not attributed to the organization or individual.

Defining SMRs

This report relies on the IAEA definition of an SMR as a nuclear reactor with power capacity of up to 300 MWe per unit, though most SMR designs currently under development are around 150 MWe or less.[1] SMRs are smaller in power output and physical size than conventional gigawatt-scale nuclear reactors and use nuclear fission reactions to create heat, which can be used directly or to generate electricity.[2] The potential advantages that SMRs have over large reactors include scalable deployment, portability, reduced proliferation risks, lower upfront capital costs, and modular manufacturing. These reactors also hold promise for diverse applications beyond electricity generation, including industrial processes, desalination, or transportation.

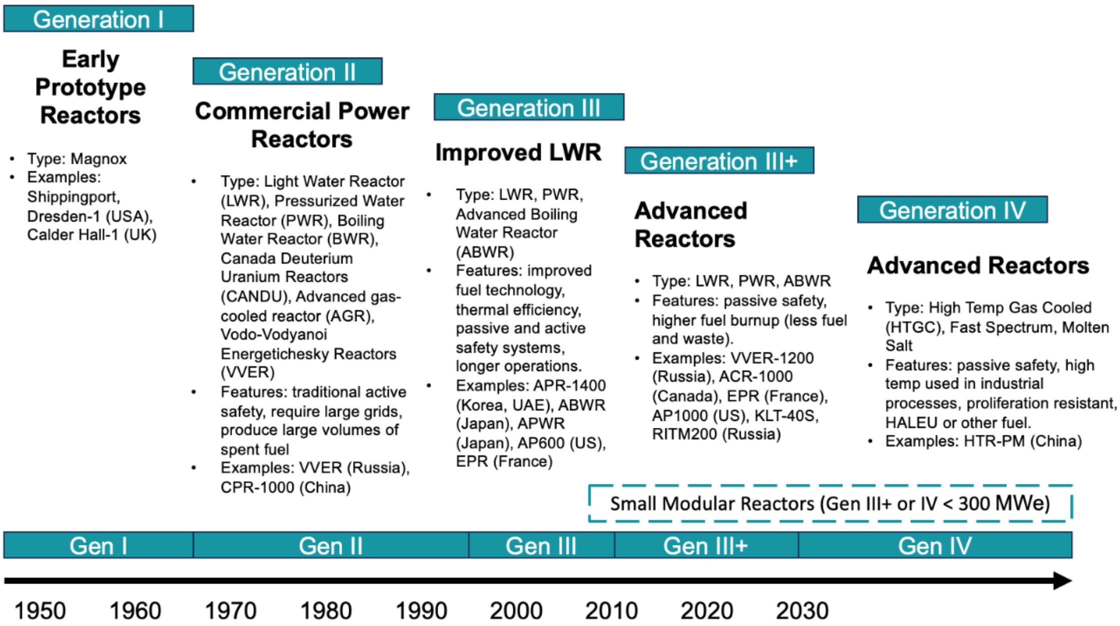
Nuclear Technology Overview

Nuclear reactor technology is classified by its generation, i.e., the timeframe when deployed, with all nuclear reactors utilizing nuclear fission to generate heat for electricity and fueled by enriched uranium or plutonium. Traditional reactors, developed in the latter part of the twentieth century, are categorized as Generation I, Generation II, and Generation III reactors. These reactors, primarily water-cooled, are custom-built for specific sites, with each successive generation incorporating improvements for extended plant lifespans, enhanced fuel efficiency, and safety features.

Advanced reactors, including Generation III+ and Generation IV, introduce novel cooling mechanisms, fuel cycles, and safety enhancements. Generation III+ systems are characterized by passive safety features, such as inherent reactivity control mechanisms and robust containment structures, and are anticipated to exhibit increased fuel burn, thereby reducing fuel consumption and waste production. Generation IV designs employ alternative cooling mechanisms, enabling reactor temperatures to exceed 320°C, thus expanding their potential applications for industry or district heating. These reactors also utilize alternative fuels, such as HALEU, which is enriched at the high end of what is defined as LEU fuel. Most new reactors under design and construction are considered Generation III+ or Generation IV. Figure 2 depicts how the various generations have evolved over the last several decades.

[1] *Small Module Reactors,* International Atomic Energy Agency (IAEA), https://www.iaea.org/topics/small-modular-reactors. (accessed April 22, 2024).
[2] "The NEA Small Modular Reactor Dashboard," *Nuclear Energy Agency*, No 7650, July 20, 2023, https://www.oecd-nea.org/jcms/pl_78743/the-nea-small-modular-reactor-dashboard.

Figure 2: Summary of Civilian Nuclear Power Reactor Technology by Generation



Source: Adapted by the authors from 'Nuclear Reactors: Generation to Generation Report' [3]

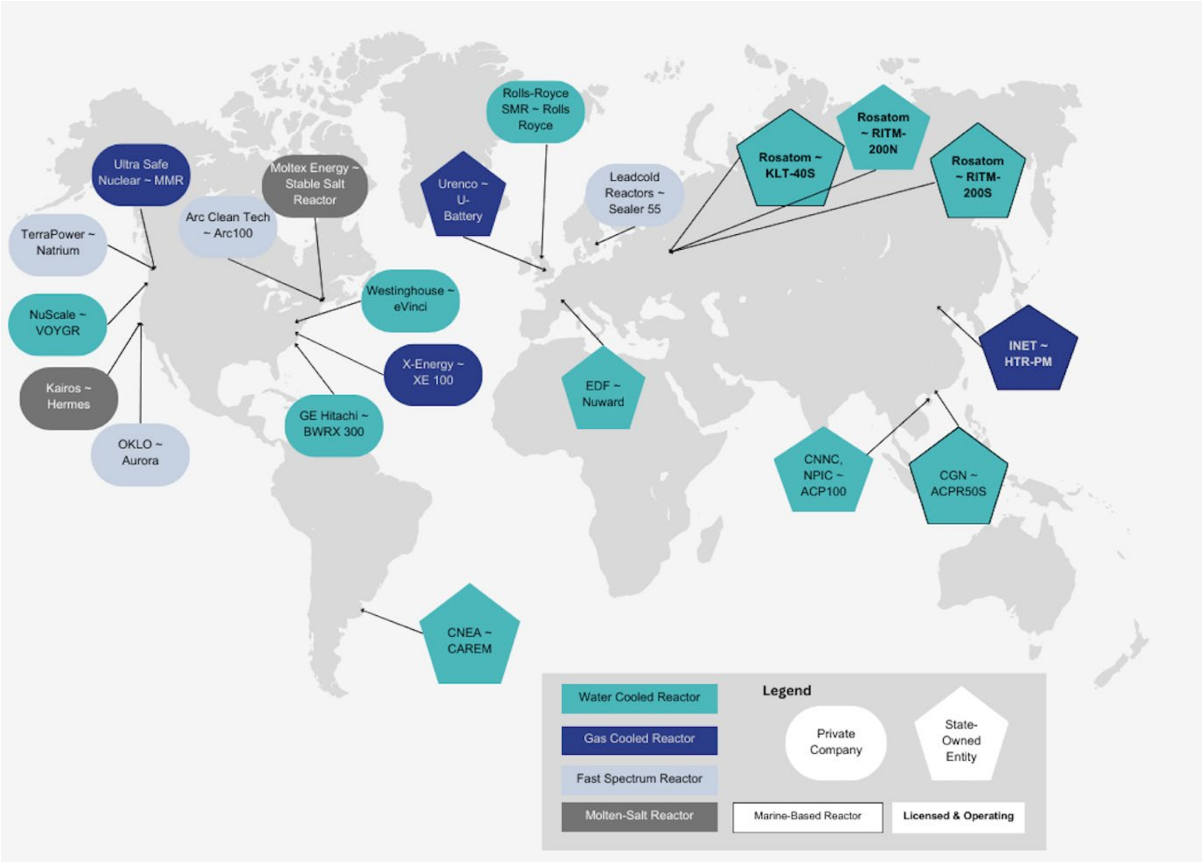
SMR Global Outlook

SMR Design Development – There are nearly a hundred SMR designs under development globally at various stages of maturity, from design conceptualization to feasibility studies, licensing and construction, demonstration, and commercial operation. Figure 3 depicts the geographical distribution of a select number of SMR designs by developer nation. Russia, China, the United States, Canada, France, Sweden, the United Kingdom, and Argentina have shown the most progress in their designs. This is underlined by the fact that these governments have established a range of domestic incentives, legislation, research and development support, and financing for demonstration projects to facilitate design development and build out. These designs are characterized as Generation III+ or Generation IV reactors and will deploy a variety of cooling

[3] Stephen M. Goldberg & Robert Rosner, "Nuclear Reactors: Generation to Generation," *American Academy of Arts and Sciences*. (2011): 4. https://www.amacad.org/sites/default/files/academy/pdfs/nuclearReactors.pdf

mechanisms, utilize traditional or novel fuel types, are designed for power generation or hybrid uses, and have land-based, marine-based, or mobile applications.

Figure 3: Geographic Distribution of Select SMR Designers



Source: Adapted by the authors from 'The NEA SMR Dashboard' [4]

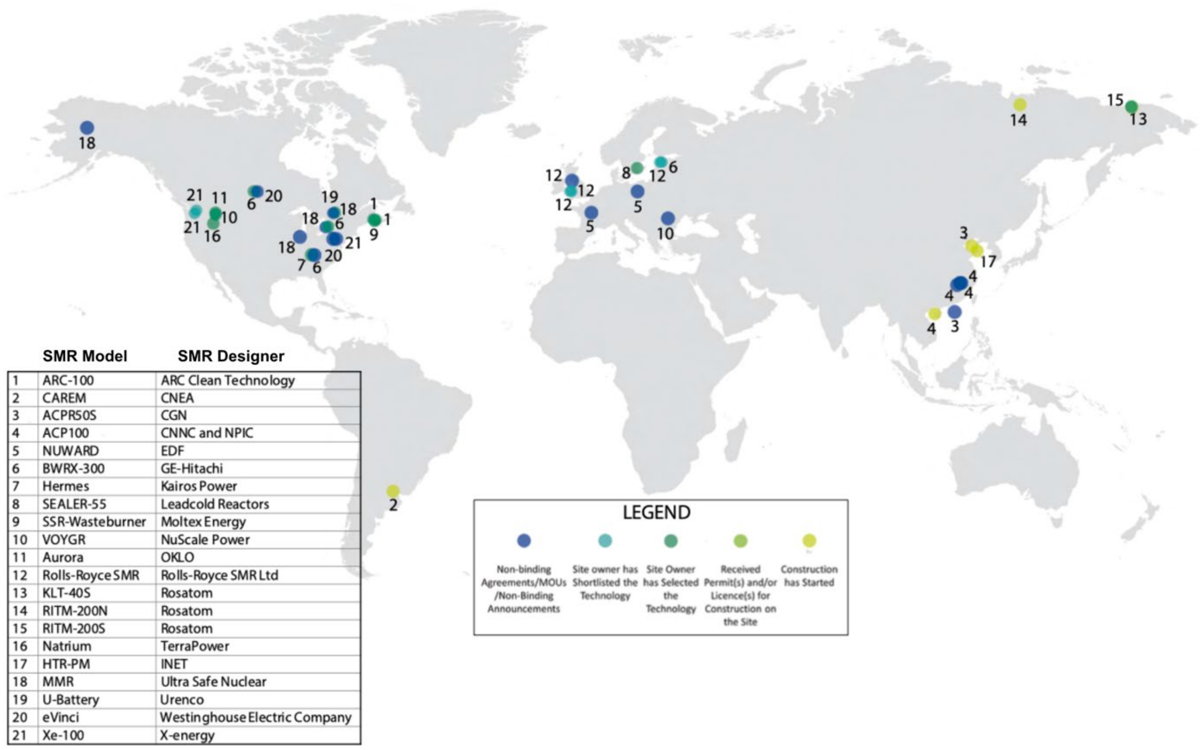
Fuel Cycle Considerations – The fuel cycle and supply chain are an important consideration for SMR deployment. Kazakhstan, Canada, France, and the United States are the world's leading uranium mining and exporting nations. Significant uranium resources have been discovered in Australia and Namibia. In terms of fuel processing, Russia is the largest supplier of LEU, a feedstock for most reactors operating today, followed by Urenco (a consortium composed of Germany, the Netherlands, and the UK), France, China, and the United States. While most water-cooled reactors utilize LEU fuel, many advanced reactors are designed to utilize HALEU fuel. Russia and China are the only nations to process and commercially sell HALEU fuel. In 2023, the United States authorized Centrus Energy Corp to begin producing this fuel at its American Centrifuge Plant in Ohio. This facility can produce 900 kilograms of HALEU per year and plans to

[4] "The NEA Small Modular Reactor Dashboard," 17.

increase capacity to 6,000 kilograms.[5] Ensuring access to this fuel is essential for the success of Generation IV designs that depend on HALEU fuel.

SMR Deployment – At the time of publication, only Russia and China have SMRs that are licensed and operating. These designs include water-cooled reactors (Russia's RITM-200 series and KLT-40S) and one gas-cooled reactor (China's HTR-PM). These projects have been supported by state-owned entities, which is the predominant model for nuclear power industries globally. The United States, Canada, the United Kingdom, and Sweden also have reactor designs in the development and demonstration phase, but few designs have received licensing approval yet. For novel non-water-cooled designs, regulatory approval and commercialization is expected to take longer than for water-cooled reactors, which are more familiar to regulatory agencies. Figure 4 illustrates the locations of SMR projects under development as of 2022, ranging from announced projects to construction works in-progress. Planned projects are primarily located in Central Europe, Canada, the United States, Russia, and China. Given the early stage of global SMR deployment and the variety of designs being developed, it is unclear which design type or vendor will lead the market.

Figure 4: Locations of SMR Projects Under Development (2022)



	SMR Model	SMR Designer
1	ARC-100	ARC Clean Technology
2	CAREM	CNEA
3	ACPR50S	CGN
4	ACP100	CNNC and NPIC
5	NUWARD	EDF
6	BWRX-300	GE-Hitachi
7	Hermes	Kairos Power
8	SEALER-55	Leadcold Reactors
9	SSR-Wasteburner	Moltex Energy
10	VOYGR	NuScale Power
11	Aurora	OKLO
12	Rolls-Royce SMR	Rolls-Royce SMR Ltd
13	KLT-40S	Rosatom
14	RITM-200N	Rosatom
15	RITM-200S	Rosatom
16	Natrium	TerraPower
17	HTR-PM	INET
18	MMR	Ultra Safe Nuclear
19	U-Battery	Urenco
20	eVinci	Westinghouse Electric Company
21	Xe-100	X-energy

Source: The NEA SMR Dashboard [6]

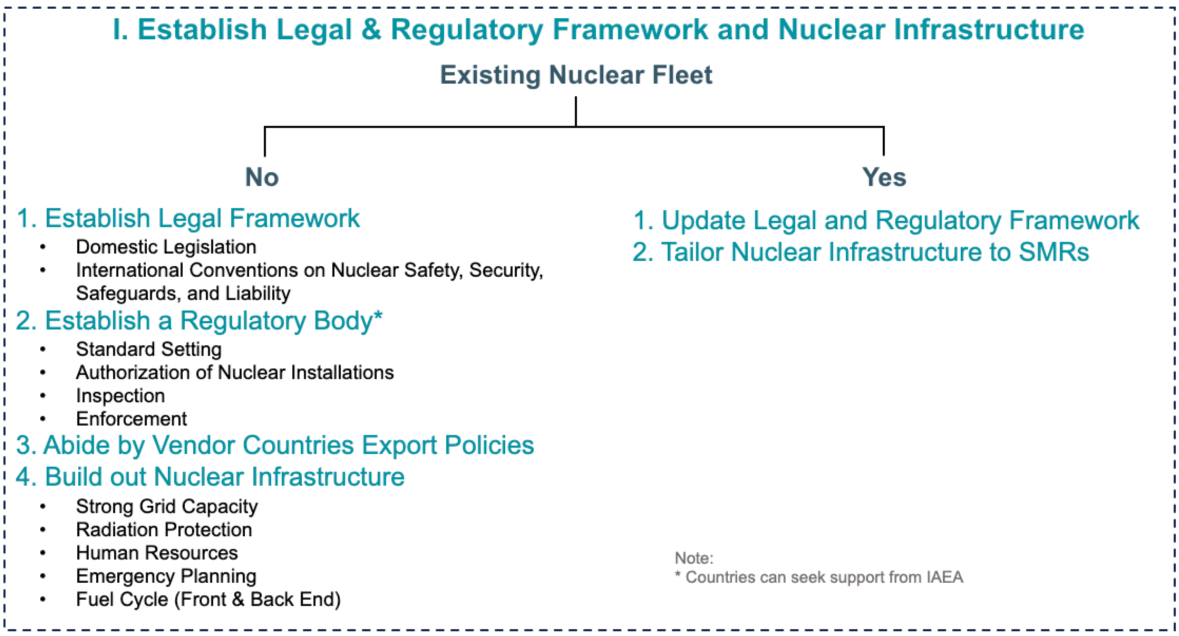
[5] "Centrus Produces Nation's First Amounts of HALEU," *Office of Nuclear Energy.* Department of Energy, November 7, 2023, https://www.energy.gov/ne/articles/centrus-produces-nations-first-amounts-haleu. (accessed April 4, 2024).
[6] "The NEA Small Modular Reactor Dashboard," 18.

Decision-Making Framework for SMR Deployment

The Decision-Making Framework for SMR Deployment is a tool that summarizes considerations for nations interested in deploying SMRs (see Figure 5). The essential prerequisites for SMR deployment, as outlined in Section I, include establishing legal and regulatory frameworks, as well as nuclear infrastructure. If a country does not have an existing civilian nuclear power fleet, the IAEA estimates that it will take approximately ten years to complete the entire process of setting up the framework and infrastructure. For countries with an existing civilian nuclear power program, some updates specific to SMRs will be necessary.

The following sections are project-specific and should be considered in a holistic way. Section II illustrates considerations for determining reactor applications, which will also depend on the project sponsor. The prevailing uses for SMRs include electricity generation, transportation, desalination, and industrial processes. Projects may be government-led or private sector driven, with greater government involvement support required for FOAK technology. Section III outlines considerations for SMR technology evaluation and design selection. This process will include assessing siting, fuel, supply chain, waste management, and decommissioning requirements for designs under consideration. Once the technology is selected and a project is proposed, Section IV outlines financing options, which includes identification of cost estimates, the business model, and financing structure, culminating in financial close and construction commencement. Given the early stage of global SMR deployment, cost estimates are largely speculative. Financing, especially for FOAK designs, will necessitate government support from both vendor and host countries.

Figure 5: Decision-Making Framework for SMR Deployment



II. Determine SMR Application and Project Sponsor

Uses

Electricity Generation
- Grid Integration
- Remote Locations

Transportation

Desalination

Industrial Processes
- Chemical Processing
- Oil Refining
- Manufacturing
- Other Industrial Processes

Sponsor

Government Sponsor
- State Owned Enterprise
- Other government sponsor [1]

Private Project Sponsors
- Utility
- Heavy Industry (Steel, Cement, Coal, Mining, etc.)
- Data Center
- Transport (Freight + Shipping)

Note:
1 Heavy government support is common for FOAK technology.

III. Select SMR Technology and Design

SMR Technology

Generation III+
- Water cooled reactors

Generation IV
- Helium/ Molten Salt/ Sodium/ Lead cooled reactors [2]

Design Considerations

Siting
- Land-based
- Marine-based
- Mobile
- Multi-module configurations

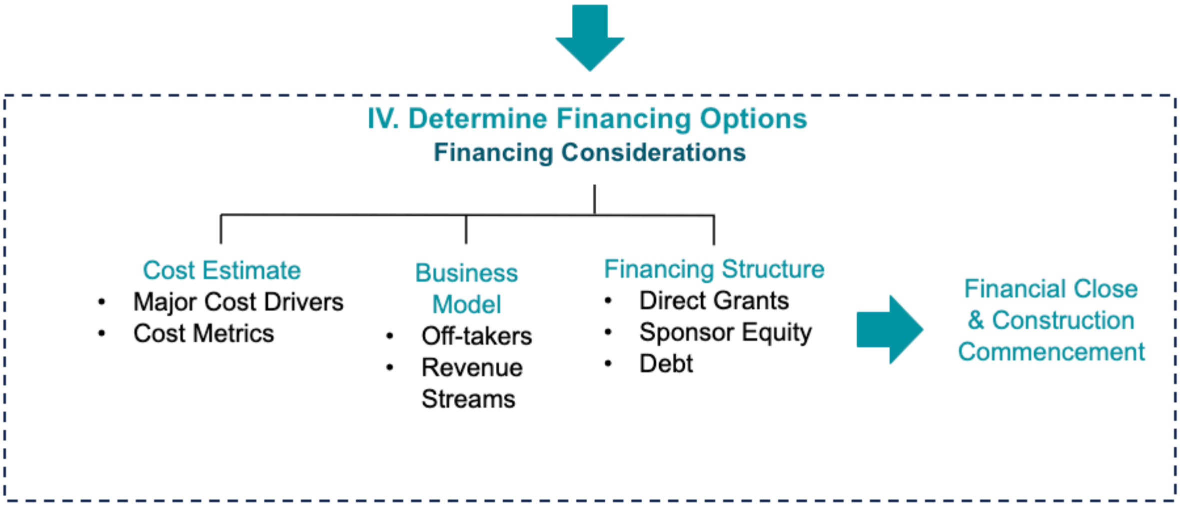
Fuel Type
- LEU
- HALEU
- MOX
- Thorium

Supply Chain

Waste Management [3]
- Dry Cask Storage
- Geological Disposal
- Reprocessing Facility
- Regional Waste Management Program

Decommissioning

Note:
2 Better for high-temperature processes (Industry)
3 Waste management process must be established before construction commences.



Source: Produced by the authors.

Key Considerations for SMR Deployment

This section explores four key themes in more depth: technical considerations; regulation and governance; cost; and financing.

Technical Considerations

This section reviews SMR technologies, including distinctions between Generation III+ and Generation IV designs and cooling mechanisms, applications, fuel types, inherent safety features, siting, supply chains, nuclear waste management, and decommissioning. When determining which SMR technology to deploy, it is essential to understand these characteristics. Supply chains and nuclear waste management processes will be determined based on the selected SMR design.

SMR Technology and Design Distinctions

SMRs under development are considered Generation III+ or Generation IV reactors. The distinction between Generation III+ and Generation IV designs lies in the type of cooling mechanism utilized in the reactor. Generation III+ SMRs typically use pressurized water as the coolant. Generation IV SMRs utilize novel coolants such as helium, molten salt, sodium, or lead which allows them to operate at higher temperatures.[7] Figure 6 illustrates the distinction in Generation III+ and Generation IV designs by heat output; Gen III+ reactors can generate process heat at up to 320°C compared to Generation IV reactors which can potentially generate industrial heat of up to 950°C.[8]

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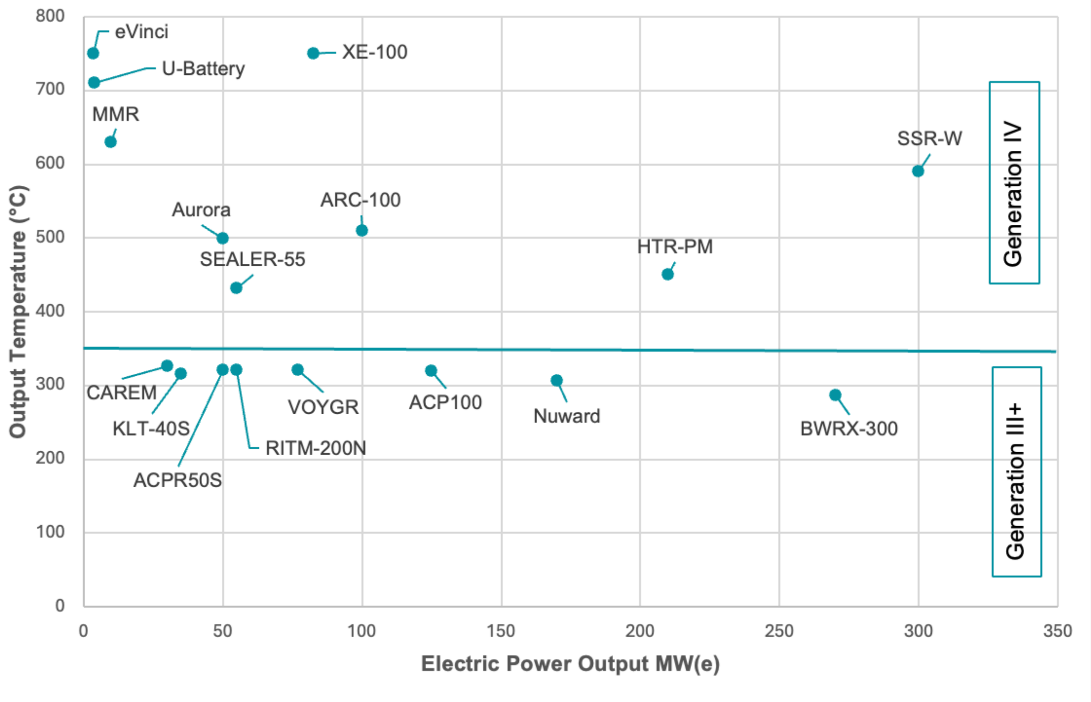
[7] Ondrej Muranksy & Mihail Ionescu. "Small Modular Reactors can be Built with Generation IV Reactor Designs," *ANSTO.* Australian Government, July 17, 2022, https://www.ansto.gov.au/news/small-modular-reactors-can-be-built-generation-iv-reactor-designs. (accessed April 18, 2024).

[8] Ibid.

Figure 6: Selected Generation III+ and Generation IV SMR Designs by Output Temperature and Power Generation Capacity



Source: Adapted by the authors from "SMRs can be Built with Generation IV Reactor Designs" [9]

The high-temperatures permit Generation IV reactors to be used both for standard low-emission electricity production, as well as for chemical manufacturing, cement production, water desalination, green hydrogen production, synthetic fuel production, fertilizer production, and primary metal manufacturing. Figure 7 categorizes SMR designs by cooling mechanism and provides further information about design generation, features, and potential applications.

[9] Ibid.

Figure 7: Summary of SMR Technologies by Cooling Mechanism

Type: Cooling Mechanism	Generation	Size	Notable Features	Potential Applications	Examples
Land-Based Water-Cooled	Gen III+	<300 MWe	These designs utilize Light Water Reactor (LWR) and Heavy Water Reactor (HWR) technologies. These have the advantage of utilizing the mature technology of existing large nuclear reactors in operation.[10]	Power Generation on land.	ACP100 is a 125 MWe integral pressurized water reactor (PWR) that started construction in China in 2021. It is on-track to be in commercial operation by 2026. CAREM is another integral PWR currently under construction in Argentina with a commercial operation target in 2026.[11]
Marine-Based Water-Cooled	Gen III+	<300 MWe	These designs utilize mature LWR and HWR technologies.	Power generation in a marine environment, such as immersible underwater power units or barge-mounted floating power units.[12]	The Russian floating barge, Akademik Lomonosov, is powered by two KLT-40S model SMRs.[13] It is the first SMR design to be connected to the grid.
High Temperature Gas-Cooled (HTGR)	Gen IV	<300 MWe	These designs can generate heat at much higher temperatures than water-cooled reactors, meaning better efficiency and dual use.	Power generation, cogeneration, industrial processes.	HTR-PM is a pebble bed HTGR that was connected to the grid in China in 2021.[14] HTTR is a Japanese prismatic HTGR in operation.[15]

[10] "The NEA Small Modular Reactor Dashboard," 19.
[11] "Advances in Small Modular Reactor Technology Developments," *A Supplement to: IAEA Advanced Reactors Information System (ARIS),* 2022 Edition. https://aris.iaea.org/Publications/SMR_booklet_2022.pdf
[12] Ibid*,* 5.
[13] Ibid, 113-114.
[14] "China's Demonstration HTR-PM Reaches Full Power," *New Nuclear.* World Nuclear News, December 9, 2022, https://world-nuclear-news.org/Articles/China-s-demonstration-HTR-PM-reaches-full-power. (accessed March 26, 2024).
[15] "Advances in Small Modular Reactor Technology Developments," 213.

Liquid Metal-Cooled Fast Neutron Spectrum	Gen IV	<300 MWe	These designs utilize fast neutron spectrum with liquid metal coolants that include sodium, lead-bismuth eutectic, and pure lead coolants.[16]	Power generation, cogeneration, industrial processes.	BREST-OD-300 is a lead-cooled fast neutron reactor under construction in Russia with a deployment target of 2026.[17] This SMR is part of the prototype project to develop a closed nuclear fuel cycle.
Molten Salt	Gen IV	<300 MWe	These comprise molten salt dissolved fuel and cooling designs. Advantages include increased safety due to a low-pressure single-phase coolant system used for molten salt, increased efficiency due to higher temperatures, and fuel cycle flexibility.[18]	Power generation, cogeneration, industrial processes.	The molten salt SMR designs are undergoing preliminary licensing and regulation in several countries including the United States, Canada, the United Kingdom, the Netherlands, and Denmark. CMSR in Denmark, LFTR in the USA, and THORIZON in the Netherlands utilize molten salt technology and are currently in the conceptual design stage.[19]
Micro Reactor	Gen III+ / Gen IV	<10 MWe	These designs use light water, helium, liquid metal, heat pipe, and molten salt cooling mechanisms.[20]	Power generation for remote off-grid locations and micro-grids. Can be used to restore power and heating after natural disasters (hospitals, water supply).[21]	Aurora is a micro reactor in a detailed design stage in the United States.[22] ELENA in Russia and MoveluX in Japan are both micro reactors in the conceptual design stage.[23]

16 Ibid, 5.
17 Ibid, 219-222.
18 "The NEA Small Modular Reactor Dashboard," 27.
19 "Advances in Small Modular Reactor Technology Developments," 4.
20 Ibid, 5.
21 Ibid, 5.
22 Ibid, 335.
23 Ibid, 4.

Source: Produced by the authors.

SMR Applications

Power Generation – The primary application of SMRs is power generation. SMRs offer a modular approach to grid expansion. First, many SMRs can be assembled in module factory fabrication before transportation to the deployment site, which can reduce construction time and costs.[24] Second, modular SMR units can be stacked on-site enabling gradual increases in grid capacity to match evolving energy demand. Thus, the modular nature of SMRs facilitates easier integration into diverse grid systems, enabling flexibility in deployment locations, allowing incremental growth in grid capacity, and potentially reducing transmission and distribution losses. SMRs can serve as reliable sources of firm dispatchable power, thereby contributing to grid stability. An important characteristic to consider, according to IAEA, when integrating SMRs into a power grid is that the SMR unit size must be less than ten percent of the total grid capacity.[25] For example, to support a 100 MWe SMR, the electric grid capacity must be greater than 1,000 MWe (1 Gigawatt of electricity). Countries that have grid sizes less than this limit must ensure grid capacity and stability by carrying out grid reinforcements.[26] Thus, the capacity of the existing grid is a key consideration when utilizing SMRs for electricity generation.

One promise of SMRs is that they can be integrated into smaller grids. To avoid overwhelming the grid, SMR units must be less than 10% of the total grid capacity if used for electricity generation.

Transportation – SMRs can also be utilized for diverse applications beyond electricity generation, including transportation. An example of this technology is Russia's SMR-equipped icebreakers operating in the Arctic Ocean to expand shipping routes to Asia and Europe.[27] SMR transportation projects require agreements and updates to nuclear conventions, as existing maritime and nuclear laws do not encompass floating SMRs.[28]

Desalination – SMRs can also be utilized for desalination. Integrating SMRs into desalination plants makes it possible to produce fresh water reliably and sustainably. The relatively compact nature of SMRs, as compared to large reactors, make them suitable for deployment near coastal regions where desalination plants are typically located. Their smaller size allows easier integration within desalination infrastructure.[29] Additionally, SMRs can provide a consistent and uninterrupted power supply, which is critical for energy-intensive desalination processes, and can ensure reliable freshwater production even in remote or off-grid areas.[30] This application of SMRs can help regions

[24] "Small Nuclear Power Reactors," *World Nuclear Association,* February 2024, https://www.world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/small-nuclear-power-reactors.aspx. (accessed March 26, 2024).
[25] "Deployment Indicators for Small Modular Reactors," *International Atomic Energy Agency.* September 17, 2018, https://www.iaea.org/publications/13404/deployment-indicators-for-small-modular-reactors. (accessed March 26, 2024).
[26] "Electric Grid Reliability and Interface with Nuclear Power Plants," *International Atomic Energy Agency*. IAEA Nuclear Energy Series No. NG-T-3.8, IAEA Vienna. 2012. *http://www-pub.iaea.org/MTCD/publications/PDF/Pub1542_web.pdf*
[27] Smruthi Nadig. "The Nuclear Icebreakers Enabling Drilling in Russia's Arctic," *Mining Technology*. August 15, 2023, https://www.mining-technology.com/features/the-nuclear-icebreakers-enabling-drilling-in-russias-arctic/?cf-view. (accessed March 26, 2024).
[28] Andrey Popov. "Russian Vision of the Problems and Prospects of the International Legal Framework in the Context of Small Modular Reactors and Transportable Nuclear Power Units." Nuclear Law, 45 – 54, January 1, 2022, https://doi.org/10.1007/978-94-6265-495-2_3.
[29] Patrycjusz Zarebski & Dominik Katarzynski. "Small Modular Reactors as a Solution for Renewable Energy Gaps: Spatial Analysis for Polish Strategy," *Qualitative Analysis and Environmental Sustainability Assessment of Energy,* Energies, 16(18), 6491, September 8, 2023, https://doi.org/10.3390/en16186491.
[30] Ibid, 5.

facing water scarcity meet freshwater needs while reducing dependence on traditional energy sources.

Industrial Processes – SMRs can be integrated into industrial processes. Given their smaller size and ability to generate high temperature heat, they can more easily be sited close to energy intensive industrial facilities, providing both a consistent supply of high temperature heat and low carbon electricity. SMRs can be tailored to meet specific process heat requirements, enabling efficient and cost-effective heat generation for various industrial applications such as chemical processing, oil refining, and manufacturing.[31] By utilizing SMR technology, heavy industry can reduce greenhouse gas emissions in hard to abate sectors, contributing to sustainable industrial development, including employment opportunities and other co-benefits.

Fuel

SMR designs utilize a diversity of fuel types, including LEU, HALEU, MOX fuel, thorium-based fuels, and others (see Figure 8). The type of fuel used in a reactor design is another factor for nations considering SMR deployment, since its availability will impact reactor operations, regulatory requirements, international partnerships, and spent fuel management.

[31] Ibid, 8.

Figure 8: Most Common Fuels Used in SMR Designs

Low-Enriched Uranium	LEU is the most widely used fuel type for all reactors and contains uranium enriched to less than 5% uranium-235 (U-235).[32] SMRs using LEU benefit from its commercial availability, established fuel fabrication processes, and proliferation resistance.
High-Assay Low-Enriched Uranium	HALEU refers to uranium enriched to levels slightly higher than conventional LEU, typically up to 20% U-235.[33] SMRs designed to utilize HALEU aim to achieve higher energy densities and longer fuel cycles compared to traditional LEU-fueled reactors.[34]
Mixed-Oxide Fuel	MOX fuel consists of a blend of uranium oxide and plutonium oxide, which allows for the utilization of surplus plutonium from dismantled nuclear weapons or spent fuel reprocessing.[35]
Thorium-based Fuel	Thorium-based fuels utilize thorium-232 as a fertile material, which can be converted into fissile uranium-233 through neutron capture and subsequent beta decay.[36]

Source: Produced by the authors.

Generation III+ SMRs typically utilize LEU or MOX fuels, which are designed to enhance fuel efficiency and reduce waste generation while maintaining compatibility with existing reactor technologies. Generation IV SMR designs use advanced fuel cycles to address long-term sustainability and safety concerns. These reactors may employ fuels such as MOX fuel, HALEU, and thorium, which offers advantages in terms of reduced nuclear proliferation risks, improved waste characteristics, and enhanced resource availability.[37] Additionally, some Generation IV designs include fast-neutron reactor technology and advanced fuel concepts like molten salt moderated solutions, which can operate at higher temperatures, increasing overall efficiency and enabling diverse applications.

The type of fuel used in a reactor design is another consideration for nations assessing SMR deployment, since its availability will impact reactor operations, regulatory requirements, international partnerships, and waste management.

[32] "Small Nuclear Power Reactors".
[33] Lucy Ashton. "Fueling the Future: Building Fuel Supply Chains for SMRs and Advanced Reactors," *International Atomic Agency,* February 5, 2024, https://www.iaea.org/bulletin/fuelling-the-future-building-fuel-supply-chains-for-smrs-and-advanced-reactors. (accessed March 26, 2024).
[34] Ibid.
[35] Jesus Rosales, Juan-Luis Francois, & Carlos Garcia. "Neutronic Assessment of a PWR-Type SMR Core with TRISO Particles Using Mixed-Oxid Fuel Strategies," *Progress in Nuclear Energy,* Volume 154, 104470, December 2022. https://doi.org/10.1016/j.pnucene.2022.104470
[36] Reza Akbari-Jeyhouni, Dariush Rezaei Ochbelagh, Jose Maiorino, Francesco D'Auria, & Giovanni Laranjo de Stefani. "The Utilization of Thorium in Small Modular Reactors – Part I: Neutronic Assessment," *Annals of Nuclear Energy*, Volume 120, 422–430 (2018). https://doi.org/10.1016/j.anucene.2018.06.013.
[37] "Advances in Small Modular Reactor Technology Developments," 378.

Inherent Safety Features

Advanced SMR designs also incorporate several inherent safety features to mitigate the risk of accidents and enhance overall reactor safety. They utilize passive safety systems that rely on natural phenomena such as gravity, natural circulation, and inherent material properties rather than active systems or operator intervention.[38] Advanced SMR designs can also incorporate inherent reactivity control mechanisms to regulate the rate of nuclear reactions and prevent the onset of criticality accidents.[39] Lastly, these SMR designs have robust containment structures that can withstand extreme external events such as earthquakes, floods, and aircraft impacts.[40] These structures provide multiple layers of defense to contain radioactive materials and prevent the release of hazardous substances into the environment, even under severe accident scenarios.[41] The inherent safety features of advanced SMR designs contribute to enhanced safety margins and reduce the risk of accidents, which can improve public acceptance of SMRs as a safe and sustainable power generation option.

SMR designs integrate inherent safety features to reduce the risk of accidents and can contribute to improved public acceptance of these reactors as safe and sustainable power generation options.

Siting

Siting requirements vary depending on the SMR design. An SMR can have land-based, marine-based, mobile, or multi-module configurations. Acquiring land rights in accordance with safety and environmental regulations is a prerequisite for the siting process.[42] This is followed by SMR design selection and licensing for SMRs in accordance with the land rights.

The compact size of SMRs presents a significant advantage over large reactors, enabling their deployment in diverse locations, including decommissioned coal plants and other energy infrastructure sites. This approach aims to leverage existing infrastructure and workforce expertise, providing economic benefits while transitioning to cleaner energy sources.[43] Despite the potential advantages, challenges remain, including the need for extensive testing and demonstration of SMRs, as well as addressing issues related to decontamination, nuclear safety, waste disposal, and public opinion.

[38] Miklos Gaspar. "Technology Neutral: Safety and Licensing of SMRs," *International Atomic Energy Agency,* August 17, 2020, https://www.iaea.org/newscenter/news/technology-neutral-safety-and-licensing-of-smrs. (accessed March 26, 2024).
[39] Ibid.
[40] "Containment Systems: Working Group on Design and Safety Analysis," *International Atomic Energy Agency,* December 2023, https://www.iaea.org/sites/default/files/24/02/smr_rf_phase_3_report_-_containment_systems.pdf. (accessed March 26, 2024).
[41] Ibid, 6.
[42] Sichen Gao, Gordon Huang, Xiaoyue Zhang, Jiapei Chen, & Dengcheng Han. "SMR Siting for the Electricity System Management," *Journal of Cleaner Production*, Volume *297*, 126621, (2021). https://doi.org/10.1016/j.jclepro.2021.126621.
[43] Nicholas Watson & Nikoleta Morelova. "Repurposing Fossil Fuel Power Plant Sites with SMRs to Ease Clean Energy Transition," *International Atomic Energy Agency,* June 16, 2022, https://www.iaea.org/newscenter/news/repurposing-fossil-fuel-power-plant-sites-with-smrs-to-ease-clean-energy-transition. (accessed March 26, 2024).

Supply Chain

The SMR supply chain refers to all processes involved in SMR deployment from design to engineering, procurement, construction, operations, and the fuel cycle. Many stakeholders and suppliers are involved. Thus, contracts and memoranda of understanding between partners must be in place to develop the SMR supply chain in the early stages of the project. SMR supply chains are still quite limited, given that most designs are FOAK and are still in demonstration phases. Supply chains can only be considered mature after construction of a FOAK unit is in progress and an orderbook is established for NOAK units, which is taken as a credible signal to suppliers.[44]

The development of the supply chain is different for each design and vendor country. For example, Russia is offering an integrated approach with a full cycle supply chain to export SMRs to other countries. This supply chain strategy includes reactor construction, operation, fuel supply, talent training, protection of the reactor, and nuclear waste management. The U.S. and its partners are working to strengthen international supply chains through commitments like the Sapporo Five, which will coordinate investment of $4.2B USD in the uranium and fuel enrichment supply chain across the United States, Japan, United Kingdom, Canada, and France. This will help diversify supply-side options for countries interested in SMRs, particularly for Generation IV reactors that utilize more diverse fuel types.

Importing countries should be aware of potential challenges posed by underdeveloped supply chains for each reactor technology, as it has a direct impact on the feasibility and timeline of SMR deployment and energy independence.

Nuclear Waste Management

SMRs, like large reactors, produce radioactive waste during operations as well as during the decommissioning process. This waste is broadly categorized as low-level waste (LLW), intermediate-level waste (ILW), or high-level waste (HLW). LLW contains small amounts of short-lived radioactivity, does not require shielding during handling or transportation, and can be disposed in near surface facilities.[45] ILW has a higher level of radioactivity than LLW and requires shielding during storage and disposal processes.[46] HLW, which refers to spent nuclear fuel (SNF), occurs from burning of uranium fuel in a nuclear reactor and requires shielding and cooling.[47] Thus, safe methods of final disposal must be applied to each category.

The management and disposal of nuclear waste from SMRs requires tailored approaches due to the unique characteristics of these reactors and the waste they generate. Design considerations significantly impact the composition and volume of radioactive waste. SMRs experience increased neutron leakage, particularly notable in smaller reactor designs.[48] Neutron leakage refers to the escape of neutrons from a nuclear reactor's core into surrounding materials or the environment that then become radioactive, rather than contributing to sustained nuclear reactions within the

[44] "The NEA Small Modular Reactor Dashboard," 26.
[45] "Radioactive Waste Management," *Nuclear Waste Disposal - World Nuclear Association*, January 2022, https://world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-wastes/radioactive-waste-management.aspx. (accessed April 18, 2024).
[46] Ibid.
[47] Ibid.
[48] Lindsay Krall, Allison Macfarlane, & Rodney Ewing. "Nuclear Waste from Small Modular Reactors," *Proceedings of the National Academy of Sciences*, *119*(23), (2022). https://doi.org/10.1073/pnas.2111833119.

reactor.[49] Mitigating neutron leakage involves design adaptations such as enriched fuel, neutron reflectors, or modified coolant types.[50] Most SMR designs incorporate one or all three strategies to enhance the core neutron economy.[51] As SMR designs become increasingly complex, it is imperative that all future designs integrate these strategies to mitigate neutron leakage.

SMRs pose distinct challenges for existing nuclear waste management processes, given the more complicated waste streams that they produce, in terms of composition and volume, as well as geographic decentralization of SMR sites.

The chemical properties of SMR coolants, such as molten salts or liquid metals, introduce additional complexities to waste management. For example, molten salt reactors release gaseous fission products and retain soluble fission products and actinides (radioactive metallic elements), demanding specialized handling to prevent environmental contamination.[52] The radiotoxicity of SMR waste depends on factors like fuel burnup and the concentration of fissile isotopes like plutonium.[53] Actinides contribute significantly to long-term risks, necessitating careful management strategies.[54]

Nuclear waste disposal from SMRs demands careful evaluation of reactor design, operational parameters, and waste characteristics to ensure safe and effective long-term storage or disposal solutions. Specialized handling and disposal methods are essential to mitigate the environmental and safety risks associated with SMR waste streams. Further research is imperative to develop effective waste management strategies tailored to the distinct characteristics of SMR waste, ensuring long-term safety and environmental protection.

Given the unique challenges of SMR nuclear waste, experts have presented four main strategies for nuclear waste management, summarized in Figure 9.

[49] John Kosowatz. "SMRs Gain Acceptance, but Waste Issues Remain," *ASME*, July 21, 2022, https://www.asme.org/topics-resources/content/energy-blog-small-nuclear-reactors-are-promising,-but-disposal-issues-remain. (accessed March 26, 2024).
[50] Krall, et. al, "Nuclear Waste from Small Modular Reactors," 2.
[51] Ibid, 2.
[52] Ibid, 6.
[53] Ibid, 7.
[54] Ibid, 8.

Figure 9: Summary of Waste Management Options for SMRs

Dry Cask Storage	Geological Disposal
• Stores nuclear waste on-site. • Currently used to store waste for large nuclear reactors and can be used for SMR waste streams. • **SMR waste storage requires evaluation of canister spacing and thermal management due to elevated neutron leakage and decay heat levels.**	• Disposal of nuclear waste in a deep underground repository with stable geological formations. • Finland is in the construction process of a geological disposal facility with operation license application under review. France, Russia, Sweden, and Switzerland have planned projects with selected sites. Further R&D is required regarding suitability for SMR waste. • **SMR waste disposal requires managing decay heat, canister spacing, and thermal considerations, along with employing extra barriers to prevent long-lived isotopes from escaping into the environment.**
Reprocessing Facility	**Regional Waste Management Program**
• A facility designed to extract usable materials from SNF for reuse while managing radioactive waste. • Currently used in France, Japan, and Russia. • **SMR waste reprocessing requires evaluation of heightened chemical reactivity of the fuel, leading to potential increased reactivity levels during reprocessing.**	• A reprocessing facility in one country, where the nuclear waste of all countries in the region is reprocessed. • Proposed but not currently politically feasible. • **SMR waste reprocessing requires evaluation of potential increased reactivity levels.**

Source: Produced by the authors.

Dry Cask Storage – This technique stores nuclear waste on-site. The dry cask storage is currently utilized for large nuclear reactors and can also be used for SMRs. This strategy must consider the higher levels of neutron leakage and decay heat to ensure that appropriate dry cask technology is used. Canister spacing and thermal management must be evaluated for this method.

Geological Disposal – The process involves inserting SNF into iron inserts, which are then placed within five-centimeter-thick copper canisters.[55] Subsequently, the entire waste package is enveloped by bentonite clay and positioned at a depth of approximately 500 meters in groundwater-saturated granitic rock.[56] Each component in this strategy serves a specific role in delaying the release of radionuclides. Engineered barriers are crafted to contain the fuel within the canister; in case of a breach in one level of protection, the next layer protects from the release of radionuclides.[57] A geological disposal facility is under construction in Finland.[58] France, Russia, Sweden, and Switzerland have planned projects with selected sites.[59] Due to decay heat from SNF, canister spacing and thermal management must be addressed for SMR waste before disposal, as well as additional barrier materials to prevent long-lived isotopes from entering into the environment. Thus, due to their high chemical reactivities, SMR fuels will need to be processed into a waste form suitable for geologic disposal.[60] Geological waste disposal for SMRs that includes treatment, conditioning, and packaging practices can introduce higher costs to the back end of nuclear fuel cycles, potential radiation exposure, and fissile material proliferation pathways.[61] Thus, geological storage of SMR nuclear waste requires further research and development, as well as government regulations and siting approvals.

Reprocessing Facility – This strategy begins with receiving SNF from nuclear power plants; then, the spent fuel undergoes several stages of treatment. Initially, the fuel is subjected to chemical separation techniques, such as solvent extraction or Plutonium Uranium Extraction (PUREX), to separate reusable fissile materials like uranium and plutonium from the remaining waste.[62] These recovered materials can be reused as fuel in nuclear reactors. The remaining waste is vitrified or solidified into a glass-like matrix for long-term disposal.[63] Nuclear reprocessing facilities have been developed in France, Japan, and Russia. This strategy can be used for nuclear waste coming from SMRs and large NPPs. One key consideration for using SMRs' spent fuel in reprocessing facilities is the high chemical reactivity of the fuel which can produce higher levels of reactivity during reprocessing. There is limited data available to quantify the waste consequences associated with reprocessing nuclear waste from SMRs.

Regional Waste Management Program – This strategy proposes the development of a reprocessing facility in one country, where the nuclear waste of all countries in the region will be reprocessed. This very challenging process requires research and development, siting, regulatory

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[55] Rodney Ewing. "*Reset of America's Nuclear Waste Management Strategy and Policies,"* Stanford University Center for International Security and Cooperation, George Washington University Elliott School of International Affairs, October 15, 2018. https://fsi9-prod.s3.us-west-1.amazonaws.com/s3fs-public/reset_report_2018_final.pdf
[56] Ibid, 74.
[57] Ibid, 74.
[58] "Storage and Disposal of Radioactive Waste," *World Nuclear Association,* 2023, https://world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-waste/storage-and-disposal-of-radioactive-waste.aspx. (accessed March 26, 2024).
[59] Ibid.
[60] Krall, et. al, "Nuclear Waste from Small Modular Reactors," 10.
[61] Ibid, 10.
[62] "Processing of Used Nuclear Fuel," *World Nuclear Association,* December 2020, https://world-nuclear.org/information-library/nuclear-fuel-cycle/fuel-recycling/processing-of-used-nuclear-fuel.aspx. (accessed March 26, 2024).
[63] Ibid.

approvals, and international agreements with SMR-specific considerations addressed above. To date, the regional waste management program is in the discussion stage. For the program to proceed to the next stage, countries in the region would need to draft multilateral agreements and identify a country where the facility would be constructed.

Decommissioning

As SMRs vary in size, uses, fuel type, waste management, and other technical aspects, decommissioning approaches will also vary for different SMR designs. Due to the modular nature of SMRs, such as factory assembly and transportation to the site, the modular units could be returned to the factory for refueling or decommissioning.[64] This feature of SMRs will allow standardization, cost, and scope of work reduction in the decommissioning process. Furthermore, knowledge of fuel and steel types utilized in manufacturing facilities allows for advanced planning for waste management and decommissioning strategies, thus reducing the length of the decommissioning process.[65] Therefore, beginning waste management and decommissioning planning early in the design stages is critical. Research on the SMR decommissioning process is limited, which showcases the early stage of SMR development.

[64] Joanne Liou. "Decommissioning by Design: How Advanced Reactors are Designed with Disposal in Mind," *International Atomic Energy Agency,* July 18, 2023, https://www.iaea.org/bulletin/decommissioning-by-design-how-advanced-reactors-are-designed-with-disposal-in-mind. (accessed March 26, 2024).
[65] Ibid.

Regulation and Governance

This section reviews regulation and governance related to SMR deployment, including domestic nuclear legislation, international conventions related to nuclear safety, security, safeguards and liability, establishment of a regulatory body and framework, and considerations for licensing and oversight, as well as nuclear export policies.

Nuclear Legislation, International Conventions, and Establishment of a Regulatory Body

When a country decides to embark on the development of its civilian nuclear power program, it is, above all, imperative to formulate comprehensive nuclear legislation. This legislation should address every domestic concern surrounding the adoption of civilian nuclear power and adhere to the principles set forth in international conventions on nuclear safety, security, safeguards and liability. It should also establish an independent regulatory body.

Nuclear Safety, Security, Safeguards and Liability

- **Nuclear Safety** – The achievement of proper operating conditions, prevention of accidents or mitigation of accident consequences, resulting in protection of workers, the public and the environment from undue radiation hazards.[66]
- **Nuclear Security** – The prevention of, detection of, and response to, criminal or intentional unauthorized acts involving or directed at nuclear materials, other radioactive material, associated facilities, or associated activities.[67]
- **Safeguards** – Through a set of technical measures, or Safeguards, the IAEA verifies that States are honoring their international legal obligations to use nuclear material and technology only for peaceful purposes. The objective of IAEA safeguards is to deter the spread of nuclear weapons by the early detection of the misuse of nuclear material or technology. [68]
- **Nuclear Liability** – To assure prompt, meaningful, and equitable compensation for nuclear damage suffered by third parties resulting from a nuclear incident at a nuclear installation or during the transport of nuclear material to and from nuclear installations by channeling strict liability exclusively to the operator and channeling all claims to one competent court.[69]

Adherence to international conventions governing nuclear safety, security, safeguards and liability is paramount for any nuclear installation, and SMRs are no exception. These conventions assure compliance with international standards and provide critical protections to states, people, and the environment, and assign responsibility and liability in the case of an incident (see Figure 10).

[66] "IAEA Nuclear Safety and Security Glossary: Terminology Used in Nuclear Safety, Nuclear Security, Radiation Protection and Emergency Preparedness and Response," *International Atomic Energy Agency,* Non-Serial Publications 2022 Edition, 2022, https://www-pub.iaea.org/MTCD/Publications/PDF/IAEA-NSS-GLOweb.pdf.
[67] Ibid.
[68] "IAEA Safeguards Glossary," *International Atomic Energy Agency*, International Nuclear Verification Series No. 3 (Rev.1), 2022, https://www-pub.iaea.org/MTCD/publications/PDF/PUB2003_web.pdf.
[69] Interview. April 25, 2024.

Figure 10: Nuclear Safety, Security, Safeguards, and Liability Instruments

Selected Examples of International Instruments on Nuclear Safety, Security, Safeguards and Liability	
Nuclear Safety and Security	• Convention on Nuclear Safety (1994) • Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management (1997) • Convention on Early Notification of a Nuclear Accident (1986) • Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency (1986) • Convention on the Physical Protection of Nuclear Material (1979) • Amendment to the Convention on the Physical Protection of Nuclear Material (2005)
Safeguards	• Treaty on the Non-Proliferation of Nuclear Weapons • Comprehensive Safeguards Agreements with the IAEA • Zangger Committee • Wassenaar Arrangement • Nuclear Suppliers Group
Nuclear Liability	• 1963 Vienna Convention on Civil Liability for Nuclear Damage (IAEA, 1963) • Protocol to Amend the Vienna Convention on Civil Liability for Nuclear Damage (IAEA, 1997) • Paris Convention on Third Party Liability in the Field of Nuclear Energy of 2004 (OECD, 2004) and the Brussels Convention on Civil Liability for Nuclear Damage (OECD, 2004) • Joint Protocol Relation to the Application of the Vienna Convention and the Paris Convention (1988) • Convention on Supplementary Compensation for Nuclear Damage (IAEA, 1997). *This provides a supplementary compensation fund above the operator's liability limit which is based on international financial solidarity where nuclear and wealthy states pay 95% of this fund.*

Source: Produced by the authors.

Safety and security conventions aim to ensure that nuclear installations are protected against internal threats, such as facility malfunctions and emission of radiation outside the premises, as well as external threats, such as theft of radioactive materials, unauthorized persons, acts of terrorism or cyber-attacks. Existing conventions can be applied to SMRs, though the potential deployment of floating power plants presents issues within maritime law and nuclear security that require further study. Safeguards are intended to ensure peaceful use of nuclear facilities and materials. The Nuclear Non-Proliferation Treaty (NPT) lies at the heart of international efforts to mitigate the risk of proliferation. It obligates non-weapons contracting states to refrain from acquiring nuclear weapons in exchange for access to peaceful nuclear technology. Based on the NPT, countries must conclude comprehensive safeguards agreements with the IAEA to accept IAEA safeguards on all its peaceful nuclear activities.[70] Additionally, the Zangger Committee, the

[70] "More on Safeguards Agreements," *International Atomic Energy Agency.* https://www.iaea.org/topics/safeguards-legal-framework/more-on-safeguards-agreements. (Accessed March 26, 2024).

Wassenaar Arrangement, and the Nuclear Suppliers Group are agreements or groups among nuclear countries aimed at controlling the export of sensitive technologies to prevent their misuse for nuclear proliferation.

Nuclear liability aims to ensure compensation is available for nuclear damage caused by a nuclear incident at an installation or during transport of nuclear materials. Conventions for nuclear liability provide a legal framework to assign liability. Under current conventions liability for nuclear damage is assigned exclusively to the operator of a nuclear installation. As a result, operators are obligated to participate in liability insurance to ensure they can meet their liability obligations in the event of an accident. Should the insurance coverage prove insufficient in an accident, governments are expected to provide additional compensation. While suppliers or vendors could potentially be sued for claims resulting from a nuclear incident, liability insurance for them is generally not available on the market. Therefore, they typically require assurance that the recipient country has a nuclear liability system in place and has ratified the relevant conventions or provided additional contractual guarantees to shield them from liability.[71] Given that SMRs present many of the same risks as large NPPs, there is limited justification for reducing the size of this fixed amount for SMRs.

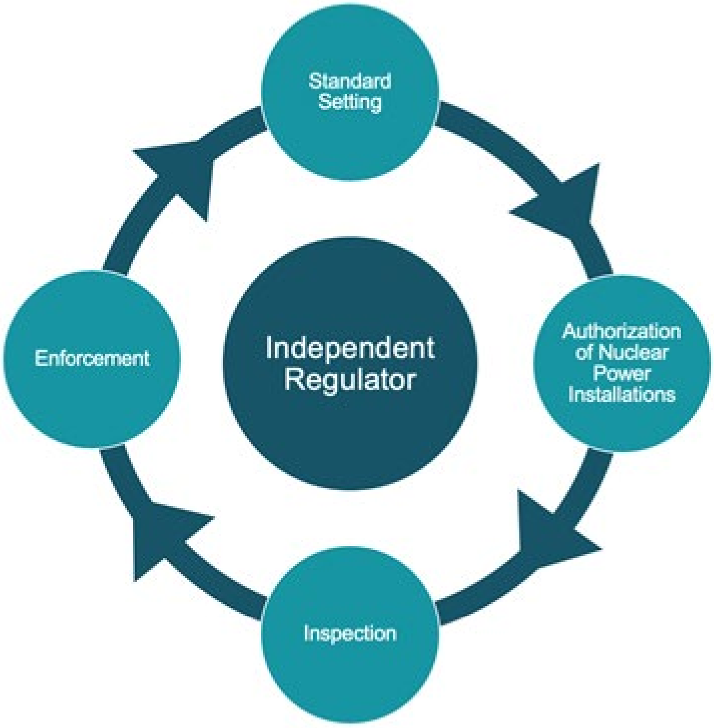
Notably, given the existence of multiple treaties and the fact that many countries have not yet become parties, liability surrounding the transport of nuclear materials remains an issue with significant ambiguities. Several factors contribute to these ambiguities, including the origin or destination of the shipment and the type of nuclear material involved.[72] The diverse fuel types used by different SMR designs add complexities to this issue. Despite its importance, this matter remains understudied and necessitates additional attention by countries when establishing nuclear legislation.

Given that SMRs present many of the same risks as large NPPs, the existing safety, security and liability principles generally apply to SMRs. However, new SMR designs introduce certain ambiguities that require additional attention from countries when establishing nuclear legislation.

Furthermore, enabling legislation should establish and determine the functions of the regulatory body to ensure that nuclear safety and security requirements are implemented and enforced. It needs to be effectively independent to avoid influence from individuals or entities advocating for nuclear energy within the government. An independent regulator broadly has four primary functions: 1) standard setting; 2) licensing and authorization of nuclear installations; 3) inspection, and 4) enforcement.[73] The regulatory body is responsible for ensuring that the entire lifecycle of NPPs from reactor design and site selection to construction, operations, waste management, decommissioning, and accident response aligns with the regulatory framework (see Figure 11). A reliable and transparent regulator demonstrates strong governmental commitment, engages stakeholders, and provides confidence to investors, vendors, and society for new civilian nuclear power infrastructure.

[71] Interview, April 25, 2024.
[72] Nathalie Horbach. "Nuclear Liability for International Transport Accidents under the Modernized Nuclear Liability Conventions: An Assessment," *International Journal of Nuclear Law*, 1(2), 189-198. (2006).
[73] Interview. April 25, 2024.

Figure 11: Functions of an Effectively Independent Regulator



Source: Produced by the authors.

International assistance is available to countries lacking experience in developing legal and regulatory frameworks, as well as nuclear infrastructure. Most prominently, the IAEA has developed a Milestone Approach that provides a structured roadmap for any member country interested in initiating a nuclear power program.[74] The roadmap outlines three progressive phases: 1) key considerations before a decision to launch a nuclear power program; 2) legal and regulatory preparatory work; and 3) activities to contract, license, and construct a nuclear power plant. It includes nineteen nuclear infrastructure considerations, including the electrical grid, emergency planning, and the nuclear fuel cycle. During the process of developing a civilian nuclear power program, the IAEA provides training and expert advice, conducts reviews, and develops country-specific integrated work plans.[75]

With a staff of over forty experts dedicated to all aspects of SMRs, the IAEA has launched an SMR platform that serves as a hub for technical assistance, knowledge dissemination, and research coordination to support member countries and expedite the development and deployment of SMRs. Additionally, through its Nuclear Harmonization and Standardization Initiative (NHSI) regulatory track, the IAEA aims to minimize redundancy in regulatory reviews across member

[74] "Milestones Approach," *International Atomic Energy Agency, October 13, 2017,* https://www.iaea.org/topics/infrastructure-development/milestones-approach. (accessed March 26, 2024).
[75] Ibid.

states, reduce the necessity for design alterations due to regulatory disparities, and establish a common regulatory framework on SMRs while respecting national sovereignty.[76]

Apart from the IAEA, regional inter-governmental nuclear organizations such as the Western European Association of Nuclear Regulators (WENRA) bring together the heads of nuclear regulatory authorities in the region and play a role in facilitating knowledge exchange on nuclear regulation, including SMRs. Notably, Poland's transition from observer to full member of WENRA in 2023 signifies its commitment to enhancing its regulatory proficiency by actively participating in working groups focused on reactor standardization and radioactive waste.[77]

In terms of bilateral collaboration, well-established nuclear regulatory bodies in developed nations such as the United States, South Korea, Canada, and the United Kingdom are actively supporting nuclear capacity-building efforts through bilateral collaborations. These collaborations include joint technical review of SMR designs, vendor engagement, and other knowledge-sharing platforms. For example, in 2021, the US State Department launched the Foundational Infrastructure for Responsible Use of Small Modular Reactor Technology (FIRST) program. Complementing the IAEA's Milestone Approach, this program offers SMR-specific capacity-building support ranging from site selection to waste management for nearly twenty countries.[78] By leveraging the expertise of nuclear-experienced countries, countries can expedite the development of robust regulatory frameworks tailored to their own circumstances. Figure 12 summarizes existing programs dedicated to supporting SMR regulation and development.

Figure 12: Selected Resources for Deploying SMRs

IAEA	IAEA has a dedicated SMR platform to provide members with technical assistance, knowledge sharing, and research coordination. The IAEA also provides assistance and guidance through its Milestones Approach and its Nuclear Harmonization Standardization Initiative.
WENRA	WENRA facilitates knowledge exchange on nuclear regulation, including SMRs. Most recently, Poland benefited from its support.
FIRST	This U.S.-driven program offers SMR-specific capacity-building support ranging from site selection to waste management for nearly twenty countries.

Source: Produced by the authors.

[76] "The SMR Platform and Nuclear Harmonization and Standardization Initiative (NHSI)," *International Atomic Energy Agency,* April 12, 2023, https://www.iaea.org/services/key-programmes/smr-platforms-nhsi. (accessed March 26, 2024).
[77] "From Observer Status to Full Membership – Poland in WENRA," *National Atomic Energy Agency,* Polish Government, November 14, 2023, www.gov.pl.web/paa-en/from-observer-status-to-full-membership--Poland-in-wenra. (accessed March 26, 2024).
[78] "Foundational Infrastructure for Responsible Use of Small Modular Reactor Technology: FIRST Program Partners," *FIRST,* https://www.smr-first-program.net/partners/. (accessed March 26, 2024).

Licensing and Oversight

Licensing is one of the major responsibilities of a regulator. The licensing process for SMRs largely mirrors the established procedures for traditional large-scale NPPs, albeit with certain adaptations to accommodate the novel technologies and features of SMRs.

➢ **Pre-application Engagement**

The licensing process starts with pre-application engagement. During this phase, the regulator and the SMR developer exchange information on technology specifications and regulatory requirements. In countries seeking to import SMRs, this stage entails regulatory authorities engaging with domestic sponsors. It is worth noting that the reduced size of SMRs does not necessarily equate to simplified regulatory processes under an existing regulatory framework. SMRs can introduce novel features such as integration of primary system components into the reactor pressure vessel and greater reliance on passive safety systems. Since existing regulatory provisions do not address these novel features, they must be justified by designers and accepted by regulators and may lead to delays in the licensing process relative to more established reactor designs. Additionally, the growing use of digital automation and remote control in many SMR designs, while it may offer certain safety advantages for plant operators, necessitates an update in the regulator's understanding of cybersecurity risks associated with SMRs.[79] Finally, among SMR designs, non-light water designs face greater regulatory scrutiny due to the lack of existing regulatory studies.[80]

While the adoption of pre-application engagement is not universal, it is seen as beneficial as it serves multiple purposes: (1) enabling the developer to identify potential licensing barriers and make necessary modifications prior to formal application submissions; (2) familiarizing the regulator with emerging technologies and identifying gaps in regulatory frameworks; and (3) facilitating resource planning and scheduling for subsequent licensing procedures, increasing regulatory efficiency overall.

The smaller size of SMRs does not equate to a simplified regulatory process under the existing regulatory framework. Novel technologies and features may extend timelines for regulatory approval.

➢ **Licensing**

After pre-application engagement, an SMR project enters its formal licensing process. This process differs by country.

The United States – The Nuclear Regulatory Commission (NRC) is the independent regulator of the nuclear power industry in the United States and is considered to be the gold standard for civilian nuclear power regulation. Historically, the issuance of construction and operation licenses in the U.S. has followed a sequential two-step process, as outlined in the Code of Federal Regulations (CFR) 10 Part 50. This process involves granting construction permits based on preliminary safety

[79] Cristina Siserman-Gray & Guy Landine. "Cybersecurity for Small Modular Reactors (SMRs): Regulatory Challenges and Opportunities," *Pacific Northwest National Laboratory (PNNL),* 2023, https://resources.inmm.org/sites/default/files/2023-07/finalpaper_378_0512115036.pdf.
[80] M.V.Ramana, Laura Hopkins, & Alexander Glaser. "Licensing Small Modular Reactors," *Energy*, Volume 61, 55-564, November 2013. https://doi.org/10.1016/j.energy.2013.09.010.

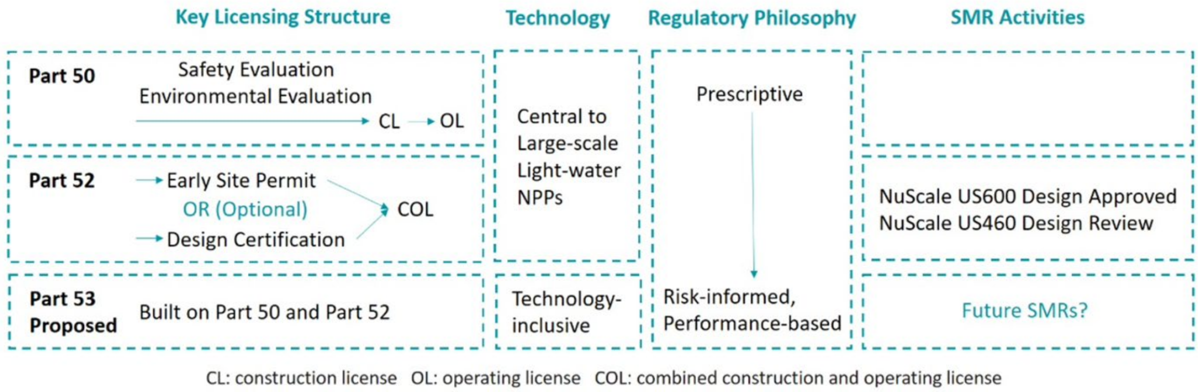
evaluation from both safety and environmental standpoints, followed by operating licenses upon completion of construction, final safety analysis, and other operational considerations. In 1989, the NRC issued Part 52 to improve efficiency and predictability, enabling applicants to pursue combined construction and operation licenses (COLs).[81] Early site permit and standard design certification are two other licensing options under Part 52. Reactor vendors or builders may obtain them at an earlier stage and later reference them in applications for COLs, thus expediting the licensing process. Under Part 52, U.S. SMR developer, NuScale, successfully received certification of its US600 12-unit 50 MWe light-water SMR design by the NRC in September 2020. This marked a significant milestone, making it the first and only SMR to date to have its design certified in the United States.[82]

Over time, the U.S. nuclear regulatory philosophy has evolved from prescriptive mandates to a risk-informed, performance-based approach. In this context, *risk-informed* entails identifying and focusing on critical systems for damage prevention, while *performance-based* allows designers the flexibility to determine how safety objectives are achieved rather than dictating specific methods.[83] This transition has not only improved regulatory efficiency but also bolstered nuclear safety. Under the Nuclear Energy Innovation and Modernization Act, the NRC is currently finalizing the draft proposed Part 53 rulemaking package. Part 53, designed to accommodate various Generation IV technologies, represents a departure from the LWR-centric regulations of existing Part 50 and Part 52. This shift would reduce the need for non-LWR applicants to seek exemptions from LWR-specific requirements and thus ease licensing.

Part 53 offers two frameworks. Framework A embraces the risk-informed, performance-based approach, utilizing Probabilistic Risk Assessment (PRA) as a primary tool. PRA employs mathematical techniques to assess the likelihood of component failures leading to the release of radioactive material.[84] In contrast, Framework B adopts a more traditional deterministic approach. It was motivated by stakeholder feedback, suggesting that certain reactor vendors may initially target international markets where licensing frameworks align more closely with traditional regulatory paradigms. Framework B could thus smooth domestic licensing in host countries of SMRs.[85] The ongoing debate surrounding Framework B underscores a short-term tension between advancing regulatory innovations within the United States and harmonizing global regulatory practices regarding SMR technologies. Figure 13 summarizes NRC Licensing Rules.

[81] Burns, S. G. "Looking Backward, Moving Forward: Licensing New Reactors in the United States," *Nuclear Law Bulletin*, 2008(1), 7–29. July 8, 2008.
[82] "Design Certification - NuScale US600," *United States Nuclear Regulatory Commission*, https://www.nrc.gov/reactors/new-reactors/smr/licensing-activities/nuscale.html. (accessed March 26, 2024).
[83] "Can Part 53 be the Nuclear Licensing Rule We Need?," *The Breakthrough Institute,* 2022, https://thebreakthrough.org/blog/can-part-53-be-the-nuclear-licensing-rule-we-need. (accessed March 26, 2024).
[84] "Nuclear Regulatory Commission Charts a Path Forward on Part 53," *The Breakthrough Institute,* 2024, https://thebreakthrough.org/issues/energy/nuclear-regulatory-commission-charts-a-path-forward-on-part-53. (accessed March 26, 2024).
[85] "SRM-SECY-23-0021: Proposed Rule: Risk-Informed, Technology-Inclusive Regulatory Framework for Advanced Reactors," *United States Nuclear Regulatory Commission,* 2024, https://www.nrc.gov/docs/ML2406/ML24064A039.pdf. (accessed March 26, 2024).

Figure 13: Overview of NRC Licensing Rules



Source: Produced by the authors.

Countries Seeking to Import SMRs from U.S. Vendors – Countries with limited regulatory expertise generally issue construction and operation licenses separately, with site and design evaluation reports formally reviewed after the investor applies for a construction license. Certification of an SMR design by the NRC generally assures its safety in countries that plan to import SMRs from U.S. vendors, though nations may also undertake additional assessments to align with domestic nuclear safety standards and enhance understanding of the technology for effective oversight during the project lifespan. This can consume substantial resources. Developing a risk-informed, performance-based regulatory framework for non-light water SMRs presents additional challenges in these countries as it requires significant experience with power reactors and quantitative techniques to estimate accident probabilities and consequences. For this reason, light-water SMRs may be easier to assess given familiarity of the technology. Nevertheless, the regulatory advancements pioneered by the NRC may help streamline licensing procedures for other countries in the long term.

The licensing process for SMRs differs by country. For regulators in a country seeking to import SMRs, it is beneficial to engage in knowledge exchange with regulators in the vendor country. It is equally important to ensure alignment with country-specific nuclear safety standards.

Russia and China – In Russia and China, where SMR power plants have been built, construction and operation licenses are issued separately. The fact that these projects are sponsored by state-owned enterprises allows for more efficient coordination in the licensing procedures between regulatory bodies and project developers than in the United States, where private companies develop a wide range of SMR designs.[86]

[86] "Licensing and Project Development of New Nuclear Plants," *World Nuclear Association*, 2015, https://www.world-nuclear.org/uploadedfiles/org/wna/publications/working_group_reports/wna_report_nuclear_licensing.pdf. (accessed March 26, 2024).

- **Oversight**

Similar to large-scale NPPs, during the construction process of an SMR plant, the regulator is tasked with conducting inspections to verify that the as-built facility adheres to the construction license. Throughout a reactor's operational lifespan, the regulatory body consistently conducts inspections, measurements, and performance assessments, promptly responding to any decline in performance of the licensees. Additionally, it oversees the decommissioning of nuclear facilities until residual radioactivity levels are reduced to a point allowing for the termination of the license.

Vendor Countries' Nuclear Export Policies

For countries seeking to import SMRs from abroad, it is important to examine the vendor countries' nuclear export policies. A prerequisite for countries seeking to import SMRs from U.S. vendors is the negotiation of Section 123 Agreements with the U.S. government, which outline legally binding frameworks for peaceful nuclear cooperation and require recipient countries to adhere to nonproliferation criteria. The State Department has the responsibility to negotiate 123 Agreements, with technical assistance and consultation from the Department of Energy (DOE) and the NRC. The president submits the agreement to Congress, where it receives approval.[87]

Russia's focus on exporting its floating SMR units has been steadily growing. This interest in nuclear reactor exports may extend to land-based SMRs, as the Russian nuclear regulator, Rostekhnadzor, has recently granted a license for the construction of the country's first land-based SMR in its Arctic region.[88] Its target markets include the Middle East, Southeast Asia, and Africa.[89] Russia does not have an equivalent to the Section 123 Agreements. In contrast to the stringent U.S. requirements for exporting nuclear materials or facilities, Russia's approach emphasizes an all-inclusive package encompassing financing options, training programs, and infrastructure development support. It positions Russia as an attractive supplier, especially for nuclear newcomers, but it also raises concerns about overdependence on Russia. In addition, Rosatom is willing to take SNF back for temporary storage and reprocessing from overseas clients, a service that the U.S. is unable to provide thus far.[90] While China stands at the forefront of SMR deployment, it shows little interest in exporting SMRs in the near term.

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[87] "123 Agreements for Peaceful Cooperation," *U.S. Department of Energy National Nuclear Safety Administration*, https://www.energy.gov/nnsa/123-agreements-peaceful-cooperation. (accessed March 26, 2024).
[88] "License Issued for Russia's First Land-Based SMR," *World Nuclear News,* 2023, https://world-nuclear-news.org/Articles/Licence-issued-for-Russia-s-first-land-based-SMR. (accessed March 26, 2024).
[89] "Russian Export Push for Floating Nuclear Power Plants," *World Nuclear News,* 2023, https://world-nuclear-news.org/Articles/Russian-export-push-for-floating-nuclear-power-plants. (accessed March 26, 2024).
[90] Nevine Schepers. "Russia's Nuclear Energy Exports: Status, Prospects and Implications," *EU Non-Proliferation and Disarmament Consortium Non-Proliferation and Disarmament Paper*, No. 61, February 2019. https://www.sipri.org/sites/default/files/2019-02/eunpdc_no_61_final.pdf.

Cost

This section reviews costs related to SMRs. Given that most SMRs are still in development and prototyping stages, cost estimation remains a challenging task. This difficulty is compounded by the diversity of reactor designs, varying cost estimation methodologies, and different assumptions underpinning these estimations, which hinder direct cost comparison amongst SMR models. This section aims to illuminate major cost drivers for SMRs, provide insights on the cost-effectiveness of SMRs in comparison to traditional large NPPs, survey various cost metrics, and expand upon potential hybrid uses for SMRs that may change the value proposition for SMRs.

Cost Drivers of SMRs

A common approach to evaluating any nuclear reactor project costs involves assessing the costs incurred over the entire lifespan of the project for power generation, also referred to as life-cycle costs. As summarized in Figure 14, these costs are broadly classified into four key categories: capital costs, O&M costs, fuel costs, and decommissioning costs.

Figure 14: Summary of Cost Drivers

	Capital costs	O&M costs	Fuel costs	Decommissioning costs
Description	• Includes all **upfront expenses** involved in constructing and commissioning the plant before operation. • Includes **overnight capital costs (OCC)** - EPC, land acquisition, site works, project management, licensing/permitting; and **financing costs** - interest accrued and capitalized during the construction.	• Includes all **non-fuel expenses** - plant staffing, replacement of consumable operational materials and equipment, repairs and refurbishments, outsourced services, nuclear insurance, taxes, and miscellaneous costs.	• Includes any expenditures related to **the procurement and processing of uranium, reprocessing of spent fuel, research activities, or waste management.** • It composes the **variable costs** associated with the plant operations period.	• Includes **plant decommissioning activities, waste management, and final remediation of the site.** • These costs are incurred at the end of the plant's useful life.
Large reactors Vs. SMRs	• Varies based on **reactor technology, size, application,** and **location.** • Capital costs are the main drivers of project costs, accounting for **50-75% of the life-cycle cost** for both large reactors and SMRs.	• O&M costs for SMRs might be **higher** compared to traditional large reactors due to a **lack of economies of scale.** • Unique characteristics of SMRs, such as **learning effects** and **co-siting economies, can potentially lower the cost.**	• Fuel costs vary based on **reactor design, fuel type, and fuel cycle length.** • Light-water SMRs fueled with LEU are expected to have similar fuel costs to large reactors. • **SMRs require less frequent refueling** (3 - 7 years) compared to large reactors (1 - 2 years), leading to **different fuel cost structures.**	• Decommissioning costs can be significant for large reactors due to the quantity and specialization required to handle and dispose of radioactive material. • There is limited information regarding decommissioning costs of SMRs, as no real-world projects have undergone this process.

Source: Produced by the authors.

Capital Costs – Capital costs, which include both overnight capital cost (OCC) and the financing cost, represent the initial investment per unit of capacity.[91] These costs include all upfront expenses involved in constructing and commissioning the plant prior to plant operation. OCC includes the costs of engineering, procurement, and construction (EPC), land acquisition, site works, project management, and licensing and permitting.[92] The financing costs refer to the

[91] "Levelized Costs of New Generation Resources in the Annual Energy Outlook," *U.S. Energy Information Administration*, 2023, https://www.eia.gov/outlooks/aeo/electricity_generation/pdf/LCOE_methodology.pdf. (accessed March 26, 2024). "The Future of Nuclear Energy in a Carbon-Constrained World," *MIT Energy Initiative,* 2018, https://energy.mit.edu/research/future-nuclear-energy-carbon-constrained-world/. (accessed March 26, 2024).
[92] "Nuclear Power Economics and Project Structuring," *World Nuclear Association,* Report No. 2017 / 100, 2017, https://world-nuclear.org/getmedia/84082691-786c-414f-8178-a26be866d8da/REPORT_Economics_Report_2017.pdf.aspx. (accessed March 26, 2024).

interest accrued and capitalized during the construction phase and depends on the project's cost of capital. Though these costs vary significantly based on reactor technology, size, application, and location, they typically account for 50-75% of the life-cycle cost of an NPP, which holds true for both large reactors and SMRs.[93]

O&M Costs – O&M costs include all non-fuel expenses, such as plant staffing, replacement of consumable operational materials and equipment, repairs and refurbishments, outsourced services, nuclear insurance, taxes, and miscellaneous costs.[94] Capital costs are often recognized as the main driver of NPP costs, and O&M costs typically have a relatively lower impact. Although available estimates on SMR O&M costs are limited, some notable trends have been observed. SMRs might face higher O&M costs compared to traditional large NPPs due to a lack of economies of scale. However, this could be mitigated by the unique advantages of SMRs, such as learning effects and co-siting.[95]

Nuclear Liability Insurance

Nuclear liability insurance, which is designed to cover any liabilities of operators for damages arising from nuclear incidents, is a critical aspect of O&M costs for SMRs. Furthermore, more advanced technology and remote monitoring capabilities raise questions about certain aspects of installation safety and security. The precise influence of these technological advancements remains uncertain, posing potential variability in the insurance costs of SMRs compared to large reactors.

Fuel Costs – Fuel costs, which includes any expenditure related to the procurement and processing of uranium, reprocessing of spent fuel, research activities, or waste management, are variable costs associated with the operations period.[96] For SMRs, fuel costs may differ from traditional NPPs due to variations in reactor design, fuel type, and fuel cycle length.[97] For example, light-water SMRs fueled with LEU, similar to large NPPs, are expected to have comparable fuel costs.[98] Some advanced SMR designs will require HALEU, which is currently only commercially produced in Russia and China. Therefore, supply chain considerations will also contribute to fuel costs. Additionally, most SMRs will have longer fuel cycles and require less frequent refueling of three to seven years, compared to the one to two years for traditional large NPPs, leading to different fuel cost structures.[99]

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[93] Mario Carelli & Daniel Ingersoll. "Handbook of Small Modular Nuclear Reactors," *Woodhead Publishing Series in Energy*, 2014, https://doi.org/10.1016/C2013-0-16379-9.
[94] "Integrated Approach to Optimize Operation and Maintenance Costs for Operating Nuclear Power Plants", *International Atomic Energy Agency,* IAEA-TECDOC-1509), June 2006, https://www-pub.iaea.org/MTCD/Publications/PDF/te_1509_web.pdf.
"Cost Estimating Guidelines for Generation IV Nuclear Energy Systems," *OECD Nuclear Energy Agency,* Rev. 4.2 GIF/EMWG/2007/004, 2007, https://www.gen-4.org/gif/upload/docs/application/pdf/2013-09/emwg_guidelines.pdf.
[95] Mario Carelli, Clark Mycoff, Paola Garrone, Giorgio Locatelli, Mauro Mancini, Marco Ricotti, Andrea Trianni & Paolo Trucco. "Competitiveness of Small-Medium, New Generation Reactors: A Comparative Study on Capital and O&M Costs," *The American Society of Mechanical Engineers,* June 24, 2009, https://doi.org/10.1115/ICONE16-48931.
[96] "IAEA Safety Glossary: Terminology used in Nuclear, Radiation, Radioactive Waste and Transport Safety," *International Atomic Energy Agency, Department of Nuclear Safety and Security*, Version 2.0, 2006, http://www-ns.iaea.org/downloads/standards/glossary/glossary-english-version2point0-sept-06-12.pdf.
[97] Stewart, W. R., & Shirvan, K. "Capital Cost Estimation for Advanced Nuclear Power Plants," *Renewable and Sustainable Energy Reviews*, 155, Article 111880, 2022, https://doi.org/10.1016/j.rser.2021.111880.
[98] "High Assay Low Enriched Uranium (HALEU)," *World Nuclear Association,* https://world-nuclear.org/information-library/nuclear-fuel-cycle/conversion-enrichment-and-fabrication/high-assay-low-enriched-uranium-(haleu).aspx. (accessed March 26, 2024).
[99] "*What are Small Modular Reactors (SMRs)?*" *International Atomic Energy Agency*, September 13, 2023, https://www.iaea.org/newscenter/news/what-are-small-modular-reactors-smrs. (accessed March 26, 2024).

Decommissioning Costs – Decommissioning costs, which include plant decommissioning activities, waste management, and final remediation of the site, are incurred at the end of the plant's useful life.[100] These costs can be significant for NPPs due to the quantity and specialization required to handle and dispose of radioactive material.[101] There is limited information regarding decommissioning costs of SMRs, as no real-world projects have undergone this process.

Cost Effectiveness of SMRs

In comparison to SMRs, traditional large NPPs are expected to have lower costs per unit of output due to economies of scale in which expenses are spread across higher total output.[102] This correlation is evident when comparing overnight capital costs and output capacity for reactors with similar reactor technology. According to studies, costs decline by 20-35% as reactor size doubles.[103] When comparing size amongst similar technologies, capital costs for SMRs are projected to be as much as 70% higher.[104] While this is a clear disadvantage to SMRs, other features of SMRs – modularization, learning effects, construction time, and co-siting economies – could potentially offset these increased costs to make SMRs more cost-effective.

On a per unit of output basis, SMRs are expected to have higher costs than large reactors, which are theoretically offset by advantages such as modularization, learning effects, shorter construction times, and co-siting economies.

Modularization – A primary benefit of SMRs is the potential for modularization in construction, which refers to a simplified construction strategy that involves uniform fabrication of reactor components which can be more easily transported and assembled at the installation site. This process, which standardizes and centralizes manufacturing, can reduce capital costs.[105] Studies suggest that the impact of modularization on cost reduction is related to the degree of modularization – that is, the proportion of the construction's direct site costs for a specific component that is transferred to factory settings. It is estimated that 60% modularity is necessary to realize cost savings.[106]

Learning Effects – In addition to savings due to modularization, costs can be further reduced as a result of learning effects, or the efficiency gains achieved due to the accumulation of experience as more units are produced and deployed.[107] It is estimated that learning could lower the cost of

[100] "Cost Estimation for Research Reactor Decommissioning," *International Atomic Energy Agency*, 2013, https://www-pub.iaea.org/MTCD/Publications/PDF/Pub1596_web.pdf. (accessed March 26, 2024).
[101] Santosh Raikar & Seabron Adamson. "Renewable Energy Finance in the International Context," *Academic Press,* Renewable Energy Finance (pp. 185-220), 2020, https://doi.org/10.1016/B978-0-12-816441-9.00013-1.
[102] Robin Cantor and James Hewlett, "The Economics of Nuclear Power: Further Evidence on Learning, Economies of Scale, and Regulatory Effects," *Resour. Energy*, vol. 10, pp. 315–335, 1988.
[103] Fatih Aydogan, Geoffrey Black, Meredith Taylor Black & David Solan. "Quantitative and Qualitative Comparison of Light Water and Advanced Small Modular Reactors," *ASME Journal of Nuclear Radiation Science*, 1(4), 041001, October 2015. https://doi.org/10.1115/1.4031098.
[104] Carelli, et al, " Competitiveness of Small-Medium, New Generation Reactors."
[105] Giovanni Maronati & Bojan Petrovic. "Extending Modularization from Modules to Super Modules: A Cost Evaluation of Barge-Transportable Small Modular Reactors," *Proceedings of the 2018 International Congress on Advances in Nuclear Power Plants (ICAPP 2018) (pp. 357-362), American Nuclear Society,* 2018, https://www.scopus.com/record/display.uri?eid=2-s2.0-85050104333&origin=inward&txGid=1fd55fa87963cc8a132087e78386fa4b.
[106] Lloyd, C., Roulstone, A., & Middleton, C. "The Impact of Modularisation Strategies on Small Modular Reactor Cost," *American Nuclear Society*, 2018. https://doi.org/10.17863/CAM.25793.
[107] Mignacca, B., & Locatelli, G. "Economics and Finance of Small Modular Reactors: A Systematic Review and Research Agenda," *Renewable and Sustainable Energy Reviews*, 118, Article 109519, 2020. https://doi.org/10.1016/j.rser.2019.109519

capital expenditures for SMRs by 5-10% as production is doubled due to higher proportions of factory fabrication, in comparison for just 1-5% for large reactors.[108] Learning curves tend to flatten after five to seven units and the accumulation of experience ceases to yield significant savings beyond a certain period.[109]

Construction Time – Given their smaller size and simpler designs, SMRs are expected to have a shorter time-to-market than traditional NPPs.[110] The target construction time for FOAK is four to five years and three to four years for NOAK, compared to six or more years for large reactors.[111] Shorter construction time is expected to lead to lower financing costs due to the subsequent reduction in interest during construction. Estimates suggest that lower construction times for SMRs could lead to capital cost savings ranging from 6-20%, with the higher end of the spectrum being projected by SMR vendors.[112]

Co-Siting Economies – SMRs can achieve co-siting economies, which involve situating multiple units at the same location, representing a unique advantage over large reactors. By allowing for incremental capacity additions in a pre-existing site, SMRs enable cost savings on certain fixed, indivisible costs, such as licensing, insurance, and human resources.[113] It is estimated that co-siting economies could lead to a reduction in capital costs of 10-25% per unit.[114] Furthermore, O&M costs can be decreased through the shared use of personnel and spare parts across multiple units.[115]

Cost Metrics

Cost metrics provide a method for comparing energy costs across different types of power generation technologies. Understanding commonly used metrics, as well as alternative metrics, can help decision makers comprehend the cost structure of SMRs. The LCOE is the most widespread metric for cost comparisons; however, the Levelized Avoided Cost of Energy (LACE) and the Levelized Full System Cost of Electricity (LFSCOE) were also highlighted by industry experts in our research as more nuanced methods of understanding costs.

Levelized Cost of Electricity – LCOE is defined as the average revenue per unit of electricity generated that is required to recover the costs of building and operating a generation plant across its lifecycle.[116] This metric is calculated using capital, O&M, and fuel costs. LCOE estimates for SMRs can differ markedly, depending on the objectives of the analysis and assumptions underpinning the estimation. LCOE can be limited in reference to SMRs as it only reflects the cost to build and operate a plant but does not account for additional grid costs —expenses related to

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108 Chris Lewis, Ray MacSweeney, Miranda Kirschel, Will Josten, Tony Roulstone, Giorgio Locatelli. "Small Modular Reactors: Can Building Nuclear Power Become More Cost-Effective?" *Department of Energy and Climate Change,* 2016, https://www.researchgate.net/publication/321715136_Small_modular_reactors_Can_building_nuclear_power_become_more_cost-effective.
109 Alexey Lokhov, Ron Cameron, & Vladislav Sozoniuk. "OECD/NEA Study on the Economics and Market of Small Reactors," *Nuclear Engineering and Technology*, 45(6), 701-706, 2013, https://doi.org/10.5516/NET.02.2013.517.
110 Giorgio Locatelli, Marco Pecoraro, Giovanni Meroni & Mauro Mancini. "Appraisal of Small Modular Nuclear Reactors with 'Real Options' Valuation," *Proceedings of the Institution of Civil Engineers - Energy*, 170(2), 51-66, 2017, https://doi.org/10.1680/jener.16.00004.
111 Lewis, C., et al. "SMRs: Can Building Nuclear Power Become More Cost-Effective?".
112 "Current Status, Technical Feasibility and Economics of Small Modular Reactors," *Nuclear Energy Agency,* 2011, https://www.oecd-nea.org/ndd/reports/2011/current-status-small-reactors.pdf. (accessed March 26, 2024).
113 Carelli, et al, " Competitiveness of Small-Medium, New Generation Reactors."
114 "Current Status, Technical Feasibility and Economics of Small Modular Reactors."
115 Carelli, et al, " Competitiveness of Small-Medium, New Generation Reactors."
116 "Levelized Costs of New Generation Resources in the Annual Energy Outlook."

integrating the plant's power into the electrical grid. These grid costs include investments for grid stability and infrastructure upgrades needed to handle the electricity flow. For SMRs, the additional grid costs might be lower compared to variable renewable resources because nuclear power provides a stable, continuous supply of electricity that can be more easily integrated into existing grid infrastructure. Moreover, SMRs can offer greater grid flexibility compared to large reactors due to modularity, which allows for incremental capacity additions at a pre-existing site.[117] Co-siting can save costs on fixed, indivisible costs such as licensing, insurance, and human resources, but is not accounted for in this metric.

Considerations of SMRs Beyond LCOE

Grid Integration Costs: The LCOE does not account for the costs related to the integration into the grid – including investments for grid stability and infrastructure upgrades to handle the electricity flow. SMRs may be located at retired fossil fuel plants to take advantage of existing transmission infrastructure. In general, SMRs may require less grid build out, given their potential for portability (marine-based) and co-siting potential. SMRs may also incur lower additional grid costs compared to variable renewable resources, given their stable and continuous electricity supply, which aligns well with the grid's firm power needs and growing demand for grid resilience.

Grid Flexibility: SMRs provide enhanced grid flexibility over traditional larger reactors due to their modularity. This allows for incremental capacity additions at existing sites, which present opportunities for co-siting savings in licensing, insurance, human resources, etc., that are not considered within the LCOE framework.

These aspects underscore the importance of looking beyond the LCOE to fully evaluate the economic potential of SMRs.

Levelized Avoided Cost of Electricity – LACE is a companion metric for LCOE that was developed by the U.S. Energy Information Agency to improve comparisons of economic competitiveness between generation technologies. It is "a proxy measure for potential revenues from the sale of electricity generated or other ancillary services produced from a candidate project displacing (or the cost of avoiding) another marginal asset".[118] It is calculated using the marginal value of energy, capacity, and spinning reserves that would result from adding a unit of a given technology to the grid. A generation technology is economically attractive if its LACE is greater than its LCOE.[119] LACE recognizes that variable power sources like wind and solar might not avoid the capital and maintenance costs of backup dispatchable sources, which are required to provide energy when it cannot meet demand. Therefore, LACE can serve as a useful complementary metric to the LCOE regarding SMRs, because it accounts for the potential cost savings realized

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[117] Sara Boarin & Marco Ricotti. "An Evaluation of SMR Economic Attractiveness," *Science and Technology of Nuclear Installations*, Volume 2014, Article ID 803698. https://doi.org/10.1155/2014/803698.
Laura Boldon, Piyush Sabharwall, Chad Painter & Li Liu. "An Overview of Small Modular Reactors: Status of Global Development, Potential Design Advantages, and Methods for Economic Assessment," *International Journal of Energy, Environment and Economics*, 22(5), 437-459, 2014, https://proxy1.library.jhu.edu/login?url=https://www.proquest.com/scholarly-journals/n-overview-small-modular-reactors-status-global/docview/1751289563/se-2
[118] "Levelized Costs of New Generation Resources in the Annual Energy Outlook."
[119] Moses Kabeyi & Oludolapo Olanrewaju. "The Levelized Cost of Energy and Modifications for Use in Electricity Generation Planning," *Energy Reports*, Volume 9, Supplement 9, 495-534, September 2023, https://doi.org/10.1016/j.egyr.2023.06.036.

from enhancing grid stability. However, this metric is more complex to estimate and requires more information about the existing power system.

Levelized Full System Cost of Electricity – LFSCOE is a relatively novel metric designed to estimate the cost of supplying an entire power system from a single energy source, complemented by a storage system. LFSCOE goes beyond LCOE by assuming full responsibility of the energy source in balancing the market and meeting supply demands, which includes the costs associated with storage necessary for this purpose. It is presented as one figure for the market.[120] SMRs could be a competitive option when evaluated using the LFSCOE metric, which effectively accounts for costs associated with fluctuating supply and demand. SMRs provide constant and reliable firm power compared to systems with high penetration of renewables like solar and wind, characterized by intermittency and expensive storage requirements. LFSCOE is better able to capture this value.

These cost metrics should be understood as a relative measure of costs within a jurisdiction; SMRs may not be the most cost-effective power source in some competitive electricity markets but could still be a promising choice for power generation compared to other energy resources available.

Cost Uncertainty Related to FOAK Technology

There is a considerable degree of uncertainty surrounding SMR costs, particularly for FOAK projects. FOAK projects will incur higher expenses which are expected to decrease with NOAK production. Still, concrete evidence supporting this claim remains elusive as nearly all reactor designs are in prototyping stages. The lack of definitive data necessitates a thorough and cautious evaluation from investors and policymakers.

Case Study: UAMPS & NuScale

The Utah Associated Municipal Power Systems (UAMPS) planned to develop the Carbon Free Power Project (CFPP), a 462 MWe project consisting of six of NuScale's 77 MWe VOYGR reactors (initially envisioned to be 924 MWe with 12 reactors), at the Idaho National Lab. The project received support from the U.S. DOE and was on track to be the first commercially viable SMR project in the United States starting operations by 2029. CFPP had intended to submit a combined operating license application to the NRC in January 2024, which if approved, would enable construction to begin in 2026 with all units to be operational by November 2030.

However, the project was terminated in November 2023 due to escalating costs and insufficient number of subscribers. Between 2016 to 2020, the target power price was $55 per megawatt hour (MWh). In 2021, when the project downsized from 12 to 6 reactors, the price increased to

[120] Robert Idel. "Levelized Full System Costs of Electricity," *Energy*, Volume 259, Article 124905, November 15, 2022, https://doi.org/10.1016/j.energy.2022.124905.

$58/MWh. By January 2023, a detailed cost estimate further increased the expected power price to $89/MWh - a 53% surge from $58/MWh. It is noteworthy that this estimate did not factor in the potential $1.4 billion DOE support or the $30/MWh subsidy available through the Inflation Reduction Act (IRA). By November, the CFPP had failed to secure the critical 80% subscription threshold required to move forward. Several of the initial subscribers withdrew, citing apprehensions about the economic feasibility as the cost estimates increased.

Hybrid Uses

SMRs present novel opportunities for a diverse range of applications beyond the scope of traditional large-scale electricity generation, potentially leading to greater cost efficiency through their hybrid uses.

SMRs could be an integral component of cogeneration systems, providing both electrical and thermal energy. They can be tailored to suit specific industrial processes with varying heat requirements. For example, SMRs operating at higher temperatures can deliver high-quality heat suitable for hydrogen and synthetic fuel production. Lower temperature heat from SMRs can be applied to district heating, the desalination process, or the pretreatment of low-temperature biomass and ethanol production. This versatility of SMRs allows for thermal energy to be redirected to these high-value applications. The potential for hybrid thermal generation could enhance the economic viability of SMRs by diversifying revenue streams and optimizing operational efficiency.

Additionally, SMRs are capable of providing a consistent and uninterrupted power supply, making them ideal for integration with other renewable energy sources. This combination addresses the issues of variability and intermittency commonly associated with wind and solar power, thereby enhancing grid stability, and ensuring a reliable energy supply. For example, in times of high renewable energy output, SMRs can modulate their electricity production to focus more on thermal applications, thus maximizing the efficiency and economic benefits of the hybrid energy system. This flexible operational approach allows SMRs to augment renewable sources, ensuring a consistent and adaptable energy supply in response to demand variations.

Financing

Financing is a critical consideration for successful SMR deployment. Given that global SMR deployment is in its early stages, FOAK SMR projects will likely incur higher costs and require greater direct or indirect government support at the outset. Capital cost estimates are a key determinate of the ability to secure financing; however, these costs are difficult to validate for FOAK technology. Demonstration projects, therefore, play an essential role in understanding these cost estimates and proving commercial viability for a select design. Several demonstration projects have reached licensing and operations phases, all of which received strong government support either through direct funding from government budgets or via state-owned entities and government research programs (see Figure 15).

Figure 15: FOAK Financing Examples for SMR Projects

CAREM	Argentina – The CAREM reactor is a 100 MW water-cooled reactor designed by the National Atomic Energy Commission (CNEA) of Argentina. Full funding for the project was written into national law and construction was approved in 2010. Plant construction began in 2014 and is ongoing.
HTR-PM	China – The HTR-PM reactor is a 210 MW gas-cooled reactor. It has been fully financed and is owned by a consortium composed of China Huanend, China Nuclear Engineering Corporation and Tsinghua University's Institute of Nuclear and New Energy Technology. It is licensed, operating, and connected to the grid.
KLT-40	Russia – The KLT-40 is a 30 MW water-cooled reactor that powers the Akademik Lomonosov, a self-contained floating nuclear power plant. The project has been financed by the Committee of the Russian Federation Budget (17%) and the Joint Stock Company Energoatom, formerly Rosenergoatom, which is a holding company for all Russian civilian nuclear plants (83%).
RITM-200N & RITM-200S	Russia – The RITM-200 is a 55 MW water-cooled reactor for land or marine-based applications. Designed by Rosatom, the design has received significant direct government funding. The land-based RITM-200N has an off-take agreement with state-owned projects in Yakutia. The marine-based RITM-200S powers industrial mining companies and has a long-term take-or-pay contract with GDK Baimskaya.

Source: Adapted by the Authors from 'The NEA Dashboard' [121]

There are many potential financing structures for SMR projects. Like large nuclear power projects, SMR projects can be structured using government or private finance. Most operating nuclear plants are financed with government involvement, either directly through a mix of equity and debt, or indirectly, e.g. the government holds a majority stake in the project sponsor company. This approach depends on government policy and market design. Projects with a private sponsor, such as a large utility, must arrange credit from lenders. Likely, SMR projects will utilize a blended financing approach, which includes a mix of direct grants, sponsor's equity, and sovereign or commercial borrowing. If projects are being constructed in host countries different from the SMR designer country, a wider array of stakeholders could be involved, ranging from export credit

[121] "The NEA Small Modular Reactor Dashboard," 32 - 62.

agencies to sovereign financial institutions, bilateral or multilateral development banks, and international commercial or investment banks.

> **Non-Recourse Financing**
>
> Representatives of a sovereign export credit agency reported that non-recourse financing, such as project financing, could eventually become a tool for SMRs in some scenarios, but it is unlikely to become the primary means of financing these builds.[122] This is related to the technical complexity, political and regulatory risks, and nuclear liabilities related to building nuclear power plants.

As SMR designs become proven, supply chains mature, and costs are more transparent, some projects will require less government support at the outset and rely more on market mechanisms for financing. In these cases, a project's bankability is critical to successful syndication. Lenders must feel comfortable with the risk profile of the project, which will vary based on SMR design, technology maturity, the regulatory environment and experience of the host country, relations with the vendor country, and the credibility of all project sponsors and contractors. The financing structure and business model of each project will necessarily be specific to the country and context.

Much like large NPPs, SMR projects are likely to be refinanced over their lifetime.[123] This generally occurs after the project planning and construction period, which is the riskiest part of the project. Plants typically have a revenue generating period of several decades, after which they are either refurbished to extend their operating lifespan or decommissioned. Refinancing is necessary for both phases.

Key Stakeholders in SMR Financing

Government Loan Programs – Governments can facilitate financing for SMR deployment, either through direct budget allocations, or through loan programs to help improve project economics, especially for FOAK technology. For example, the U.S. DOE, through its Loans Program Office (LPO), has provided loan guarantees for domestic projects and funding for feasibility studies and demonstration projects to encourage SMR development, as well as HALEU enrichment capabilities.[124]

Export Credit Agencies (ECAs) – In both exporting and importing countries, ECAs will play a large role in SMR financing given their unique position to underwrite large infrastructure investments under the authority of a sovereign state. They effectively provide loan guarantees for non-domestic projects, thereby reducing risk for other investors. In Russia, the nuclear agency Rosatom works in collaboration with the Bank for Development and Foreign Economic Affairs (Vnesheconombank) to support investments for overseas nuclear power projects. France, Canada, China, South Korea, the United States, Japan, Sweden, and Russia all have ECAs involved in supporting nuclear energy projects.[125]

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[122] Interview. January 8, 2024.
[123] Interview. September 21, 2023.
[124] "Advanced Nuclear Energy Projects," *Loans Program Office,* Department of Energy, https://www.energy.gov/lpo/advanced-nuclear-energy-projects. (accessed April 20, 2024).
[125] "Financing Nuclear Energy," *World Nuclear Association,* March 2024, https://world-nuclear.org/information-library/economic-aspects/financing-nuclear-energy.aspx. (accessed April 20, 2024).

The Role of U.S. Export – Import (EXIM) Bank

The U.S. export credit agency, EXIM Bank, is best suited to support exports of U.S. SMR technology, given its ability to provide direct loans or loan guarantees, and enhanced Letters of Interest to projects to shore up other financial support. The EXIM Bank's main priority in a funding decision is bankability; however, it recently released a financing toolkit to encourage investment and export in this sector. Getting the EXIM Bank's support for an SMR project is important for U.S. vendor technology. A key requirement is sovereign support from the importing country – that is, the EXIM Bank may provide loans directly to commercial entities in foreign countries under the condition that the loan is guaranteed by a sovereign entity in that foreign country. Other requirements of the EXIM Bank's support include a 123 Agreement and adherence to other environmental and social due diligence guidelines, as established by the EXIM Bank, the IAEA, the International Finance Corporation, the Equator Principles, and the host country, as well as design approval by the U.S. NRC. The EXIM Bank and other U.S. government support is coordinated via 'Team USA', which is an interagency process to support government activities promoting U.S. nuclear technology.[126]

Multilateral Development Banks (MDBs) – MDBs play an important role in financing large infrastructure projects; however, these banks have historically been reluctant to invest in nuclear energy projects. The World Bank has not funded any nuclear power infrastructure projects since 1959, when it made its first loan to construct an NPP in Italy.[127] This lender is unlikely to change its position until major donor countries encourage support for nuclear infrastructure financing. Other MDBs, such as the European Bank for Reconstruction and Development, are involved in financing nuclear-safety related initiatives, including decommissioning, safe management of radioactive waste, and remediation of contaminated sites.[128] At the time of writing, MDB support for construction of nuclear power projects, including SMRs, is limited.

Sovereign Financial Institutions – Some countries involved in building and exporting nuclear infrastructure have established financial institutions dedicated to lending for civilian nuclear power projects. The participation of these state banks in nuclear financing is important given the absence of traditional development finance. The China Huaneng Group engages in investment, construction, and operation of nuclear power generation assets. The U.S. Development Finance Corporation has indicated some limited interest and willingness to collaborate on nuclear energy related projects, which could include SMRs.

Nuclear Infrastructure Bank – To help fill the financing gap for nuclear power infrastructure, the creation of the International Bank for Nuclear Infrastructure (IBNI), has been proposed and is projected to be established in 2026. The goal of the bank is to provide early-stage financing and project endorsement to improve bankability and leverage financing from other lenders for SMRs and large nuclear power projects. IBNI aims to streamline the process of SMR financing and avoid the complex requirements that delays financing decisions from financial institutions that are not

[126] Interview. January 8, 2024.
[127] "Loan for Nuclear Power," *The World Bank,* 2016, https://documents.worldbank.org/en/publication/documents-reports/documentdetail/700621467993172257/loan-for-nuclear-power. (accessed April 20, 2024).
[128] "Nuclear Safety," *European Bank for Reconstruction and Development,* https://www.ebrd.com/nuclear-safety.html. (accessed April 20, 2024).

specialized in the civilian nuclear sector. This funding would be available to any IBNI member state, which is foreseen to include a coalition of IAEA members who subscribe to IBNI's mission.

Alternative Financing & Business Models

Numerous financing models are being explored by SMR advocates to reduce investment risks and more effectively share the cost of FOAK infrastructure. The models detailed below have been applied in various countries for large NPPs or to promote FOAK technology investment and could be modified to suit the needs of SMRs.

Mankala Model – This model originated in Finland to facilitate investment in large-scale energy infrastructure like hydropower and nuclear power plants. In this cooperative structure, major power off-takers, like industrial companies, co-finance the plant through the creation of a limited liability company (LLC) with each participant contributing equity. While the LLC does not pay dividends, each owner can purchase energy from the generation company on a cost-price basis that is proportional to their equity stake in the LLC. This model has been successful in Finland but given the high capital costs of nuclear projects, it requires the presence of large industrial companies or energy wholesale or retail companies capable of contributing capital at the necessary scale.

Carbon Free Power Project

The CFPP project to install NuScale reactors in the United States was called off in November 2023 primarily due to low subscription numbers from rising cost estimates. The project was owned by the Utah Associated Municipal Power Systems (UAMPs), which serves fifty member municipalities located across seven states including California, Idaho, Nevada, New Mexico, Utah, and Wyoming. The model developed to finance CFPP was based on attracting subscribers, mostly municipal members of UAMPS or other power off-takers, who would be entitled to carbon-free power from the plant, once operational, based on their contribution to the development costs. This model shares many characteristics of the cooperative financing model detailed above. While theoretically it could be used to finance future SMR projects, accurate data around SMR costs is essential to avoid a similar outcome to the CFPP.

Build-Own-Operate (BOO) – This model, used by the Russian atomic agency Rosatom for its recent NPP in Turkey, is an integrated offer for turnkey construction, fuel, training, services, infrastructure development, and legal and regulatory structures. This has enabled Rosatom to deliver large NPP with LCOE no more than $50-$60 per MWh.[129] Rosatom collaborated with the Bank for Development and Foreign Economic Affairs (Vnesheconmbank) to develop these projects overseas. While currently it has been deployed for large NPPs, this model could also be used to export SMRs. China is also exploring this model.

Contract for Difference (CfD) – Under this model, the government guarantees an electricity price to the project sponsor. If the market price is lower than the guaranteed price, the government will compensate the generating company for the difference. If the price is higher, the generating company pays the difference. Under this model, the owner of the project bears the upfront cost of construction and related risks. This model has been used in the United Kingdom to finance the

[129] "Nuclear Power in Russia," *World Nuclear Association*, March 2024, https://world-nuclear.org/information-library/country-profiles/countries-o-s/russia-nuclear-power.aspx. (accessed April 20, 2024).

Hinkley Point C nuclear reactor project. It is also being considered in Poland to finance the Westinghouse AP1000 reactor project.[130]

Regulated Asset Base (RAB) – This model is used to finance the capital costs of large infrastructure investments through a small supplemental fee to consumers' bills, which can be added during asset construction. The potential advantages of the RAB model include bringing down the overall cost of an NPP, potentially lowering the cost of borrowing as lenders are guaranteed to recoup costs and facilitating shorter payback periods. This financing option must be supported by legislation or a regulatory framework that allows utilities to integrate the cost of the new investment into the tariff schedule. In the spring of 2022, the United Kingdom passed the Nuclear Energy Bill that introduced the RAB model.[131] In the United States, a similar model was deployed to finance the Vogtle nuclear power station in Georgia. The project has been criticized for being significantly over-schedule and over-budget, with customers bearing much of the financial risk as a result of the financing model.[132]

Cost Stabilization Facility (CSF) – Proposed by the Energy Futures Initiative Foundation in the United States, the cost stabilization facility is an augmented loan product that could be used to mitigate the risk of FOAK SMR development and construction.[133] It requires an orderbook for a predetermined number of SMR units of the same design; individual project sponsors (e.g. utilities) would pool investments (debt and equity, however sourced) into a Special Purpose Vehicle (SPV). Project sponsors would have collective undivided ownership in the SPV, and their contributions would finance construction of the orderbook under a tiered cost sharing arrangement. In the case that pooled funds by all project participants cannot cover any contingencies that arise, the CSF would be triggered, and the U.S. LPO would provide backstop financing to complete the orderbook. The goal for this mechanism is to facilitate construction of a chosen SMR technology and enable vendors to determine a reliable and commercially viable NOAK unit cost. This could help kickstart the SMR industry in the U.S. and provide an avenue for eventual export of the technology.

[130] "Poland / Government Considering Contracts for Difference Financing for First Nuclear Plant, Reports Say," *Nucnet*, January 30, 2024. https://www.nucnet.org/news/government-considering-contracts-for-difference-financing-for-first-nuclear-plant-reports-say-1-2-2024. (accessed April 20, 2024).
[131] "Nuclear Energy (Financing) Act 2022," *UK Parliament*, April 5, 2022, https://bills.parliament.uk/bills/3057.
[132] "Georgia Nuclear Power Plant Vogtle Rates Costs," ***Associated Press,*** May 2025, https://apnews.com/article/georgia-nuclear-power-plant-vogtle-rates-costs-75c7a413cda3935dd551be9115e88a64. (Accessed April 30, 2024).
[133] Ernest Moniz, Joseph Hezir, Stephen Comello, & Jeffrey Brown. "A Cost Stabilization Facility for Kickstarting the Commercialization of Small Modular Reactors," *EFI Foundation,* 2023, https://efifoundation.org/wp-content/uploads/sites/3/2023/10/20231011-CSF-FINAL-1.pdf.

Conclusions

As a low carbon, dispatchable electricity generation technology, nuclear power can be an important tool for decarbonization. SMRs, with their smaller capacities and modular features, present several advantages over traditional large NPPs. This report outlines a decision-making framework for countries interested in SMR deployment (see Figure 5). The path to a successful SMR project involves a series of steps, from establishing nuclear legislation and regulatory bodies, to developing robust nuclear infrastructure, identifying suitable applications and sponsors, selecting appropriate technologies and vendors, conducting cost estimations, and structuring business models and financing mechanisms. The ability to deliver on SMRs' promises demands significant commitments from numerous stakeholders.

The key considerations described in detail in the report above are distilled into nineteen key findings here:

1. **SMR deployment requires a coordinated and sustained effort across governments, industry, and international institutions.** The specific features of civilian nuclear power plants (NPPs) necessitate the full endorsement of host governments, even if projects are led by private sponsors. This requirement hinges on various characteristics of a national government, including its ability to create an enabling environment that makes nuclear power feasible. SMR designers must work early with government and regulatory counterparts who can help facilitate these processes. International dialogue and collaboration should also be initiated at early stages to establish conducive trade relations and successful partnerships for the export of SMR technology.

2. **Countries with substantial vested interests in SMRs are willing to embrace the First-of-a-Kind (FOAK) risk associated with this new technology.** For emerging economies, this could include countries with limited alternatives for firm electricity generation, those facing high electricity costs where SMRs can offer competitive prices, or nations deeply concerned with energy and water security, as well as climate resilience. Countries concerned with nuclear reactor export competitiveness are heavily involved in advancing their own domestic SMR industries. These nations will set the standard for SMR deployment globally.

3. **SMRs offer enhanced flexibility for low-carbon power generation.** A key promise of many SMR designs is modularity, meaning that they can be factory fabricated, transported to the site, assembled, and stacked to reach the desired total energy output. This feature enables more flexibility in deployment locations, allows for better load following in grid systems with higher penetrations of variable renewable resources, and permits incremental growth in output capacity. This is important for smaller grid systems and is a distinct advantage that SMRs have over large NPPs. However, if used for power generation, guidelines from the International Atomic Energy Agency (IAEA) state that SMR units should still be less than ten percent of the total grid capacity to avoid overwhelming the grid. Countries with small grid sizes must carry out grid reinforcements to ensure grid stability.

4. **Nations must consider fuel types when selecting a reactor design, since its availability will impact reactor operations, regulatory requirements, international partnerships, and waste management.** Some SMR designs utilize low enriched uranium (LEU) or mixed-oxide fuels (MOX), which are commonly used in large reactors and is commercially available in numerous countries. Other designs employ more novel fuel types, such as high-assay low-enriched uranium (HALEU) or thorium-based fuels, which offer some advantages in terms of improved waste characteristics and reduced nuclear proliferation risks. However, these fuels are not as widely commercially available.

5. **SMR designs integrate inherent safety features that reduce the risk of accidents and could contribute to greater public acceptance of these reactors as safe and sustainable power generation options.** Advanced SMR designs have inherent safety features, including passive systems that utilize gravity, natural circulation, and material properties rather than active systems or operator intervention. Designs also integrate reactivity control mechanisms and robust containment structures capable of withstanding extreme events. These features enhance safety margins and reduce accident risks, fostering greater public acceptance of SMRs.

6. **The choice of technology partner holds long-term implications for energy security, supply chains, and international partnerships.** SMR technology importing countries must consider the long plant lifecycles of SMRs and establish strong ties with countries integral to its supply chain to ensure continued access to fuel and other essential components.

7. **SMRs pose distinct challenges for existing nuclear waste management processes.** SMRs produce more complicated waste streams, in terms of both composition and volume. This complexity is driven by increased neutron leakage from their smaller reactor cores, which occurs when neutrons escape and interact with surrounding materials, leading to more radioactive material. SMR designs utilize three strategies to mitigate neutron leakage, including enriched fuel, neutron reflectors, or modified coolant types. However, the variety of fuel waste types and diverse coolants presents challenges to waste disposal due to their divergence from established technologies and practices for nuclear waste management. Thus, further research is required to adequately address these challenges.

8. **SMR deployment necessitates adherence to the same international conventions governing nuclear safety, security, safeguards, and liability as large NPPs.** Countries considering civilian nuclear power, including SMRs, must develop a domestic legal framework addressing nuclear safety, security, safeguards, and liability. This framework should adhere to the principles outlined in international conventions. These principles provide essential protections to states, people, and the environment, and assign responsibilities and liabilities in the event of incidents. Given that SMRs present many of the same risks as large NPPs, the existing principles generally apply to SMRs. However,

new SMR designs introduce certain ambiguities that require additional attention from countries when establishing nuclear legislation.

9. **An independent regulator is an essential prerequisite to SMR deployment.** Nuclear legislation should establish and determine the functions of an effectively independent regulatory body, which broadly include standard setting, licensing and authorization of nuclear installations, inspection, and enforcement. The independence of the regulatory body is important to avoid influence from individuals or entities advocating for nuclear energy within the government. The regulator is responsible for ensuring that the entire lifecycle of NPPs from reactor design and site selection to construction, operations, waste management, decommissioning, and accident response aligns with the regulatory framework. A reliable and transparent regulator demonstrates strong governmental commitment, engages stakeholders, and provides confidence to investors, vendors, and society for new civilian nuclear power infrastructure.

10. **The smaller size of SMRs does not equate to a simplified regulatory process under existing regulatory frameworks.** SMRs require many of the same enabling environments as traditional NPPs. Establishing nuclear infrastructure and regulatory frameworks can be a long process, often spanning several years. This is especially true for nuclear newcomers who have yet to implement a civilian nuclear power program and will need to comply with relevant international conventions and any other requirements dictated by exporting countries. While there are efforts to harmonize these requirements, it is unlikely that these processes can be significantly shortened or streamlined. Moreover, the novel features of many advanced reactors may extend timelines for authorization by regulators.

11. **While SMRs may introduce complexities into the licensing process, regulatory reforms hold the promise of accelerating SMR deployment at scale.** SMR licensing can be facilitated by improvements to the existing regulatory framework, which focuses on traditional large light water nuclear reactors. Regulators may introduce a more technology-neutral stance that takes a risk-informed, performance-based approach.

12. **When estimating the life-cycle cost of SMRs, four cost drivers should be considered: capital costs, operations and maintenance (O&M) costs, fuel costs, and decommissioning costs.** The life-cycle cost encompasses all the costs incurred over the entire lifespan of the nuclear reactor project for power generation. These costs may vary based on SMR reactor technology, size, application, and location. In comparison to large reactors, SMRs are expected to have higher costs per unit of output due to a lack of economies of scale in which expenses are spread across higher total output.

13. **Unique characteristics of SMRs, such as modularization, learning effects, shorter construction times, and co-siting economies can potentially reduce costs for SMRs.** Modularization allows for uniform fabrication of reactor components which can be more easily transported and assembled at the installation site. This standardizes and centralizes manufacturing, thus reducing costs. As a result of learning effects, or the efficiency gains

achieved due to the accumulation of experience as more units are produced and deployed, costs can further be reduced. SMRs are expected to have a shorter construction time compared to large reactors, thereby reducing financing costs. SMRs also allow for co-siting at pre-existing facilities, enabling cost savings on certain fixed, indivisible costs, such as licensing, insurance, and human resources.

14. **The commonly used cost metric, levelized cost of electricity (LCOE), does not account for grid integration costs and grid flexibility. It is important to look beyond the LCOE to fully evaluate the economic potential of SMRs.** In general, SMRs may require less grid build out, given their potential for portability and co-siting. SMRs may also incur lower additional grid costs compared to variable renewable resources, given their stable and continuous electricity generation, which aligns well with the grid's firm power needs and growing demand for grid resilience.

15. **The lack of definitive data for SMR costs necessitates a thorough and cautious evaluation from investors and policymakers.** There is a considerable degree of uncertainty surrounding SMR costs, particularly for FOAK projects. FOAK projects will incur higher expenses which are expected to decrease with Nth-of-a-Kind (NOAK) production. Until more units are produced and deployed and potential cost benefits of SMRs become a reality, true SMR costs are still unknown.

16. **Governments can provide critical financial support to FOAK SMR projects.** Given the early stage of global SMR deployment, FOAK projects will likely incur higher costs and other project risks. The government is in a unique position to fund demonstration projects, allocate spending through various government programs, or help contain project costs by providing loan guarantees or other tailored loan products.

17. **Demonstration projects play an essential role in understanding cost estimates for specific SMR designs and demonstrating commercial viability.** Most SMRs in operation today are demonstration projects; this is an important step for both SMR designs deployed domestically, as well as for designs destined for export. Demonstration projects are an important indicator to investors and can help establish an orderbook for future projects.

18. **There are many potential financing structures and business models for SMR projects.** SMR projects can be sponsored directly or indirectly by national governments or by private sponsors, including utilities, industrial companies, data centers, or other power off-takers. Projects will likely utilize a blended financing approach, relying on some mix of grants, debt, and equity, however sourced. The specific business model of the project will determine its commercial viability. Projects may have unique power off-takers and revenue streams given the range of applications for SMRs and diverse policy and regulatory landscapes in a host country.

19. **SMR projects will rely on financing from numerous stakeholders and dedicated financial institutions.** If SMRs are exported to other host countries, a wider range of stakeholders could be involved in financing the project. For example, export credit agencies are uniquely positioned to help finance these projects by providing direct loans or loan guarantees to foreign commercial entities. Several countries have sovereign lenders dedicated to nuclear infrastructure investments. Progress is also being made to establish the International Bank for Nuclear Infrastructure, which is still in its fundraising phase at the time of report publication but could play a specific role in early-stage financing and project endorsement.

References

"123 Agreements for Peaceful Cooperation." *U.S. Department of Energy National Nuclear Safety Administration*. https://www.energy.gov/nnsa/123-agreements-peaceful-cooperation. (accessed March 26, 2024).

"Advanced Nuclear Energy Projects." *Loans Program Office*, Department of Energy. https://www.energy.gov/lpo/advanced-nuclear-energy-projects. (accessed April 20, 2024).

"Advances in Small Modular Reactor Technology Developments." *A Supplement to: IAEA Advanced Reactors Information System (ARIS),* 2022. https://aris.iaea.org/Publications/SMR_booklet_2022.pdf

Akbari-Jeyhouni, R., Rezaei Ochbelagh, D., Maiorino, J. R., D'Auria, F., & Stefani, G. L. "The Utilization of Thorium in Small Modular Reactors – Part I: Neutronic Assessment." *Annals of Nuclear Energy*, Volume 120, 422–430 (2018). https://doi.org/10.1016/j.anucene.2018.06.013.

Ashton, L. "Fueling the Future: Building Fuel Supply Chains for SMRs and Advanced Reactors." *International Atomic Energy Agency*. February 5, 2024. https://www.iaea.org/bulletin/fuelling-the-future-building-fuel-supply-chains-for-smrs-and-advanced-reactors. (accessed March 26, 2024).

Aydogan, F., Black, G., Taylor Black, M. A., & Solan, D. "Quantitative and Qualitative Comparison of Light Water and Advanced Small Modular Reactors." *ASME Journal of Nuclear Radiation Science*, 1(4), 041001. October 2015. https://doi.org/10.1115/1.4031098.

Boarin, S., & Ricotti, M. E. "An Evaluation of SMR Economic Attractiveness." *Science and Technology of Nuclear Installations*, Volume 2014, Article ID 803698. https://doi.org/10.1155/2014/803698.

Boldon, L., Sabharwall, P., Painter, C., & Liu, L. "An Overview of Small Modular Reactors: Status of Global Development, Potential Design Advantages, and Methods for Economic Assessment." *International Journal of Energy, Environment and Economics*, 22(5), 437-459, 2014. https://proxy1.library.jhu.edu/login?url=https:// www.proquest.com/scholarly-journals/n-overview-small-modular-reactors-status-global/docview/1751289563/se-2.

Burns, S. G. "Looking Backward, Moving Forward: Licensing New Reactors in the United States." *Nuclear Law Bulletin*, 2008(1), 7–29. July 8, 2008.

"Can Part 53 be the Nuclear Licensing Rule We Need?" *The Breakthrough Institute*, 2022. https://thebreakthrough.org/blog/can-part-53-be-the-nuclear-licensing-rule-we-need. (accessed March 26, 2024).

Carelli, M. D., & Ingersoll, D. T. "Handbook of Small Modular Nuclear Reactors," *Woodhead Publishing Series in Energy*, 2014. https://doi.org/10.1016/C2013-0-16379-9.

Carelli, M. D., Mycoff, C. W., Garrone, P., Locatelli, G., Mancini, M., Ricotti, M. E., Trianni, A., & Trucco, P. "Competitiveness of Small-Medium, New Generation Reactors: A Comparative Study on Capital and O&M Costs." *The American Society of Mechanical Engineers*, June 24, 2009. https://doi.org/10.1115/ICONE16-48931.

"Centrus Produces Nation's First Amounts of HALEU," *Office of Nuclear Energy*. Department of Energy, November 7, 2023. https://www.energy.gov/ne/articles/centrus-produces-nations-first-amounts-haleu. (accessed April 4, 2024).

"China's Demonstration HTR-PM Reaches Full Power." *New Nuclear*. World Nuclear News, December 9, 2022. https://world-nuclear-news.org/Articles/China-s-demonstration-HTR-PM-reaches-full-power. (accessed March 26, 2024).

"Containment Systems: Working Group on Design and Safety Analysis." *International Atomic Energy Agency*. December 2023.

https://www.iaea.org/sites/default/files/24/02/smr_rf_phase_3_report_-_containment_systems.pdf. (accessed March 26, 2024).
"Cost Estimating Guidelines for Generation IV Nuclear Energy Systems." *OECD Nuclear Energy Agency*, Rev. 4.2 GIF/EMWG/2007/004, 2007. https://www.gen-4.org/gif/upload/docs/application/pdf/2013-09/emwg_guidelines.pdf.
"Cost Estimation for Research Reactor Decommissioning." *International Atomic Energy Agency*, 2013. https://www-pub.iaea.org/MTCD/Publications/PDF/Pub1596_web.pdf. (accessed March 26, 2024).
"Current Status, Technical Feasibility and Economics of Small Modular Reactors." *Nuclear Energy Agency*, 2011. https://www.oecd-nea.org/ndd/reports/2011/current-status-small-reactors.pdf. (accessed March 26, 2024).
"Deployment Indicators for Small Modular Reactors." *International Atomic Energy Agency*. September 17, 2018. https://www.iaea.org/publications/13404/deployment-indicators-for-small-modular-reactors. (accessed March 26, 2024).
"Design Certification - NuScale US600." *United States Nuclear Regulatory Commission*, https://www.nrc.gov/reactors/new-reactors/smr/licensing-activities/nuscale.html. (accessed March 26, 2024).
"Electric Grid Reliability and Interface with Nuclear Power Plants." *International Atomic Energy Agency*. IAEA Nuclear Energy Series No. NG-T-3.8, IAEA Vienna. 2012. http://www-pub.iaea.org/MTCD/publications/PDF/Pub1542_web.pdf
Ewing, R. "Reset of America's Nuclear Waste Management Strategy and Policies." *Stanford University Center for International Security and Cooperation, George Washington University Elliott School of International Affairs*. October 15, 2018. https://fsi9-prod.s3.us-west-1.amazonaws.com/s3fs-public/reset_report_2018_final.pdf
"Financing Nuclear Energy." *World Nuclear Association*, March 2024. https://world-nuclear.org/information-library/economic-aspects/financing-nuclear-energy.aspx. (accessed April 20, 2024).
"From Observer Status to Full Membership – Poland in WENRA." *National Atomic Energy Agency*, Polish Government, November 14, 2023. www.gov.pl.web/paa-en/from-observer-status-to-full-membership--Poland-in-wenra. (accessed March 26, 2024).
"Foundational Infrastructure for Responsible Use of Small Modular Reactor Technology: FIRST Program Partners," *FIRST*. https://www.smr-first-program.net/partners/. (accessed March 26, 2024).
Gao, S., Huang, G., Zhang, X., Chen, J., & Han, D. "SMR Siting for the Electricity System Management." *Journal of Cleaner Production*, Volume 297, 126621, 2021. https://doi.org/10.1016/j.jclepro.2021.126621.
Gaspar, M. "Technology Neutral: Safety and Licensing of SMRs." *International Atomic Energy Agency*, August 17, 2020. https://www.iaea.org/newscenter/news/technology-neutral-safety-and-licensing-of-smrs. (accessed March 26, 2024).
"Georgia Nuclear Power Plant Vogtle Rates Costs." *Associated Press,* May 2025. https://apnews.com/article/georgia-nuclear-power-plant-vogtle-rates-costs-75c7a413cda3935dd551be9115e88a64. (Accessed April 30, 2024).
Goldberg, Stephen M., & Rosner, Robert. "Nuclear Reactors: Generation to Generation." *American Academy of Arts and Sciences*. (2011):4. https://www.amacad.org/sites/default/files/academy/pdfs/nuclearReactors.pdf
"High Assay Low Enriched Uranium (HALEU)." *World Nuclear Association*. https://world-nuclear.org/information-library/nuclear-fuel-cycle/conversion-enrichment-and-fabrication/high-assay-low-enriched-uranium-(haleu).aspx. (accessed March 26, 2024).
Horbach, N. L. "Nuclear Liability for International Transport Accidents under the Modernized Nuclear Liability Conventions: An Assessment." *International Journal of Nuclear Law*, 1(2), 189-198. (2006).

"IAEA Nuclear Safety and Security Glossary: Terminology Used in Nuclear Safety, Nuclear Security, Radiation Protection and Emergency Preparedness and Response," *International Atomic Energy Agency,* Non-Serial Publications 2022 Edition, 2022, https://www-pub.iaea.org/MTCD/Publications/PDF/IAEA-NSS-GLOweb.pdf.
"IAEA Safeguards Glossary." *International Atomic Energy Agency*, International Nuclear Verification Series No. 3 (Rev.1), 2022. https://www-pub.iaea.org/MTCD/publications/PDF/PUB2003_web.pdf.
"IAEA Safety Glossary: Terminology used in Nuclear Radiation, Radioactive Waste and Transport Safety." *International Atomic Energy Agency*, Department of Nuclear Safety and Security, Version 2.0, 2006. http://www-ns.iaea.org/downloads/standards/glossary/glossary-english-version2point0-sept-06-12.pdf.
Idel, R. "Levelized Full System Costs of Electricity." *Energy*, Volume 259, Article 124905, November 15, 2022. https://doi.org/10.1016/j.energy.2022.124905.
"Integrated Approach to Optimize Operation and Maintenance Costs for Operating Nuclear Power Plants." *International Atomic Energy Agency*, IAEA-TECDOC-1509), June 2006. https://www-pub.iaea.org/MTCD/Publications/PDF/te_1509_web.pdf.
Kabeyi, M. J. B., & Olanrewaju, O. A. "The Levelized Cost of Energy and Modifications for Use in Electricity Generation Planning." *Energy Reports*, Volume 9, Supplement 9, 495-534, September 2023. https://doi.org/10.1016/j.egyr.2023.06.036.
Kosowatz, J. "SMRs Gain Acceptance, but Waste Issues Remain." *ASME*. July 21, 2022. https://www.asme.org/topics-resources/content/energy-blog-small-nuclear-reactors-are-promising,-but-disposal-issues-remain. (accessed March 26, 2024).
Krall, L. M., Macfarlane, A. M., & Ewing, R. C. "Nuclear Waste from Small Modular Reactors." *Proceedings of the National Academy of Sciences*, 119(23), (2022). https://doi.org/10.1073/pnas.2111833119.
"Levelized Costs of New Generation Resources in the Annual Energy Outlook." *U.S. Energy Information Administration, 2023.* https://www.eia.gov/outlooks/aeo/electricity_generation/pdf/LCOE_methodology.pdf. (accessed March 26, 2024).
Lewis, C., MacSweeney, R., Kirschel, M., Josten, W., Roulstone, T., & Locatelli, G. "Small Modular Reactors: Can Building Nuclear Power Become More Cost-Effective?" *Department of Energy and Climate Change*, 2016. https://www.researchgate.net/publication/321715136_Small_modular_reactors_Can_building_nuclear_power_become_more_cost-effective.
"License Issued for Russia's First Land-Based SMR." *World Nuclear News*, 2023. https://world-nuclear-news.org/Articles/Licence-issued-for-Russia-s-first-land-based-SMR. (accessed March 26, 2024).
"Licensing and Project Development of New Nuclear Plants." *World Nuclear Association*, 2015. https://www.world-nuclear.org/uploadedfiles/org/wna/publications/working_group_reports/wna_report_nuclear_licensing.pdf. (accessed March 26, 2024).
Liou, J. "Decommissioning by Design: How Advanced Reactors are Designed with Disposal in Mind." *International Atomic Energy Agency*, July 18, 2023. https://www.iaea.org/bulletin/decommissioning-by-design-how-advanced-reactors-are-designed-with-disposal-in-mind. (accessed March 26, 2024).
Lloyd, C., Roulstone, A. & Middleton, C. "The Impact of Modularization Strategies on Small Modular Reactor Cost." *American Nuclear Society*, 2018. https://doi.org/10.17863/CAM.25793.
"Loan for Nuclear Power," *The World Bank*, 2016. https://documents.worldbank.org/en/publication/documents-

reports/documentdetail/700621467993172257/loan-for-nuclear-power. (accessed April 20, 2024).
Locatelli, G., Pecoraro, M., Meroni, G., & Mancini, M. “Appraisal of Small Modular Nuclear Reactors with ‘Real Options’ Valuation.” Proceedings of the Institution of Civil Engineers - Energy, 170(2), 51-66, 2017. https://doi.org/10.1680/jener.16.00004.
Lokhov, A., Cameron, R., & Sozoniuk, V. “OECD/NEA Study on the Economics and Market of Small Reactors,” *Nuclear Engineering and Technology*, 45(6), 701-706, 2013. https://doi.org/10.5516/NET.02.2013.517.
Maronati, G., & Petrovic, B. "Extending Modularization from Modules to Super Modules: A Cost Evaluation of Barge-Transportable Small Modular Reactors.” *Proceedings of the 2018 International Congress on Advances in Nuclear Power Plants* (ICAPP 2018) (pp. 357-362), American Nuclear Society, 2018. https://www.scopus.com/record/display.uri?eid=2-s2.0-85050104333&origin=inward&txGid=1fd55fa87963cc8a132087e78386fa4b.
Mignacca, B., & Locatelli, G. “Economics and Finance of Small Modular Reactors: A Systematic Review and Research Agenda.” *Renewable and Sustainable Energy Reviews*, 118, Article 109519, 2020. https://doi.org/10.1016/j.rser.2019.109519
“Milestones Approach.” *International Atomic Energy Agency*, October 13, 2017. https://www.iaea.org/topics/infrastructure-development/milestones-approach. (accessed March 26, 2024).
Moniz, E., Hezir, J., Comello, S., & Brown, J. “A Cost Stabilization Facility for Kickstarting the Commercialization of Small Modular Reactors.” *EFI Foundation*, 2023. https://efifoundation.org/wp-content/uploads/sites/3/2023/10/20231011-CSF-FINAL-1.pdf.
“More on Safeguards Agreements.” *International Atomic Energy Agency*. https://www.iaea.org/topics/safeguards-legal-framework/more-on-safeguards-agreements. (accessed March 26, 2024).
Muransky, O., & Ionescu, M. “Small Modular Reactors can be Built with Generation IV Reactor Designs.” *ANSTO*. Australian Government, July 17, 2022, https://www.ansto.gov.au/news/small-modular-reactors-can-be-built-generation-iv-reactor-designs. (accessed April 18, 2024).
Nadig, S. “The Nuclear Icebreakers Enabling Drilling in Russia’s Arctic.” *Mining Technology*. August 15, 2023. https://www.mining-technology.com/features/the-nuclear-icebreakers-enabling-drilling-in-russias-arctic/?cf-view. (accessed March 26, 2024).
“Nuclear Energy (Financing) Act 2022.” *UK Parliament*, April 5, 2022. https://bills.parliament.uk/bills/3057.
“Nuclear Power in Russia.” *World Nuclear Association*, March 2024. https://world-nuclear.org/information-library/country-profiles/countries-o-s/russia-nuclear-power.aspx. (accessed April 20, 2024).
“Nuclear Power Economics and Project Structuring.” *World Nuclear Association*, Report No. 2017 / 100, 2017. https://world-nuclear.org/getmedia/84082691-786c-414f-8178-a26be866d8da/REPORT_Economics_Report_2017.pdf.aspx. (accessed March 26, 2024).
“Nuclear Regulatory Commission Charts a Path Forward on Part 53.” *The Breakthrough Institute*, 2024. https://thebreakthrough.org/issues/energy/nuclear-regulatory-commission-charts-a-path-forward-on-part-53. (accessed March 26, 2024).
“Nuclear Safety.” *European Bank for Reconstruction and Development*. https://www.ebrd.com/nuclear-safety.html. (accessed April 20, 2024).
“Poland / Government Considering Contracts for Difference Financing for First Nuclear Plant, Reports Say,” *Nucnet*, January 30, 2024. https://www.nucnet.org/news/government-considering-contracts-for-difference-financing-for-first-nuclear-plant-reports-say-1-2-2024. (accessed April 20, 2024).

Popov, Andrey. “Russian Vision of the Problems and Prospects of the International Legal Framework in the Context of Small Modular Reactors and Transportable Nuclear Power Units.” *Nuclear Law*, 45 – 54, January 1, 2022. https://doi.org/10.1007/978-94-6265-495-2_3.

“Processing of Used Nuclear Fuel.” *World Nuclear Association*, December 2020. https://world-nuclear.org/information-library/nuclear-fuel-cycle/fuel-recycling/processing-of-used-nuclear-fuel.aspx. (accessed March 26, 2024).

R. Cantor and J. Hewlett, “The Economics of Nuclear Power: Further Evidence on Learning, Economies of Scale, and Regulatory Effects,” *Resour. Energy*, vol. 10, pp. 315–335, 1988.

“Radioactive Waste Management.” *Nuclear Waste Disposal - World Nuclear Association*, January 2022. https://world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-wastes/radioactive-waste-management.aspx. (accessed April 18, 2024).

Raikar, S., & Adamson, S. “Renewable Energy Finance in the International Context,” *Academic Press, Renewable Energy Finance* (pp. 185-220), 2020. https://doi.org/10.1016/B978-0-12-816441-9.00013-1.

Ramana, M., Hopkins, L. B., & Glaser, A. “Licensing Small Modular Reactors.” *Energy*, Volume 61, 55-564, November 2013. https://doi.org/10.1016/j.energy.2013.09.010.

Rosales, J., François, J.-L., & García, C. "Neutronic Assessment of a PWR-Type SMR Core with TRISO Particles Using Mixed-Oxid Fuel Strategies.” *Progress in Nuclear Energy*, Volume 154, 104470, December 2022. https://doi.org/10.1016/j.pnucene.2022.104470

“Russian Export Push for Floating Nuclear Power Plants.” *World Nuclear News*, 2023. https://world-nuclear-news.org/Articles/Russian-export-push-for-floating-nuclear-power-plants. (accessed March 26, 2024).

Schepers, N. “Russia's Nuclear Energy Exports: Status, Prospects and Implications.” *EU Non-Proliferation and Disarmament Consortium Non-Proliferation and Disarmament Paper*, No. 61, February 2019. https://www.sipri.org/sites/default/files/2019-02/eunpdc_no_61_final.pdf

Siserman-Gray, C., & Landine, G. “Cybersecurity for Small Modular Reactors (SMRs): Regulatory Challenges and Opportunities.” *Pacific Northwest National Laboratory* (PNNL), 2023. https://resources.inmm.org/sites/default/files/2023-07/finalpaper_378_0512115036.pdf.

“Small Module Reactors.” *International Atomic Energy Agency (IAEA).* https://www.iaea.org/topics/small-modular-reactors. (accessed April 22, 2024).

“Small Nuclear Power Reactors.” *World Nuclear Association*, February 2024. https://www.world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/small-nuclear-power-reactors.aspx. (accessed March 26, 2024).

“SRM-SECY-23-0021: Proposed Rule: Risk-Informed, Technology-Inclusive Regulatory Framework for Advanced Reactors.” *United States Nuclear Regulatory Commission*, 2024. https://www.nrc.gov/docs/ML2406/ML24064A039.pdf. (accessed March 26, 2024).

Stewart, W. R., & Shirvan, K. “Capital Cost Estimation for Advanced Nuclear Power Plants.” *Renewable and Sustainable Energy Reviews*, 155, Article 111880, 2022. https://doi.org/10.1016/j.rser.2021.111880.

“Storage and Disposal of Radioactive Waste.” *World Nuclear Association*, 2023. https://world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-waste/storage-and-disposal-of-radioactive-waste.aspx. (accessed March 26, 2024).

“The Future of Nuclear Energy in a Carbon-Constrained World.” *MIT Energy Initiative*, 2018. https://energy.mit.edu/research/future-nuclear-energy-carbon-constrained-world/. (accessed March 26, 2024).

“The NEA Small Modular Reactor Dashboard.” *Nuclear Energy Agency*, No 7650. July 20, 2023. https://www.oecd-nea.org/jcms/pl_78743/the-nea-small-modular-reactor-dashboard.

"The SMR Platform and Nuclear Harmonization and Standardization Initiative (NHSI)." *International Atomic Energy Agency*, April 12, 2023. https://www.iaea.org/services/key-programmes/smr-platforms-nhsi. (accessed March 26, 2024).
"Treaties under IAEA Auspices." *International Atomic Energy Agency*. https://www.iaea.org/resources/treaties/treaties-under-IAEA-auspices. (accessed March 26, 2024).
Watson, N., & Morelova, N. "Repurposing Fossil Fuel Power Plant Sites with SMRs to Ease Clean Energy Transition." *International Atomic Energy Agency*, June 16, 2022. https://www.iaea.org/newscenter/news/repurposing-fossil-fuel-power-plant-sites-with-smrs-to-ease-clean-energy-transition. (accessed March 26, 2024).
"What are Small Modular Reactors (SMRs)?" *International Atomic Energy Agency*, September 13, 2023. https://www.iaea.org/newscenter/news/what-are-small-modular-reactors-smrs. (accessed March 26, 2024).
Zarębski, P., & Katarzyński, D. "Small Modular Reactors as a Solution for Renewable Energy Gaps: Spatial Analysis for Polish Strategy." *Qualitative Analysis and Environmental Sustainability Assessment of Energy, Energies*, 16(18), 6491. September 8, 2023. https://doi.org/10.3390/en16186491.

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