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Small Modular Reactor Deployment and Obstacles to Be Overcome

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Abstract: To meet climate policy goals, it will be necessary to deploy a series of low-carbon energy technologies, including nuclear power. The small modular reactor (SMR) can potentially support climate change mitigation and energy security issues. Small modular reactors (SMRs) are gaining popularity; however, one crucial debate is whether SMRs can compete economically with conventional nuclear reactors or not. From a commercial point of view, SMRs will be able to provide process heat in various industrial applications, replace older nuclear, natural gas, and coal power facilities, and serve smaller energy markets with less established infrastructure. Realizing these advantages would rely heavily on the near-term quick up-scaling of SMRs; this paper, then, examines and identifies some of the most hindering constraints and barriers for the quick deployment of SMR such as the technology choice, licensing, economy of scale and financing, public acceptance, supply chain, and proliferation. A clear identification of the evident and more hidden bottlenecks preventing a quick deployment is made putting in evidence areas in need of much deeper analysis than the one conducted by the SMR community so far.

Keywords: small modular reactor deployment; licensing; public acceptance; financing; supply chain

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1. Introduction: SMR Technology Overview

Nuclear energy is a reliable and environmentally friendly energy source, with emissions similar to, or lower than, those from renewable sources [1,2]. Although other sources have lower capital costs, they are constrained by nature regarding lower reliability, capacity considerations, and location [3]. In addition to helping relieve environmental concerns brought on by rising fossil fuel usage globally, it is essential to meet the expanding clean energy needs [4–8], which is beneficial in two major ways: first of all, it does not suffer from seasonal fluctuations (and increasingly, shortage of water) with respect to renewables; second, it is a low-carbon emission technology with very low air pollution (mainly ppm 2.5 and 10). According to scientists, air pollution caused by the combustion of fossil fuels was responsible for one in every five deaths worldwide in 2018—a total of 8.7 million lives lost [9]. Improving energy security, especially in light of the recent events in Ukraine and energy crisis in Europe, is a significant reason for advancing nuclear power in general and small modular reactors in particular [2,10,11]. Small modular reactors (SMRs) have gained popularity as cutting-edge alternatives to large conventional reactors due mainly to their potential for significantly improved safety performance and smaller unit sizes, resulting in lower upfront capital requirements and affordability, grid considerations, and better adequacy in regard to electricity demand and market uncertainty [12–20].

Small modular reactors (SMRs) are newer-generation nuclear reactors with components and systems such that their design lends itself to modular manufacturing in a factory and then movement as modules to the site. This will introduce greater certainty of lowering construction costs and timelines by utilizing manufacturing learning and minimizing on-site work [21–27]. Although fewer components are handled during factory manufacturing which enhances worker safety on-site [28], and cost savings in labour and construction may result from factory fabrication, it is anticipated that the costs for the supply chain would be rather expensive [28]. Tokuhiro et al. [29] considered various plausible scenarios corresponding to proposed cost savings in commercial construction and deployment of SMRs.

Furthermore, unlike larger reactors, SMR designs are more compact because many parts, including reactor coolant pumps, pressurizers, and steam generators, are incorporated into a single reactor vessel [11,30–32]. SMRs are smaller in size and power capacity than current conventional reactors [18,33–35]. Small modular refers to a factory-constructed, portable, and scalable reactor that can be grouped with other modules to form a large-scale nuclear power plant with an equivalent electric power of less than 300 MW [36–39].

Modularization is an essential aspect of SMR engineering development as it provides the benefits of cheaper initial capital investment, scalability, and siting flexibility in areas unable to handle a large conventional reactor [40,41]. Moreover, modularity (a plant designed by assembling nearly similar reactors of lower capacity) [42] enables co-siting economies [43,44], cogeneration for the load following of nuclear power plants (NPPs) [45], greater and quicker learning, and improved flexibility [46]. Additionally, during the manufacturing and assembly stage, modularization enables functional and system testing, resulting in a better degree of parallelism and, as a result, a shorter time [47,48]. It usually refers to techniques from more established sectors such as shipbuilding and aircraft manufacturing or automotive industry. These approaches combine gains in quality and efficiency resulting from serial factory manufacturing and attempts at component standardization to the degree practical. As stated by those businesses, more simple on-site installation of preassembled modules enables more regulated working conditions [31,34,49–52].

In theory, SMRs are made to order, with modules tested in the factory before being delivered to utilities for installation. Moreover, SMRs would need shorter construction durations and fewer interest payments because of their smaller sizes [53–55]. A conventional large nuclear reactor would need 5–8 years to complete; factory-built SMRs hope to do this in 4–5 years for the FOAK (First-of-a-kind) and 3–4 years for the NOAK (*n*th-of-a-kind) [38,56–59]. Therefore, these methods are designed to shorten construction periods while also improving quality and lowering the financial costs of today's large construction projects [60–62]. The most fundamental purpose of SMR technology is to dramatically minimize the scheduling risk and financing costs associated with nuclear reactor construction [52,55].

SMRs provide several advantages, including economy of scale from standardization of components and design simplification [41,63–65], modularity, lower financial risk, load following design, factory manufacturing and assembly, and adaptability for off-grid applications [66–69]. SMRs are viable in remote places where qualified staff and greater transportation costs are a major concern [59,70]. They can also provide electricity and heat on demand to meet the needs of large energy consumers [71]. Thus, to facilitate the transition to low-carbon power systems, SMRs may provide new options [72]. Many SMR systems include compact design features and passive or inherent safety, which minimize fuel damage and radiation emissions caused by coolant loss or reduced coolant flow [73–75]. Additionally, the smaller fuel inventory of SMRs lowers the full release that might occur in the case of an adverse occurrence [11].

With the introduction of SMRs to the market, the requirement for flexible power production for a broader range of customers and applications may be met, and traditional nuclear reactors' financial and safety constraints can be overcome [34,76]. SMR designs have used a variety of reactor types, including water-cooled reactors, high-temperature gas-cooled reactors, liquid metal, sodium, and gas-cooled reactors with rapid neutron spectrum, molten salt reactors, and most recently, microreactors. In 2020, the IAEA released an update of the advanced reactors information system (ARIS) manual, which displays the present status of some 75 different SMR designs [77].

The SMR design and engineering are completed after the regulatory review and/or construction inside a nation has received regulatory permission. Only the American NuScale, Korean SMART, Argentinian CAREM, Russian, and Chinese designs have received regulatory clearance or are currently under construction. Many designs' proposals will not complete regulatory approval or construction by 2030. To encourage SMRs, the Canadian Nuclear Safety Commission (CNSC) has launched an optional three-phase prelicensing vendor evaluation that analyses new reactor designs against CNSC design standards [78].

SMRs, given their low cost and potential for modularization, represent also a great candidate for integration and harmonization with renewable technologies to fight climate change. The possibility to have nuclear load following SMRs makes them an ideal partner for renewable energy sources strongly mitigating, if not fully eliminating, the source of uncertainty associated with renewables [79]. Energy policy activities should then aim to develop energy strategies to reach this goal [80].

2. Methods: Main Obstacles to Large-Scale SMR Deployment

To start a new nuclear power program, considerable planning, preparation, public engagement, time, and money are required. It will be essential for the economic viability of SMRs to have a sufficiently large market to sustain the economies of scale dynamics [81]. Even if the world's nuclear capacity deficit is not evident until 2030–2050, action must be taken immediately. Due to nuclear project timelines, decisions must be made in advance to guarantee sufficient globally deployed nuclear capacity for a net zero scenario [82,83]. To lower project costs, improve deployment timelines, boost public confidence, and address financial constraints, targeted legislation, continued funding, and international cooperation are required [84,85].

The next section of the study describes the problems and issues that must be overcome for massive SMR deployment to be possible. Six major areas are identified as critical to the development of future small modular reactors, identifying the most significant bottlenecks and hindering situations seen with the current development. As the international community and companies proceed in the development phase, other issues might arise or might change prospective due, for example, to the geopolitical international situation [86,87].

3. Methods: Complexity and System Level Analysis Perspectives

Applied complexity analysis, specifically for nuclear systems, is consideration of the various levels of system analysis—the total number of variables and parameters (V&P) that may describe or characterize the complexity of the system [88]. Here, variables and parameters may include associated uncertainties, whether they are attributed to technical and/or non-technical influences. If scenarios are defined by the total number of V&P, the combinatorial explosion thereof (the mathematical factorial) can easily exceed $\sim 1.0 \times 10^{64}$ (for 50 factorial or 50!). Judicial or methods-based use of heuristics, for example, by Kahnemann [89], is one of the ways to propose practical solutions to complex problems. Here, while the issues and challenges identified below are major factors and influences, the complexity of the challenge is self-evident. As described, proposed and asserted by Tokuhiro [90] and simply stated, the "level of public acceptance (LOA) is proportional to the ratio of perception of benefit to the perception of risk". Further, a high-level V&P for both technical and non-technical issues and challenges may be characterized by heuristics as follows: (LENDIT) length, energy, number, distribution, information, and time. This heuristic metric may serve as an effective communication tool across many stakeholders. Use of heuristics can offer practical solution of complex issues when consensus agreement by stakeholders is difficult to secure [91] and has recently been proposed to examine both energy decision-making processes and bias present even when using (AI) Artificial Intelligence.

3.1. Methods: Technology Choice

Large-scale and global markets are essential for investments in large-scale industrial fabrication facilities; hence, technology selection is crucial. As long as there are multiple competing SMR designs, no single design or vendor will be able to gain a substantial market share [92].

Despite approximately 70+ SMR design ideas being produced throughout the globe, no SMRs are under construction at this time with announced plans to connect to an existing electrical grid. The first offers for genuine sales in the market are still several years away, but certain design businesses may contest this. The present barrier is that these designs have not shown that they can compete in the marketplace for energy production and/or process heat, lack regulatory permission and/or approval, or both [93]. However, only a small number of SMRs are now being constructed worldwide (mostly under national support), and they are all being used as prototypes for products that may eventually be sold more widely [94].

Therefore, it is likely that no single design or provider will be able to take a significant portion of the market share as long as there are still a number of competing SMR designs [92].

Table 1 provides a summary of vendors who have service agreements with the Canadian CNSC for prelicensing engagements for their new reactor designs using the Vendor Design Review (VDR) procedure. Based on the vendor's anticipated timetable, the duration of each review is estimated. A Phase 1 review (can take) takes 12–18 months, whereas a Phase 2 review (can take) takes 24 months [52].

Table 1. VDR service agreements between the vendor and the CNSC. Adapted from [52] (as of November 2020).

No.	Name of Design	Capacity (MWe)	Moderator and Coolant Type	Status (Canadian Regulator)
1	IMSR	200	Integral molten salt reactor	Phase 2 in progress
2	MMR-5 and MMR-10	5–10	High temperature gas	Phase 1 completed (12/2016)
3	SEALER	3	Molten lead	Phase 1 started, on hold
4	ARC-100	100	Liquid sodium	Phase 1 complete
5	Moltex Energy Stable Salt Reactor	300	Molten salt	Phase 1 in progress
6	SMR-160	160	PWR	Phase 1 in progress
7	NuScale	60	iPWR	Phase 2 in progress
8	U-Battery	4	High temperature gas	Phase 1 started
9	BWRX-300	300	BWR	Phase 2 in progress
10	Xe-100	75	High temperature gas	Phase 2 in progress
11	eVinci Micro-Reactors	25	Solid core heat pipe	Phase 2 started
12	StarCore Module	10	High temperature gas	Series Phase 1 and 2

3.2. Methods: Licensing and Regulations

One of the significant potential obstacles to deploying these novel SMR designs is the capability of individual national regulatory bodies to evaluate and approve them [95]. Moving the work from the factory to the site is one of the main concepts behind modularization. This implies that most licensing-related tasks might be carried out at one or more factories. As a result, the regulatory body's most significant problem would be ensuring the traceability of components while considering the whole supply chain [96,97]. Additionally, several countries throughout the globe that have never constructed a nuclear power plant are actively looking at the deployment of nuclear power plants that need licensing and regulations to be in place [98,99].

To aid in designing and developing these FOAK reactors and ensuring that the path to construction and operation is as safe, quick, and affordable as possible, regulators and developers will need to collaborate [52]. The Cooperation on Reactor Design and Licensing (CORDEL) group of the World Nuclear Association has established a task force for SMRs. In 2015, this task force published 'Facilitating International Licensing of Small Modular Reactors' that examined SMR licensing [100].

Critical difficulties in licensing and design certification for SMRs have been recognized by the IAEA's Nuclear Power Technology Development Section, ranging from first-of-its-kind engineering, the viability of multiple modules per site, proliferation resistance, security, control room staffing, emergency planning zone, and technology transfer and proprietary design protection [98,100–102].

Furthermore, licensing of SMRs is one of the most challenging issues for SMR vendors. As the first step to deployment, each SMR design should be licensed in one or more nations, usually its "home" country. This is based on the notion that countries may be reluctant to purchase an SMR if the design has not received regulatory approval from the nation of origin [103]. For nations considering their first nuclear power station, the IAEA recommends the following advice to address this issue: "a finished and frozen nuclear reactor design, especially one that has passed regulatory scrutiny in other nations, might reduce project risks. A full design helps assure that the project will be completed on time and under budget, even though some revisions may be necessary owing to regional regulatory requirements or specific site conditions [104].

Moreover, licensing any new nuclear reactor design is not straightforward due to the lack of test facilities or expertise in running such reactors to verify new designs [94]. Additionally, licensing, particularly in the United States and Western Europe, is time-consuming and expensive, requiring extensive analysis and assessments [35,105]. Any SMR design is unique, featuring many never-before-used characteristics [106]. These unique concepts are rarely regulated for approving safety cases [105]. To address these issues, nearly all countries have licensing procedures for large reactors. Although most countries would likely need to adjust their licensing procedures to accommodate SMRs, this can significantly facilitate the SMR licensing process [92,103,107], especially during the early phases [104]. However, planning to license SMRs should consider the design's modularity and the potential to produce a significant portion of the plants off-site in factories [108].

Considering the financial elements of SMR licensing and nuclear regulation is crucial. If they do not account for the reactor's power production, the cost of the license fee, nuclear insurance, and cost of funds borrowed during construction may be important cost considerations [24]. Due to the anticipated significance of being the first SMR to be marketed internationally, as well as the strong commitment of national governments in countries developing SMR designs, regulators are likely to face pressure to approve these changes; yet, the accompanying delays may be reduced, and the process may be facilitated by a government program supporting licensing [105,109,110].

To this end, although there are emerging bi-/tri-lateral initiatives in regulatory "harmonization", at the beginning of 2023, any landmark harmonization agreement is 5–10 years away. Although this is a worthy goal, international or multiple-party, international agreements require much time, and are not all-encompassing as nations prefer preserving developed and national (own) regulatory practices. A key to each national (SMR, new nuclear) approach is the expectation and/or requirement of a spent fuel and/or radioactive waste and decommissioning plan or strategy, elements or which were discussed and presented in [111].

In the end, how effectively a nation can solve cross-border licensing, liability, and regulatory concerns—who regulates and who is responsible—is another evident difficulty [99] to be overcome.

SMR designs with various technical specifications have been proposed and are in development. Many of these designs are light water reactor concepts. However, there are specific non-LWR concepts based on different fuel types and coolant choices (gas, molten salt, liquid metal). Tables 1 and 2 give a snapshot of reactor concepts—design engineering and regulatory status. One will note that, broadly, there can be nationally defined and funded initiatives that are "self-funded" such as in the United States, Russia, China, France, Japan, South Korea, India, and Argentina [103]. Self-funded usually means under the national budget that may yield a test-to-demonstration reactor with no or limited connection to an electrical grid. These units often answer open technical and non-technical questions, and in so doing, provide lessons, reduce the uncertainty risks, and establish strategies for commercial deployment under the guise of a national effort.

Table 2. Major nuclear countries' design and licensing progress. Adapted from [68,103].

Reactor Design	Technology	Country of Origin	Status
AHWR	Light-water-cooled, heavy-water-moderated; thermal spectrum, Th-based fuel. 300 MWe/920 MWth.	India	Prelicensing design safety review. Last update, ~2013.
HTR-PM	Graphite-moderated, helium (gas)-cooled; thermal spectrum. 211 MWe/500 MWth	China	Preliminary safety analysis report review. Full power and connected to grid, December 2022. Originally started in ~1986.
ACP-100 (Linglong One)	Light-water-moderated and -cooled; thermal spectrum. ~125 MWe/385 Mwth.	China	Under development. Design ~2010. As of 2021, under construction.
SMART	Light-water-moderated and -cooled; thermal spectrum. 100 MWe/330 MWth	South Korea	Standard design approval received. Integral, scaled facility operating as of 2023.
KLT-40S	Light-water-moderated and -cooled, thermal spectrum. 70 MWe/300 MWth	Russia	Licensed. Nationally under construction.
SVBR-100	Lead–bismuth-eutectic-cooled, no moderator; fast spectrum. 101 MWe/280 MWth	Russia	Under development.
mPower	Light-water-moderated and -cooled, thermal spectrum. ~180 MWe/~540 MWth	United States	Development stopped in 2017.
NuScale	Light-water-moderated and -cooled; thermal spectrum. 77 MWe/~250 MWth	United States	(US) Regulator certified. Integral, scaled facility operating.
Westinghouse SMR	eVinci is a micro-reactor; 5 MWe/up to 13 MWth	United States	Under development. Test engineering program.
HiSMUR (Holtec)	Light-water-moderated and -cooled; thermal spectrum.	United States	Under development since ~2011.

3.3. Methods: Supply Chain and Trained Human Resource

It will be challenging to create a supply chain with the appropriate technical know-how and quality control methods, and it will be essential to have confirmation from the power markets that this is necessary. After the supply chain is established, interruptions in industrial orders may be expensive, leading to the sale of essential equipment and the termination of critical employees. Reassembling a discontinued product line might be rather expensive. As a consequence, a reactor designer may employ ordinary commercial items or depend on reputable nuclear suppliers to a greater extent; this may make this problem easier to control. This might include assembling a well-coordinated supply chain of nuclear-qualified suppliers and distributors [52]. SMRs, in this sense, are more sensitive than large-scale facilities as they are planned to be manufactured massively in a modular fashion, reducing the unit cost substantially.

As with LWRs, a supply chain is key to SMR competitiveness. Even while new construction projects have helped reconstruct global supply networks, more work must be done. Strategic collaborations for critical components will be needed to share the risks of early SMR projects and speed up implementation. After a few modules are delivered, the SMR supply chain may consolidate (i.e., have fewer vendors) to gain economies of scale. These estimates depend on market trends and harmonization to drive competitiveness. Future supply chain management techniques may integrate more to increase efficiency. Collaboration to harmonize regulations and standards might boost localization options and the pool of suppliers, resulting in a more competitive supply chain and cutting costs. SMRs may need changes to the fuel cycle. Collaboration in R&D is also crucial. SMR supply chain collaborations with research institutions and colleges will provide a trained workforce and R&D infrastructure. This partnership will also speed up the adoption of advanced manufacturing and other digital applications [92].

Modules are built on-site or off-site, delivered to their ultimate location, and then assembled in a building [112,113]. These construction methods for reactor buildings need enormous lift and rigging capabilities, sometimes the construction of temporary buildings, higher transportation expenses by truck, rail, or barge, and installation close to the user, such as residential housing areas, hospitals, military bases, or large governmental complexes [114]. However, because of the small size of many SMR modules, large specialized carriers, highway closures, or bridge reinforcing along the transportation route are not always required. SMRs make it considerably easier to transport all of the construction equipment to the job site [31,115].

However, the modules may be manufactured concurrently with early site excavations and preparatory work, decreasing the total construction period and, consequently, the long-term financing costs associated with borrowed capital [52,116].

In the past, supply chain operations were affected by the timeliness of engineering and design deliverables to define materials and components. The supply chain must recognize when site delivery is needed to assist construction and minimize extra site storage. This affects procurement. In addition to permanent plant equipment, suppliers must supply operating and maintenance instructions, replacement parts suggestions, and technical assistance for installation, commissioning, and operation. Past procedures lacked this assistance. For this, a completely integrated project schedule is vital. Engineering teams must know when their deliverables are needed for activities such as solicitations and orders. Timing is not the sole factor. The purchase requirements must be followed in engineering papers. Architect engineering companies have interface needs and technical procurement specification methods. SMR stakeholders must ensure that processes and procedures are current and meet the demands of all parties, including commissioning and operations teams [117].

Furthermore, SMR suppliers are collaborating with regulatory organizations to show that they can shrink the size of the necessary EPZs (Emergency Planning Zone). Suppose the local population can more readily accept the technology. In that case, this will also provide SMR vendors greater freedom in future siting, and SMRs have more potential sites than major nuclear power plants [52,118].

3.4. Methods: Public Perception and Acceptance

Opposition to nuclear power has historically been generated from both factual damage attributed to nuclear disasters (for example Chernobyl, Fukushima Daiichi), and societal perception of risk (versus benefit)—suggested early by Starr [119], Starr, Rudman, and Whipple [120], and later by Slovic [121] and Slovic and Peters [122]. Over 100+ years, starting both from the risks and benefits of radioactivity, to the risks of atomic-based weapons, to the subsequent development of nuclear energy, and to socio-technical discourse on spent nuclear fuel and radioactive waste forms, radiation and nuclear energy have been widely discussed [123,124]. Increasingly, in the presence of social media and with cost of infrastructure as a prime discourse topic, both the historical cost and uncertainties associated with new nuclear construction projects generate opposition to deployment of new plants. We note as emerging and self-evident that the conflict in Ukraine will continue to define impacts of energy infrastructure and the generated risks of various types therein.

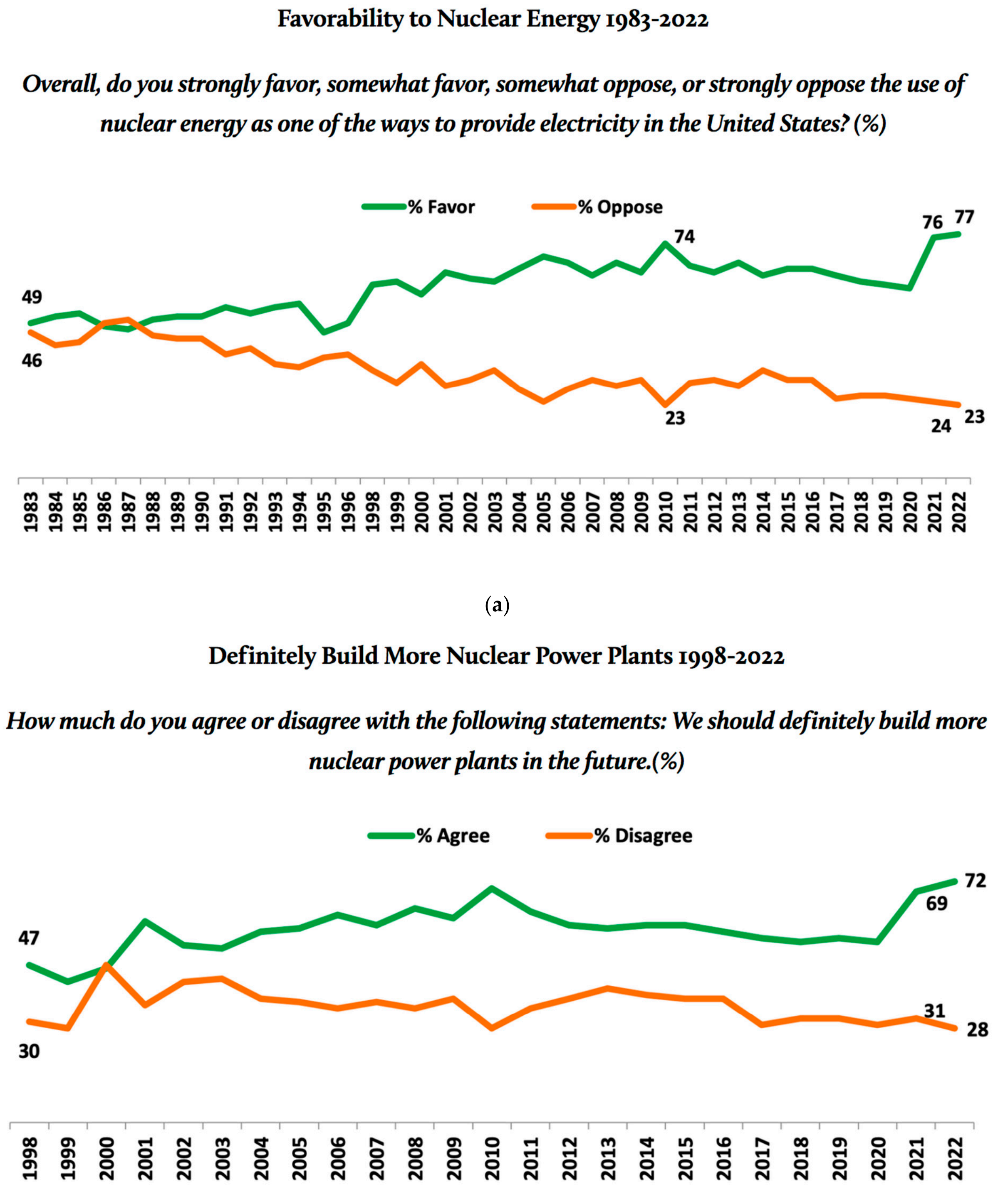
According to early research, the public considers involuntary activities more dangerous than voluntary ones. The tendency of people to emphasize consequence over probability is known as probability neglect, according to more recent research [88,125].

Safety concerns and expenses may be significantly reduced through passive safety design, integration of key components into a single unit, and underground deployment [27,126,127]. SMRs with better passive safety mechanisms and smaller source terms should be more widely accepted by the public in various situations when compared to larger multi-gigawatt reactors. Furthermore, the potential for domestic job creation is provided by the capacity to localize specific construction work and the production of non-safety components, which helps with public acceptance in places where employment is a significant problem [11,52,92,128].

Public views of the risk variables may differ across nations and regions and are often possibly impacted by proximity to a nuclear source. A change in perspective may take place over time with an improved understanding of the need and available options as new experiences, knowledge, or public information spreads [99,129,130].

As with any nuclear reactor technology, the public remains worried about reactor safety, nuclear waste disposal, nuclear proliferation, and nuclear security [131]. People worldwide are becoming more concerned about climate change and becoming more aware of the possible role nuclear energy may play in mitigating it. According to the Intergovernmental Panel on Climate Change (IPCC), global energy production and consumption must be entirely decarbonized by 2050, with fast emission reductions commencing immediately [132]. Therefore, the only way to do this is to integrate several technologies, including nuclear power and renewable energy [52].

The percentage of people who supported nuclear energy rose to 77% in 2022 (survey conducted in mid-May) (Figure 1a), with similar trends for support to build new nuclear power plants in the future (Figure 1b peak in 2022 at 72%). The increasing trend (dotted blue line) is mainly attributed to the resurgence of energy interest at the turn of the millennium, even in the presence of an ongoing worldwide geopolitical crisis due to the war in Ukraine. In California and other places, energy supply issues have begun to appear. Rising support for nuclear energy, particularly among women and democrats, was fuelled by its inclusion in the public discourse as a solution to climate change and a source of clean energy, as well as a discussion of a “nuclear energy renaissance” [133–135]. Consequently, opposition to nuclear energy has been on average decreasing over time (dotted red line). It would be interesting to re-evaluate this trend particularly in the EU, after the turbulent winter of 2022–2023. The geopolitical international crisis, in addition to the very acute European energy crisis occurring alongside the events in Ukraine, is clearly setting the stage for a strong reconsideration by Europeans of the importance and reliability of nuclear power in general, but it is hard to evaluate all together as the EU does not have a common energy policy and leaves it to single states to deal with it. Opposing attitudes exist, for example, in France and Germany towards nuclear energy and nuclear power. Decision-making processes are highly politically biased even in the presence of strong support or opposition towards nuclear energy in general.



Favorability to Nuclear Energy 1983-2022

Overall, do you strongly favor, somewhat favor, somewhat oppose, or strongly oppose the use of nuclear energy as one of the ways to provide electricity in the United States? (%)

(**a**)

Definitely Build More Nuclear Power Plants 1998-2022

How much do you agree or disagree with the following statements: We should definitely build more nuclear power plants in the future.(%)

(**b**)

Figure 1. (**a**). Trends for support and opposition to nuclear energy among Americans from 1983 to 2022: Annual averages percentage—Based on data from [133–135]. (**b**). Trends for support and opposition to the construction of new nuclear power plants among Americans from 1998 to 2022: Annual averages percentage—Based on data from [135].

3.5. Methods. Finance, Investment, and Political Support

The notion of modular deployment, which promotes economies of multiples and investment scalability, underlies much of the appeal of SMRs as an investment [18,100].

Although some of the policy implications are technical, most focus on institutions and policies or the interaction between institutional and policy concerns and technological difficulties. Additionally, one of the most intriguing sociopolitical topics is anti-nuclear politics, which is mainly on the rise anytime a nuclear catastrophe causes an incremental growth in the public's opposition [97].

Since SMRs may be built one module at a time, they reduce financial risk and provide financing flexibility. Additionally, owners/operating organizations may install SMRs at existing power plant sites if coal and oil plants are decommissioned, considerably reducing costs associated with site infrastructure and transmission [52].

Government involvement with the pioneers of FOAK (first-of-a-kind) technology has a long history. Governments routinely provide funding to universities, research facilities, and companies for R&D and linkage to a technology. The government must also ensure that effective and efficient measures are taken to protect the public's health and safety. To lower the financial risk of investing in the facilities and personnel needed to develop, fabricate, test, and qualify FOAK components, systems, and structures for the first SMRs to be built and fully demonstrated, some kind of government support and/or incentives are anticipated to be necessary [52,97]

Furthermore, similar to LRs, investments in SMRs are prone to regulatory risk, shifting public opinion, and shifting energy policy [97]. Financial yield characteristics should be considered, including net present value, internal rate of return (IRR), economic evaluation production cost, upfront investment, etc. The related risk and cash flows, capital cost, construction time, etc., are some secondary but crucial aspects that need to be assessed. When the investment's economic factors are taken into account, the so-called "economy of scale" makes SMRs less attractive than larger reactors [24,35,134,135]. However, SMRs may reduce some of the economic issues of large reactors. SMR size allows incremental investment, eliminating the huge financial resources needed for LRs and the associated financial risk [27]. Despite lower upfront capital expenditures per unit, SMRs are predicted to have higher initial investment costs per kWe installed than LRs. This may result in a higher cost per kilowatt hour than LRs [21,97] Although the financial investment required to start developing SMRs at a site is proportionately less and simpler to finance than LRs, realized revenue from existing modules may also boost investor confidence [21].

Table 3 provides a summary of approximate nuclear financing models in recent times. Although variations in approach define overlap amongst the identified models, five approaches are noted. The primary differences are customisation to local/regional (stakeholder) needs and allocation of identified and agreed to risks that may be linked to a "risk holder". Further details are given in [136,137], based on an OECD–NEA workshop on funding approaches in a "new nuclear" nation, Poland. In short, risks are as follows: burden of borrowing funds during construction, construction of the plant, change in electricity market price, changes in policy/political support. Foremost on-time completion of construction, progress to full-power operations (beyond testing), connection to the grid, and generation of revenue are key. We briefly note the importance of nuclear and energy infrastructure laws and subject matter experts in infrastructures going forward; that is, under signed-to and agreed-to non-disclosures, memoranda of understanding, conditions and stipulations, integrating both technical and non-technical identified issues and challenges.

Table 3. Summary of approximate nuclear financing models in recent times.

#	Financing Model Name	Attributes, Distribution (Holding) of Risk/Risk Factors	Reported Use of Model
1	Rate based, loan guarantees, contract for defined differences	Distributed but mostly commercial, contingent upon investors and government support.	US, Vogtle site
2	Regulated Asset Base (RAB)	Government and partners. Similar to "1".	Sizewell C site
3	"Mankala" Model	Reduced. Prioritized generation, instead of profit/dividends. Shareholder "own" generation capability.	Finland, various energy infrastructure
4	Power Purchase Agreements	Distributed to power purchasers. Based on forecast needs. Garner governmental support.	Some US SMR vendors
5	Partially disclosed to undisclosed government loans (translucent)	National government assumes risks. (Includes test, demonstration—non-commercial reactors)	National reactor projects in China, Russia, Argentina, South Korea, France, US, Japan

3.6. Methods: Proliferation Risks

If SMRs prove to be commercially viable, the number of deployed SMRs might increase to several hundred or perhaps thousands. Two OECD–NEA reports [138,139] describe the (nuclear) financing challenges, relative to cost of capital and managing risks. There may be additional concerns about (nuclear) safeguards, security, and proliferation issues [140]. SMRs (and large-scale Generation IV reactor concepts) consider designs, manufacturing setups, cost burdens, and fuel-cycle details that are more proliferation-resistant if they are widely deployed [141]. However, only few research works have been reported on SMRs' proliferation resistance, and the methods currently used to evaluate that resistance are not yet well adapted for these cutting-edge configurations [142,142–145]. It has been proposed, for example, that an SMR design with a long-lifetime sealed core might decrease the potential for material diversion [146].

SMRs are currently considered for their potential to be safer and more cost-competitive than larger (and well-experimented) reactors per unit of power produced. However, as the technological and commercial competition is still open to determine which design or designs will be more effective both locally and worldwide, many considerations regarding fuel, fuel handling, and waste management are difficult to undertake. Only designs closer to existing technological concepts (LWR) might offer a more concrete analysis at this point in time. So all risk analyses and related costs must be adjusted according to the current perspectives of safeguards and non-proliferation [52] which will be more evident once the development phase and the market will have established which reactors are going to be effectively implemented.

SMR concepts and designs either have the same or similar fuel cycle issues in comparison to the existing fleet of large reactors.

Proliferation risks may be found at every fuel cycle stage, including at the front end, throughout the operation, and at the back end, with spent fuel management (including ultimate disposal) and decommissioning [97]. This is predicated on the assumption that fuel cycles are typically "once-through" and that a transition is required to close this fuel cycle to one that recycles spent fuel forms. Moreover, SMR designs may potentially impact regulators' capacity to protect the materials in the reactor core. For example, if SMRs are deployed in large numbers and distant areas, the implementation of safeguards (or challenge thereof) will be challenging [147]. Due to the potential widespread deployment of SMRs, it is crucial to establish a roadmap and repurposed safety/safeguard measures (with heavy use of remote wireless monitoring) [148]. We note that the predominant uranium-based (generating plutonium) fuel forms and thorium-based fuel forms, using various reactor concepts, generate a spectrum of little-acknowledged proliferation issues, including safeguard challenges.

3.7. Methods: Further Issues

The major remaining issue with potential deployment of SMRs is reconsideration of the nuclear fuel cycle and approach to spent fuel remediation. Although previously investigated for large reactors (LWRs), burn-up and spent fuel isotopic composition of SMR spent fuel is just gaining reconsideration in recent times. Oettingen and Cetnar [149] investigated the post-burnup (PWR) estimate of actinide content in spent fuel. A more recent paper, [150], is specific to SMRs and subject to ongoing debate.

Validation of spent fuel isotopic composition of SMR will be an open issue for the next 10 years, until such information is reported and shared. It is embedded within a larger discussion on fuel cycle options, including (again) closure of the nuclear fuel cycle.

4. Discussion: SMR Roadmap

Given the growing interest of member states in near-term SMR deployment, the IAEA roadmap aims to propose model technological roadmaps that can be tailored to their unique projects. These roadmaps are based on the greatest ideas presented during worldwide gatherings on this topic. These roadmaps assume nuclear newcomer countries have created or are well on their way to creating the requisite infrastructure to operate a nuclear power program [52].

Figure 2 illustrates a flowchart of the IAEA's SMR roadmap's essential actions. The form and content of the IAEA roadmap reflect technical meeting debates and feedback during drafting and review [52].

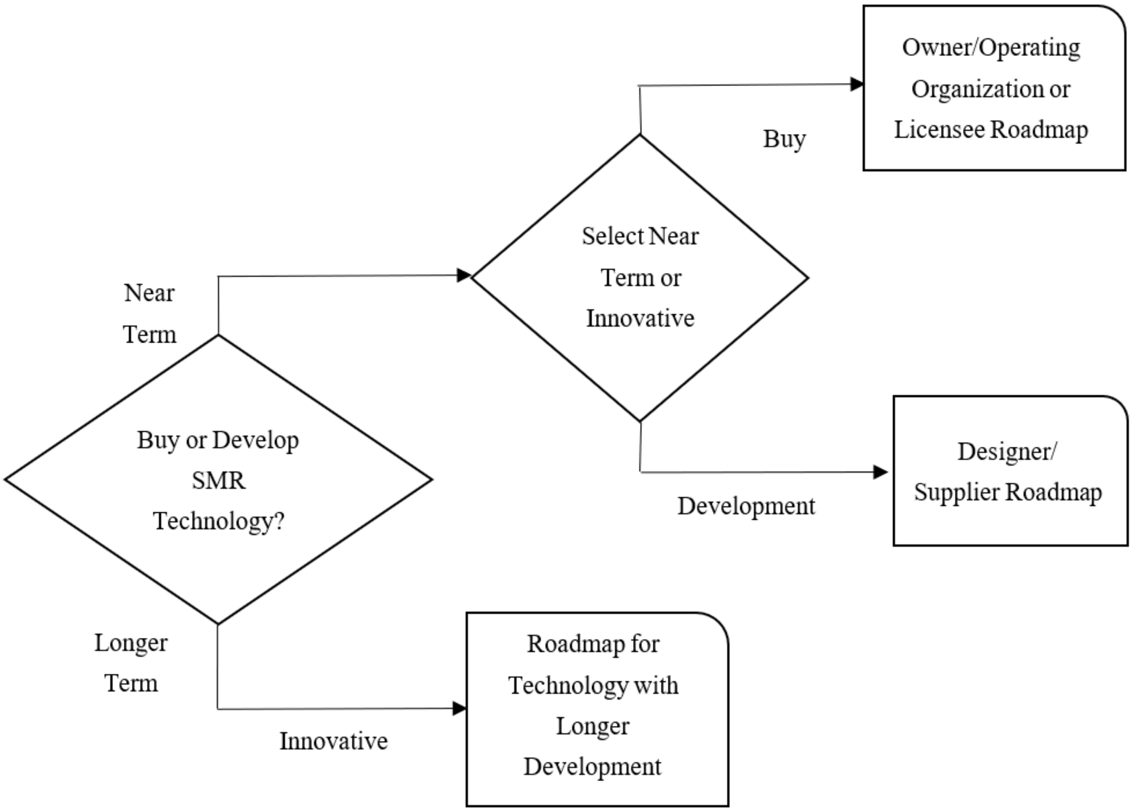


Figure 2. Flowchart of SMR technology roadmap—Own elaboration based on data from [52].

The IAEA has produced a plan for developing a nuclear power program's infrastructure. This milestones method, depicted in Figure 3, was devised to give the Member States "guideposts" to indicate their progress during the planning stages and to show national and international stakeholders their commitment to nuclear safety and control. A nuclear power program's infrastructure contains aspects for safe, responsible, and sustainable use of nuclear technology [52].

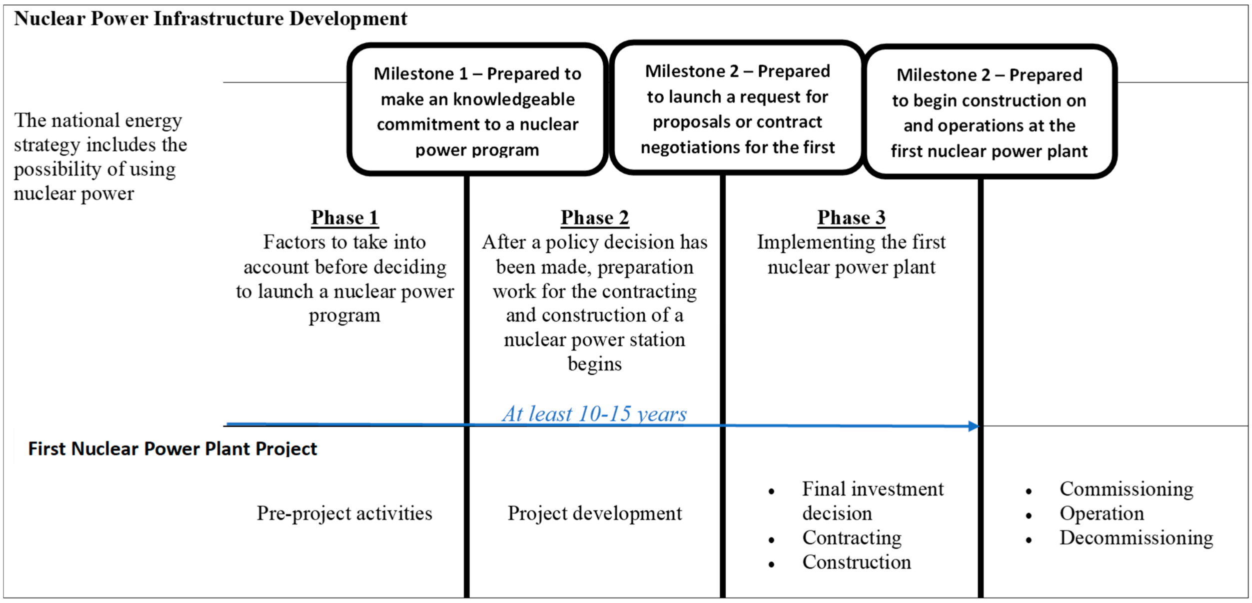


Figure 3. Developing infrastructure for a nuclear program: key milestones—Own elaboration based on data from [52].

All major nuclear nations are making strategic investments to position their industries to profit, including Canada. Canada's roadmap outlines early action priorities and thorough suggestions for "Team Canada". It asks key enablers to commit to concrete action on the suggestions. The following three activities are necessary to put the roadmap into action:

1. Critical enablers for acting quickly on priority proposals.
2. Team Canada will respond to these recommendations with pledges for additional specific action in a Canadian SMR Action Plan.
3. Senior executives and Ministers will co-create Canada's Nuclear Energy Advisory Council to review progress annually and identify future strategic priorities [151].

5. Conclusions

Nuclear energy is a dependable, low- to lower-carbon (clean) energy source with emissions comparable to renewable sources. As a result, numerous nations throughout the globe have nuclear power aspirations and plans. Yet, one has to mention the persistent anti-nuclear views, because of the acceptance of mass fear of the knowns and unknowns. Others are considering small modular reactors (SMRs), where the word "modular" is meant to convey the idea that an anticipated deployment scenario might place several smaller units on a given site rather than one (or more) NPPs, using proven, yet expensive large construction technologies.

A variety of small modular reactors (SMRs) are being developed to be marketable nuclear products. Their techno-economic characteristics resolve, partially to fully, delivery issues that previous nuclear projects have experienced, but also transform the value proposition that nuclear technology can be flexible and dispatchable as a low-carbon energy and heat option across several industries. Hence, the major areas of concern are identified and discussed.

The ideal SMR design in fact should meet demands for sustainability, passive safety, resistance to proliferation, in-factory fabrications, and ease of installation and operation, but also affordability, transportability and site selection flexibility, smaller plant footprint, and lower investment risk. SMRs might be widely employed by smaller utilities, smaller nations with financial or infrastructure limitations, remote locations or dispersed power demands, and many non-electrical uses. In particular, the supply chain and financing structure appear to be the areas where more detailed research is needed in order to address the current situation.

Still, there are several technical and institutional challenges to be addressed with further R&D: industry-accepted testing and validation of technological innovations in components, systems, and engineering, less reluctance of first-of-a-kind reactor designs, the economy of scale (promised but not yet proven), perceived risk factors for nuclear power plants, and regulatory and licensing issues, requiring strong government involvement, commitment, and financial support, and a concerted effort between governments, regulators, vendors, suppliers, and future owners to address the different challenges simultaneously.

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