Received: 30 September 2021 | Revised: 8 December 2021 | Accepted: 10 December 2021
DOI: 10.1002/wene.429

ADVANCED REVIEW

WIREs ENERGY AND ENVIRONMENT WILEY

A hopeless pursuit? National efforts to promote small modular nuclear reactors and revive nuclear power

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Edited by: Peter Lund, Editor-in-Chief

Abstract

Nuclear power plant construction has historically been challenged by problems of high cost, cost escalation, and construction delays. The newest set of large reactor projects have also been overbudget and overtime. This has prompted interest in new reactor technologies that proponents claim would not suffer these problems, specifically small modular reactors (SMRs), a class that encompasses a wide range of technologies. This article examines national efforts in three countries, Canada, the UK, and the United States, which are pursuing SMRs vigorously and where the government has funded their development generously. We compare the different strategies and foci of these national strategies, analyzing the various forms of support offered by the separate agencies of the government, and the private companies that are trying to develop SMRs. We also offer an overview of the different types of reactor technologies being pursued in these different countries. Following these, we outline the main challenge confronting SMR technologies: their ability to generate electricity in an economically competitive manner, highlighting the problems resulting from economies of scale being lost. By examining the experience so far, we find that even designs based on well-tested technology cannot be deployed till after 2030 and the more radical designs might never be.

This article is categorized under:

Policy and Economics > Research and Development
Policy and Economics > Regional and International Strategies
Energy and Power Systems > Energy Infrastructure

1 | INTRODUCTION

Nuclear power has been on the decline for a quarter century now. Its share of global electricity generation has come down from 17.5% in 1996 to around 10% in 2020 (BP, 2021). The ordering rate for nuclear power plants has been in the doldrums for more than three decades and hopes of a revival in orders through new designs, especially the so-called Generation III + light water reactors (LWRs), or through Russian and Chinese vendors opening up new markets, have proved false dawns (Thomas, 2018, 2019).

Nuclear advocates have usually responded to these problems by suggesting that new nuclear reactor designs can overcome these challenges. In the past 20 years, there have been several claims that small modular reactors (SMRs) would solve the perceived problems of inadequate safety, high costs, frequent construction cost and time overruns, and waste disposal (Carelli et al., 2004; HATCH, 2016; Ingersoll, 2009; Kessides, 2012).

At the same time, not all supporters of nuclear technology are sold on SMRs. In fact, most countries with nuclear power plants have shown little or no interest in SMRs and, among OECD countries, only the United States, the UK, and Canada are actively pursuing this option. There are SMR development programs in Russia, France, China, and South Korea, but apart from a possible sale of a Korean SMR to Saudi Arabia, there appears to be little attempt to build them in their home market in large numbers or market them internationally.[1]

Most traditional reactor vendors have either not pursued SMRs or have abandoned development work, in large part because market prospects for SMRs are poor.[2] Therefore, it might not be surprising that the SMR designs are under development are largely from companies with no previous experience of supplying power reactors, with several being start-up companies. Barring a few exceptions, electric utility companies have shown little interest in SMRs. A good illustration of this claim is the absence of a domestic customer for South Korea's System-Integrated Modular Advanced Reactor (SMART), a 100 MW pressurized water reactor.[3]

This state of affairs prompts the question: will the rhetorical commitments, policy incentives, and financial investments in those countries that appear to be interested in SMRs suffice to overcome the various challenges faced by these technologies if they are to be commercialized. This review of SMR programs in the United States, the UK, and Canada attempts to answer this question. We start with a description of the SMR programs, and the larger nuclear power plant programs, in these three countries. We follow this by explaining the salient features of SMRs, followed by a detailed discussion of country policies towards SMRs. After comparing the national policies of the three countries, we conclude by assessing the prospects for a significant volume of SMR orders in the next two or three decades, an absolute necessity for the commercialization of any small nuclear reactor design.

We focus on the economics and commercial viability of these designs. We do not consider other important factors, such as their safety and the impact on nuclear proliferation.

2 | THE UK, US, AND CANADA NUCLEAR PROGRAMS

The three countries that we have focused on were pioneers of nuclear power, designing and building their first civil power reactors entering service 50 or more years ago. However, ordering in all three countries had essentially ended by 1980. All three tried to revive new nuclear ordering in the decade after 2000 but these attempts have failed or are failing. In Canada, a nuclear tender was abandoned because of the high prices bid (Hamilton, 2009). The United States introduced the Nuclear 2010 program in 2002 and the United States Energy Policy Act (EPACT) in 2005 with the aim of restarting orders for nuclear plants (CBO, 2008). Although utilities developed plans for more than 30 reactors (Holt, 2014, pp. 6–9), only two nuclear plants proceeded to construction. One of these two plants was abandoned in mid-construction because cost had escalated out of control, leaving residents of the state with billions in payments but with no electricity in exchange (Brown, 2018). In the UK, the government's Nuclear Industrial Strategy program was expected to lead to 16 GW of new capacity by 2030 (Department for Business, Innovation and Skills, 2013). That program will result in at most 3 GW with four out of five of the stations planned abandoned or in serious doubt.

The reactor supply industries of these countries have fared correspondingly badly (Minin & Vlček, 2018). In the United States, of the four reactor vendors that supplied all the operating reactors in the country, only Westinghouse and GE are still active. However, GE has won only a handful of orders in the past 40 years, while Westinghouse has performed little better than GE in terms of orders won.[4] Indeed, in 2017, Westinghouse filed for bankruptcy protection due to its financial troubles (Cardwell & Soble, 2017). Canada's federally owned reactor supply company, AECL was privatized and its CANDU technology was sold in 2011 to SNC-Lavalin, which has not won any reactor orders since. The UK's reactor supply industry was never strong and has not existed for 40 years.

Nevertheless, the long history of nuclear exploitation in these countries has left strong institutional forces, particularly within government, that have been very receptive to the claims of new nuclear technologies, specifically small modular reactors. An example of such an institutional force is the US Department of Energy. Just as important to the interest in SMRs on the part of these governments is the vast amount of lobbying that the new nuclear vendors have invested in. For example, in February 2019, representatives from several nuclear energy firms, including NuScale and TerraPower, met with US President Donald Trump to persuade him to help sell nuclear reactors, including SMRs, to other countries (Dlouhy et al., 2019).

3 | WHAT ARE SMRS?

The term SMR stands for "small, modular reactors." The term "small" refers to the electrical output being less than 300 MW (electrical) but this rule does not preclude larger designs: the UK's main SMR design from Rolls Royce is around 470 MWe (Rolls Royce, 2021a). At the lower end, some SMRs are designed to produce only 3 MWe.

These reactors can be modular in two senses: they could be built in clusters of interdependent reactors on the same site, so that capacity could be added in small increments as demand dictates; and they could be assembled from factory manufactured modules. While a cluster of reactors sharing a central facility seems likely to reduce costs, it could raise safety issues if failure in a central facility, such as a control room, could affect all the reactors at a site.

Underlying the push for SMRs has been the very high costs of, and extensive delays associated with, constructing large nuclear plants. The Vogtle project consisting of twin AP1000 reactors being constructed in the United States since 2013 is currently projected to cost $29 billion, more than twice the estimate of $14 billion when construction started (Hargreaves, 2012; NIW, 2020). The EPR being constructed in Flamanville in France since 2007 is "running a decade behind schedule" and "expected to cost 12.4 billion euros" (Vidalon & Clercq, 2019), about four times the cost forecast when construction started.

Prospects for more large nuclear reactors in the countries we are discussing are bleak at best. As Rolls Royce, the UK's leading proponent of SMRs, puts it, "in order to successfully deliver large new build reactors, there are three significant hurdles to overcome. First, financing new large plants is expensive; second, few organizations are willing to take on such construction risks; and third, there is low confidence that these projects can be delivered on time" (Rolls Royce, 2017b, p. 4).

SMR vendors claim that they can construct reactors at a fraction of this cost. To quote Rolls Royce again: "By reducing plant size, and therefore capital costs, SMRs can be financed via conventional project approaches, with financing limited to under £2.5 billion" (Rolls Royce, 2017b, p. 12). Likewise, NuScale announced in 2015 that the overnight cost for its 12 module units of 50 MWe each (the design capacity at that time) for a total of 600 MWe would be $2.895 billion (Cooke, 2015; Surina & McGough, 2015). Such estimates for the total cost are much lower than the cost figures mentioned above for large reactors, and may have played a part in persuading US, UK, and Canadian governments that if they want to promote nuclear power, then their only chance would come from SMRs.

The term SMRs covers a wide range of technologies. These designs could be water, gas or molten salt cooled, and could operate in the thermal or fast neutron spectrum.[5] Proponents of each of these designs claim major benefits, including reduction or even elimination of the production of nuclear waste (e.g., Parmentola & Rawls, 2011; Slessarev, 2008), or greater proliferation resistance (e.g., Benchrif et al., 2013; Senor et al., 2007; Shropshire, 2011). In reality, no single design solves all of the problems confronting nuclear power (Ramana & Mian, 2014). Nonetheless, this diversity of designs for SMRs helps proponents by implying that the claims of desirable properties for a particular design apply to all SMRs.

However, many designs are based on the most widely built reactor design, the pressurized water reactor (PWR).[6] Only the BWRX-300 design is based on the other widely built reactor design, the boiling water reactor (BWR). Both PWRs and BWRs use water as coolant and moderator and are referred to as LWRs.

The other (non-LWR) designs use technologies that have so far been built as demonstration or prototype reactors or not yet built at all. In 2000, the Generation IV Forum[7] (GIF) proposed six categories of reactor designs as being the most likely to be safer, cheaper, less likely to lead to weapons proliferation and use natural uranium more economically than existing designs. GIF includes SMRs and designs that would produce outputs larger than 300 MWe.

Among the GIF categories, the options most pursued as SMRs are: lead cooled fast reactor (LFR); molten salt reactor (MSR); sodium-cooled fast reactor (SFR); and very high-temperature reactor (VHTR). There has been no experience with building power reactors based on the LFR and the MSR. The latter two have been pursued since the 1950s as prototypes and demonstration plants, but these have tended to have high-construction costs, experienced operational problems, and have frequently suffered early closure (IPFM, 2010; Ramana, 2016). The more complex fuel cycle required by the SFR means its operating costs will be high (Suchitra & Ramana, 2011). Nevertheless, several countries, notably Russia, China, and India, are either operating or constructing SFRs. China is the only country building an HTR, which became critical in September 2021, 4 years behind schedule.

When "the International Generation-IV Initiative was established in 2000" it sought "commercial deployment by 2020–2030" (Abram & Ion, 2008, p. 4323). GIF's, 2002 Roadmap forecast in a best-case scenario, the SFR would be deployable by 2015, the VHTR in 2020, and the LFR and MSR in 2025 (GIF, 2002). In its 2018 update, GIF identified major technological issues for all four designs and it concluded: "The time perspective is a readiness for commercial

TABLE 1 SMR-related features in the UK, the United States, and Canada

	The United States	Canada	The UK
Government support	Direct to NuScale, mPower, X-energy, and Terrapower	Directly to Terrestrial and Moltex and through Provincial government to ARC-100	Direct mainly to Rolls Royce
Utility interest	Limited	Some through publicly owned and privately owned utilities	None
Regulatory reviews	Full review of NuScale	Preliminary review of several	None
Proposed uses	Grid	Isolated communities, industrial processes and grid	Grid

Source: Authors' research.

fleet deployment by around 2045 (for the first systems)" (GIF, 2018). Other entities, such as France's Institut de Radioprotection et de Sûreté Nucléaire (IRSN), and a number of US academics, have also offered cautionary evaluations (Abdulla et al., 2017; Anadón et al., 2012; Ford et al., 2017; IRSN, 2015; Morgan et al., 2018).

4 | COUNTRY POLICIES

Among OECD countries, the United States, Canada, and the UK have by far shown the most interest in SMRs. However, the approach, priorities, and methods of support vary significantly (Table 1). In this section, we examine the historical evolution of policies in these countries.

4.1 | The United States

In the United States, the idea of small reactors goes back to the 1950s and 1960s, but these early experiments largely failed (Ramana, 2015).[8] During the 1980s, as orders for nuclear reactors plummeted from the highs of the 1970s to zero, the US Department of Energy (DOE) claimed to have observed "new interest in small and medium size reactors and in more advanced reactor concepts other than those marketed today" (Department of Energy, 1988, p. 3). That new interest did not translate into construction.

The next iteration came in 2000, when the US Congress funded the DOE "to undertake a study to determine the feasibility of and issues associated with the deployment of... small reactors" (Department of Energy, 2001; "Senate," 2001). The resulting report concluded that "the most technically mature small modular reactor (SMR) designs and concepts have the potential to be economical and could be made available for deployment before the end of the decade, provided that certain technical and licensing issues are addressed" (Department of Energy, 2001, p. iii). Twenty years after that report, no SMR design is yet licensed for deployment in the United States.

The US Nuclear Regulatory Commission (NRC) has largely also supported the DOE and nuclear vendors in their optimistic forecasts for SMRs. Going by a talk given by an NRC official in October 2008, the NuScale and the Pebble Bed Modular Reactor would have submitted applications for design certification in 2010 and the licensing process would be completed by 2015[9]; the timelines mentioned for the Hyperion reactor (currently Gen4 Energy) and the Toshiba 4S foresaw application submissions by the beginning of 2012 and mid-2009, respectively, and certifications by end of 2015 and mid-2013, respectively (Baker, 2008). None of that happened.

The failure to commercialize SMRs by the end of the first decade of the 21st century did not prevent the DOE from continuing to support SMRs; in 2012, it established a cost-share funding opportunity to "guide two small modular reactor designs through the nuclear regulatory process by 2022" (McMahon, 2012). Under this program, the DOE selected two SMR designs—mPower in 2012 and NuScale in 2013—for awards of up to US$226 million each.

The mPower design was proposed by Babcock & Wilcox (B&W) and, for a while, seemed poised to be the first SMR to be built in the United States. When DOE selected mPower, James Ferland, president of B&W, pronounced that the award represented "another key milestone in the work to establish *the world's first commercially viable SMR nuclear plant*" (our emphasis) (Anonymous, 2013). By 2013, B&W had signed a contract with the Tennessee Valley Authority geared towards "deploying up to four mPower SMR reactors" (BWXT, 2013). The same year, a DOE Deputy Assistant Secretary announced: "Success of this project will be an enabling factor for the follow-on programs and policies supporting broader SMR deployment" (Kelly, 2013).

Things unraveled quickly after that. B&W tried to find other investors into project development or customers willing to enter into a contract for an mPower reactor. In April 2014, a B&W spokesperson admitted that "neither of those things have happened" (Ruiter, 2014). The company drastically reduced the budget for the SMR project from about US $80 million/year to "a maximum of $15 million per year" (WNN, 2014).

In 2016, the mPower team attempted to resuscitate the project. Its partner, Bechtel Corporation, which was previously responsible only for the construction of reactors, started leading the project and exploring "options of outside investors and future potential customers"; however, Bechtel gave itself a 1-year deadline, after which the program was to be terminated, if "no adequate investors or customers were found" (Davis, 2017). In March 2017, "Bechtel notified BWXT that it was unable to secure sufficient funding to continue the Generation mPower program and that it was invoking the settlement scenario provisions of the framework agreement to terminate the program" (Davis, 2017).

The other company that was funded by DOE, NuScale, has continued developing its reactor design, and, in March 2017, NRC began reviewing NuScale's application (NEI, 2017). The NRC issued a Final Safety Evaluation Report in August 2020 (Proctor, 2020), but there are many safety problems that need resolution before any possible construction of the design can start (Advisory Committee on Reactor Safeguards, 2020a, 2020b; Cho, 2020; Sondgeroth, 2020).

The DOE's has also supported NuScale in other ways. In February 2016, it entered into an agreement with the Utah Associated Municipal Power Systems (UAMPS) "to support possible siting… within the boundary of DOE's Idaho National Laboratory (INL) site" (DOE, 2016). In October 2016, UAMPS chose a location within the Idaho National Laboratory (Anonymous, 2016).

In addition to $226 million through the 2012 program, DOE provided another grant of US$40 million to NuScale in 2018 (Danko, 2018). Further funding became available in February 2020, when the DOE "agreed to spend up to $350 million in new matching funds" (Chaffee, 2020a).

NuScale has also been funded by its parent company, the Fluor Corp. According to NuScale's Chairman and Chief Executive Officer, as of March 2020, "Fluor and its investors contributed $643 million, or 67% of expenditures to date, and the Federal government has contributed $314 million," for a total of $957 million (Hopkins, 2020).

To put these investments in perspective, demonstrating the adequacy of a new reactor design to a nuclear regulator will require "several million person-hours of design/engineering work and 15–20 years" and will cost in the range of $1–$2 billion (Buongiorno et al., 2018, p. 86). This scale is exemplified by NuScale, which anticipates spending $525–$700 million in addition to what it has already spent, and the DOE has agreed to fund half of that (Chaffee, 2020b).

The projected cost of constructing the NuScale design has been rising dramatically—and this is before the design has even been finalized. In 2015, NuScale projected an overnight construction cost of $2.895 billion (Cooke, 2015). In a February 2018 presentation, UAMPS announced a "preliminary estimated" construction cost of around $4.2 billion; there is in addition an "Estimated Development Costs to the Completion of Development" component of $587 million (UAMPS, 2018). Since then the total construction cost has increased to $6.1 billion, with the development costs now estimated at $1375 million (UAMPS, 2020a).

There are three sets of problems with NuScale that are still to be tackled before construction starts, with no guarantees that they can be tackled: safety problems identified during the review; the process of obtaining construction and operating license, which requires some party to satisfactorily resolve the safety concerns identified so far; and finding investors who are willing to put in the requisite capital to complete the development process in advance of construction (Ramana, 2020).

While NuScale has received the bulk of the funding offered by the DOE, other companies too, including ones that are developing non-LWR designs have received grants from the DOE. In October 2020, the DOE awarded X-energy and Terrapower $80 million each to build reactors (Cha & Freebairn, 2020). Then in December 2020, DOE awarded $30 million to five companies in initial funding for risk reduction (WNN, 2020b).

To summarize, despite the US government investing hundreds of millions of dollars, the United States is still far from deploying an SMR. While many SMR vendors have received funding, none of these have procured the level of funding needed—around $1–2 billion—to develop a reactor design to the point where it can be licensed. The only exception to that is NuScale, but its claim that the first SMR units will start operating in 2029–2030 (UAMPS, 2020b), is highly optimistic. Even if this were to be achieved, it would still represent the first SMR units operating two decades after the 2010 timeline projected by the Department of Energy in 2001. The anticipated cost of the proposed NuScale unit also makes it unlikely that there will be follow-up orders or that it would be commercially successful.

4.2 | Canada

Canada, too, has a long history of the building and exporting nuclear reactors, including small reactors. The first two electricity-producing reactors were the 22 MWe Nuclear Power Demonstration reactor, completed in 1962, and the 200 MWe CANDU reactor at Douglas Point. Douglas Point was operated from 1968 to 1984 but experienced frequent and costly maintenance outages (Cadham, 2009, p. 5). But it was the basis for the CANDU reactor exported to India in the 1960s (Graham & Stevens, 1974); modified versions of this were constructed till the 1990s. All of these can be categorized as small reactors. Ultimately, Canada (and India, for that matter) moved to much larger reactor designs, presumably to take advantages of economies of scale.

In the last decade or so, however, Canada too has turned to SMRs to revive prospects for nuclear power. Government officials, both at the federal level and provincial levels, have been advocating for SMRs and would like the country to be a world-leader in SMR technology. The Federal government funded the Canadian Nuclear Association, "a non-profit organization established in 1960 to represent the nuclear industry in Canada and promote the development and growth of nuclear technologies for peaceful purposes" to come out with a "roadmap which will identify the opportunities for on and off-grid applications of Small Modular Reactors (SMRs) in Canada" (CNA, 2020; NRCAN, 2018). The eventual roadmap was put out by a "Steering Committee" that included a number of utilities, among them Ontario Power Generation, Bruce Power, SaskPower, and NB Power.

The roadmap identifies "three potential applications for SMRs in Canada: on grid, heavy industry, and remote communities" (A Call to Action: A Canadian Roadmap for Small Modular Reactors, 2018). The interest in using SMRs to meet the electricity needs of isolated communities and mines, and to provide high-temperature process heat, mostly aimed at processing tar sands, is unique to Canada.[10] In December 2020, Canada's Minister of Natural Resources released an action plan for SMRs, which listed seven principles starting with the intention to act "together and within our jurisdictions and areas of authority to support the development and deployment of various SMR technologies in Canada, with first units in operation by the late 2020s" (NRCAN, 2020).

There is support for SMRs from some provinces in Canada. The Premiers of Ontario, Saskatchewan, and New Brunswick announced in 2019 that they would cooperate on research and the building of SMRs (von Scheel, 2019). Saskatchewan has announced that its goals for 2030 include the development of SMR technology (WNN, 2019b). Ontario has promised to support Ontario Power Group and Bruce Power, the two nuclear-operating companies in the province, to build SMRs (Bruce Power, 2020; OPG, 2020b).

The Canadian Federal Government has provided CAD 20 million (around US$16 million) to Terrestrial Energy (GlobeNewsWire, 2020), and CAD 50.5 million (around US$ 40 million) to Moltex (Poitras, 2021c). The province of New Brunswick awarded CAD 20 million (around US$16 million) in February 2021 to ARC-100, a sodium-cooled fast reactor design (Poitras, 2021b). Earlier, the province's utility, New Brunswick Power, awarded $5 million each to Moltex and ARC-100 (Poitras, 2021a). Although these two vendors and New Brunswick Power have talked about these new designs being ready for operations by 2030 or earlier, the utility's forecasts and its integrated resource plan do not envision SMRs coming online within that timeframe (Énergie NB Power, 2021; Poitras, 2021a). Neither of these designs has been licensed by the Canadian Nuclear Safety Commission.

For its part, the CNSC offers a three-phase "pre-licensing vendor design review" (CNSC, 2020b). The first phase carries out "an overall assessment of the vendor's nuclear power plant design against the most recent CNSC design requirements for new nuclear power plants in Canada" as well as "all other related CNSC regulatory documents and Canadian codes & standards". The second phase tries to identify "any potential fundamental barriers to licensing the vendor's nuclear power plant design in Canada". The third phase "allows the vendor to follow-up on certain aspects of Phase 2 findings by:

- seeking more information from the CNSC about a Phase 2 topic; and/or
- asking the CNSC to review activities taken by the vendor towards the reactor's design readiness, following the completion of Phase 2."

Progress with the reactors that have begun the prelicensing vendor design review is shown in Table 2.

Three of these, NuScale Power, X Energy, and GE-Hitachi, went directly to Phase 2 review, which will also address Phase 1 objectives within the scope of work.

The CNSC clarifies that prelicensing vendor design review process "does not certify a reactor design and does not involve the issuance of a license under the Nuclear Safety and Control Act. It is not required as part of the licensing process for a new nuclear reactor facility. The conclusions of a design review do not bind or otherwise influence decisions

TABLE 2 Vendor design review service agreements in force between vendors and the CNSC (*Source*: CNSC website)

Vendor	Name of design and cooling type	Approximate capacity (MW electrical)	Applied for	Review start date	Status
Terrestrial Energy Inc.	IMSR Integral Molten Salt Reactor	200	Phase 1	April 2016	Complete
			Phase 2	December 2018	Assessment in progress
Ultra-Safe Nuclear Corporation	MMR-5 and MMR-10, High-temperature gas	5–10	Phase 1	December 2016	Complete
			Phase 2	June 2021	Assessment in progress
LeadCold Nuclear Inc.	SEALER, Molten lead	3	Phase 1	January 2017	On hold at vendor's request
Advanced Reactor Concepts Ltd.	ARC-100, Liquid sodium	100	Phase 1	September 2017	Complete
Moltex Energy	Moltex energy stable salt reactor, Molten salt	300	Series Phase 1 and 2	December 2017	Phase 1 completed
SMR, LLC. (A Holtec International Company)	SMR-160, Pressurized light water	160	Phase 1	July 2018	Complete
NuScale Power, LLC	NuScale, Pressurized light water	60	Phase 2[a]	January 2020	Assessment in progress
U-Battery Canada Ltd.	U-Battery, High-temperature gas	4	Phase 1	February 2017	Project start pending
GE-Hitachi Nuclear Energy	BWRX-300, Boiling water	300	Phase 2[a]	January 2020	Assessment in progress
X Energy, LLC	Xe-100, High-temperature gas	75	Phase 2[a]	July 2020	Assessment in progress

Source: CNSC website, 25 August 2021;
[a]Represents the fact that NuScale Power, X Energy, and GE-Hitachi, have opted to have Phase 1 objectives be addressed within the Phase 2 scope of work.

made by the Commission, with whom the authority resides to issue licenses for nuclear reactor facilities" (CNSC, 2018). In other words, the fact that a number of designs are undergoing the prelicensing vendor design reviews does not mean that they will soon receive licenses for construction.

The main organizations in Canada that are pursuing their own strategies to build SMRs are Canadian Nuclear Laboratories, which is managed by a consortium of private companies called Canadian National Energy Alliance; New Brunswick Energy Solutions Corporation, a joint venture between the New Brunswick provincial government and New Brunswick Power, itself owned by the provincial government; Ontario Power Generation, a Corporation owned by the province of Ontario; and Bruce Power, a consortium of several private corporations that operates eight nuclear reactors (Thomas et al., 2019, p. 29).

There are proposals to build two SMRs in Canada: Global First Power has proposed building the demonstration Micro Modular Reactor at the Chalk River site (GFP, 2019), and has submitted a license application to the CNSC (CNSC, 2020a)[11]; Ontario Power Generation is proposing to build a grid scale SMR at the Darlington nuclear site, for which it considered designs proposed by GE Hitachi, Terrestrial Energy, and X-Energy (WNN, 2020a). In December 2021, Ontario Power Generation announced that the chosen design was GE Hitachi's BWRX-300 reactor (McClearn & Stone, 2021; Ontario Power Generation, 2021). GE Hitachi is yet to submit a license application to the CNSC, and thus, the design has not been cleared for construction yet.

4.3 | The UK

The UK government's publicly expressed in interest in SMRs when it published a feasibility study on SMRs in 2014 (NNL, 2014). The study "was co-funded by seven nuclear industry organisations including Rolls Royce" and "projected a potential world market of 65-85 GW by 2035 with 7-21 GW installed in the UK, suggesting that the world market would be worth £250-400bn, implying a construction cost of about £4000/kW" (Thomas et al., 2019, p. 5). The study took "the IAEA definition of SMRs as being less than 300MW, and considered designs expected to be deployable within ten years" (Thomas et al., 2019, p. 23).

It identified four PWR designs as meeting these criteria: "ACP 100+ (CNNC, China), mPower (B&W/Bechtel, USA), Westinghouse SMR (USA), and NuScale (Fluor, USA)" and claimed that a "FOAK (First of a Kind) SMR would be cost competitive with a FOAK large reactor. However, it claimed that there was more scope for cost reduction with SMRs and therefore a Next Of A Kind (NOAK) SMR would be cheaper than a NOAK large reactor" (Thomas et al., 2019, p. 23).

Of these, NuScale is the only realistic possibility today. Soon after the report was published, the companies responsible for the mPower and Westinghouse SMR designs stopped development work (Davis, 2017; Litvak, 2014). There is no evidence of any interest in the UK in the CNNC option.

The scenarios were highly optimistic even at the time it was published. The estimate of the world market size was unreasonably large and the time line assumed for deployment (by 2024) was not feasible. The cost forecasted was also optimistic: even by 2019, the cost estimate for Hinkley had become 80% "more than the assumed SMR cost of £4000/kW" (EDF, 2019; Thomas et al., 2019, p. 23).

In 2015, the UK chancellor announced that the government would spend "at least £250 m...by 2020 on an "ambitious" program to "position the UK as a global leader in innovative nuclear technologies"... paving the way "towards building one of the world's first SMRs in the UK in the 2020s" (Carrington, 2015).

In March 2016, the government "launched the first phase of the competition by publishing a request for expressions of interest" (WNN, 2016). It was to result in an "SMR Delivery Roadmap" later that year (Department for Business, Energy, & Industrial Strategy, 2016; WNN, 2016). This phase was completed only in December 2017. A Rolls Royce design was included despite having a capacity of 450 MW, much higher than the 300 MW definition for SMRs. Despite the prior termination of the mPower and Westinghouse programs, the four options identified in the NNL feasibility study were also considered eligible (Thomas et al., 2019).

Things changed dramatically by December 2017 and the UK government effectively abandoned the Roadmap and the SMR competition. Instead, it published an independent report that projected a generation cost of £101/MWh from the first reactor (Gosden, 2017). This was comparable to electricity costs from Hinkley Point C and much more than Rolls Royce was forecasting for their design. In terms of policy, the £250 million competition was replaced by competition with funding of up to £44 million for advanced modular reactor (AMR) designs, which were "defined as a broad group of advanced nuclear reactors, differ from conventional reactors, which use pressurised or boiling water for primary cooling" (i.e., non-LWR) (Department for Business, Energy, & Industrial Strategy, 2018).

The following year, the UK government promised £200 million in its "Nuclear Sector Deal" to develop new technologies (Clark, 2018). The largest element in this package was £86 m for nuclear fusion technology. It also incorporated the £44 million previously announced in December 2017, increasing funding for those to £56 m, and offered £62 m to an *"advanced manufacturing and construction programme"* and a *"new national supply chain programme"*. In other words, there was no funding specifically for LWR SMRs. Rolls Royce responded by threatening to end their SMR development (Hollinger & Pfeifer, 2018). The following January, the *Financial Times* reported that the Rolls Royce consortium had "asked for more than £200 m in government funding to help develop its project for small nuclear reactors" but "any amount would be matched by the consortium" to develop the "technology through to the later stages of the licensing process in order to attract private investment" (Pfeifer & Sheppard, 2019). In July 2019, the UK government offered Rolls Royce up to £18 million (Clark, 2019).

The Rolls Royce design is a newcomer to the market only being announced in 2016 when the size was said to be in the range 220–440 MWe. In 2017, it settled on about 450 MWe with the first demonstration unit operating by 2030 (Rolls Royce, 2017b). In 2021, Rolls Royce announced an increase in size to 470 MWe (Rolls Royce, 2021a). As mentioned earlier, the Rolls Royce does not meet the criteria for being small. Rolls Royce does claim that it "is fully modularised to enable the plant to be transported by road, rail or sea" (Rolls Royce, 2017a, p. 3).

The prestige of the brand in the UK and Rolls Royce's monopoly over UK orders for nuclear submarine propulsion units mean it is commonly perceived to be the front-runner for any UK SMR orders. Nevertheless, Rolls Royce has placed some extraordinary requirements on the UK government for it to go ahead with the development of the design. These included:

- "Choosing one preferred technology preferably with input from a selected UK team to deploy and maximize local content;

- A UK industrial policy that supports IP, advanced manufacturing and long-term high-value jobs;
- Match funding (at a minimum) up to the end of the licensing phase;
- A Generic Design Assessment (GDA) slot;
- A suitable site to develop a First of a Kind (FOAK);
- A guaranteed UK electricity market of 7 GWe;
- Sustainment of a national nuclear supply chain capability across both Defense and Civil Nuclear;
- If a UK-only technology is selected for the UK SMR programme, assistance identifying and developing export markets; and
- If a non-UK technology is selected for the UK SMR programme, assistance dealing with the relevant partner government(s) in order to secure IP and a role for the UK nuclear supply chain" (Thomas et al., 2019, p. 16).

These demands might represent naivety on the part of Rolls Royce. Or they might represent its historical business practices, especially with the Ministry of Defense. However, it seems implausible that a government could meaningfully "commit a future government to place a large number of SMR orders a decade or more in the future, especially when there are such serious doubts about the economic viability of the technology" (Thomas et al., 2019, p. 27).

Subsequently, Rolls Royce has made it clear that the demonstration plant would be on-line 10 years after *order* (Castia, 2020). This is likely to reflect the fact that the design still needs considerable development before it is ready to undergo a detailed assessment by the UK's safety regulator. It also made it clear that it expects the components for the demonstration plant to be made on production lines rather than individually fabricated. Its demands of a guarantee of 7 GW of orders (15–16 reactors), with each reactor estimated at around £2 billion, means, in essence, that it requires a government commitment of more than £30 billion. This commitment of more than £30 billion is to a design that is not complete, has not been approved by the UK safety regulator much less been proven technically and economically.

In November 2020, the government announced a further £525 million for Advanced Nuclear Technology development.[12] Of this, £215 million was allocated "to develop a domestic smaller-scale power plant technology design that could potentially be built in factories and then assembled on site" but this seems to be predicated on unlocking "up to £300 million private sector match-funding."

The government also committed "up to £170 million for a research and development programme on Advanced Modular Reactors. These reactors could operate at over 800°C and the high-grade heat could unlock efficient production of hydrogen and synthetic fuels". "Our aim is to build a demonstrator by the early 2030s at the latest to prove the potential of this technology and put the UK at the cutting edge against international competitors." The recipients of the funding were mainly U-Battery, a 3 MW high-temperature gas-cooled reactor, and the 450 MW Westinghouse lead-cooled fast reactor (Westinghouse., 2019a, 2019b). The current designs fall well short of the criterion of operating at 800°C with U-Battery expected to operate at 710°C and the Westinghouse LFR at 650°C. No timing was given for spending this money or how it would be spent and these commitments are "subject to value-for-money and future spending rounds." Given the experience with the 2015 proposals, it is far from clear how much of this money will be spent.

In November 2021, Rolls Royce announced it had secured the £195 million necessary to release the UK government's offer of £210 million matching funds (Rolls Royce, 2021b). It is not clear from the announcement how far this funding is expected to go in taking the design to a commercially orderable one.

5 | COMPARISON OF NATIONAL POLICIES

The comparison of the three countries' SMR programs can usefully be analyzed under three dimensions: the role of government; the role of the reactor developers; and the choice of technology.

5.1 | Government

The central governments of all three countries have arguably played the key role; without such support, especially substantial funding, SMR development in all three countries would barely exist. Indeed, in the UK, central government is solely responsible for the interest. In Canada, unlike the United States, provincial governments have also played a major role. This role has been evolving with time. In the UK, after strong enthusiasm when the program was launched in 2015, there is now little clear direction to the program. In the United States, support has been relatively constant while in Canada, the momentum seems to be increasing.

The three cases also show that these governments have operated in very different ways. In the UK, the government is in control of all the processes determining which designs are funded. However, after the first wave of enthusiasm around 2015 with ambitious targets to spend a large amount of taxpayer money by 2020, identifying the most appropriate design, and setting out a roadmap to get to first commercial order, enthusiasm appears to have largely cooled. Little of the funds allocated were spent; in response, the government is only offering significant sums to the Rolls Royce design despite it not going through any competitive process. Only small budgets are being offered to more radical designs.

In the UK, there does seem to be an emerging implicit competition between the plans for large reactors that have been announced, and small modular reactors. Both EDF, as the organization that is likely to construct any large reactors, and Rolls Royce, which is the leading SMR proponent, are lobbying the government to fund their plans (Chaffee, 2020c). Given limited resources, the government is likely to have to make a choice between funding large and small reactors.

The US government has substantial ongoing federal funds, much larger than the UK's funds, for nuclear power and these have been used to fund development of designs. The United States has also had a history of funding "advanced nuclear" reactors, spending about $2 billion just between 1998 and 2015 on these (Abdulla et al., 2017). Its funding for SMRs has been much more substantial than in other countries, especially in the case of NuScale, and it has also expressed an interest in buying or taking a stake in demonstration plants, such as the UAMPS NuScale project.

For Canada, while the Federal government is trying to play a coordinating role and has provided large grants to two vendor companies, the programs are being driven by four separate organizations, albeit dominated by public ownership. Provincial governments, especially in Ontario and New Brunswick that have operating nuclear power plants, are also supportive, and New Brunswick has provided sizeable funding to the two vendors that are hoping to build reactors in the province.

There may be a number of factors behind this strong government support. In all three countries, nuclear power has not been a political issue, with all major parties broadly supportive of nuclear power. So there has seldom been political opposition to public spending on nuclear power. There remains strong residual support among policy-makers for nuclear energy despite its continued failure to meet the promises made for it. The collapse or near collapse of new nuclear programs in the United States, Canada, and the UK has meant that SMRs were the only way governments could be seen to be supporting nuclear power.

In all three countries, the possibility of SMR exports have been a prominent part of discussions. As mentioned above, the 2014 UK SMR Feasibility study projected a large potential market that they estimated as being worth £250–400 billion "if the economics are competitive" (NNL, 2014, p. 3). The UK's Expert Finance Working Group on Small Reactors also suggested that once the first "small reactors can be commercially developed the export potential for the market is seen as significant" (Expert Finance Working Group on Small Reactors, 2018, p. 9). Canada's 2018 Roadmap for Small Modular Reactors talked about "substantial export potential" (A Call to Action: A Canadian Roadmap for Small Modular Reactors, 2018, p. 2). In 2011, the US Department of Commerce claimed that markets were "ripe for SMRs" and went on to rate 27 countries that were identified as "markets of interest" for their likelihood of importing SMRs (ITA, 2011, pp. 4, 9). These exports are speculative at best and are very unlikely to materialize (Cogswell et al., 2017; Ramana & Agyapong, 2016; Ramana & Ahmad, 2016). Yet, talk of exports can serve to garner government support.

In the United States, the argument about exports has gained greater currency because subsidies offered by China and Russia to export nuclear reactors to the developing world are seen as posing a geopolitical risk to US interests (Crapo et al., 2019; EFI, 2017). This is related to the concern in the United States about its declining role in nuclear power markets.

Another factor that may have led to support for an SMR program in the United States and the UK is the connection with military nuclear programs. In recent years, there have been many public calls by high-level officials and prominent organizations seeking government support for nuclear power because of its "national security" benefits (Crapo et al., 2019; EFI, 2017; Gattie et al., 2018; Parliament House of Commons Innovation, Universities, Science and Skills Committee, 2009; Stirling & Johnstone, 2018). Rolls Royce promoted this linkage explicitly in its 2017 SMR report: "Currently, the UK Government is required to invest funding to sustain the skills and capability necessary for the maintenance of the Royal Navy's nuclear submarine program... the expansion of a nuclear-capable skilled workforce through a civil nuclear UK SMR program would relieve the Ministry of Defence of the burden of developing and retaining skills and capability. This would free up valuable resources for other investments" (Rolls Royce, 2017b, p. 22).

5.2 | Reactor developers

Traditional reactor vendors have either shown little interest in SMRs or have abandoned development at the point when significant quantities of their own funds were required. Examples include Framatome, Westinghouse, and B&W.

The near absence of orders for large reactors in all three countries for four decades has left the reactor supply industry in all three countries weak. Despite this weakness, the national nuclear trade associations remain vociferous and apparently influential.[13]

SMR development has primarily been through start-ups driven by motivated individuals and will depend on major financial support, probably from the government. It will also require the expertise of a large company with expertise in the power sector if these start-ups are to bring their design to the market. NuScale, the company that is furthest along on the path to build an SMR, has attempted to meet these requirements with substantial support from the US government and from the Fluor Corporation, and is continuing to enter into agreements with large corporations (Danko, 2021; Fluor Corporation, 2020; Ramana, 2020; WNN, 2019a).

5.3 | Technology choice

There is more diversity between the three countries when it comes to technology choice. Canada, in particular, has shown more interest in speculative and long-term non-LWR designs, although the first grid-connected SMR design selected for construction is an LWR.[14] The UK policy on whether to focus on LWRs or non-LWRs is unclear and although the Rolls Royce PWR option is seen as the likely winner of any UK program, there is no commitment to provide the support it is asking for: a guarantee of orders for 16 reactors. Small parcels of UK money are being directed to the non-LWR options; an increasing emphasis on reactors that can operate at high temperatures suggests the use of these reactors to manufacture hydrogen as a motive. In the United States, the majority of government LWR support has gone to NuScale; although non-LWRs have also been supported, the available funding seems to be split between many competing designs (Abdulla et al., 2017). However, unlike Canada and the UK where central government ownership of reactors is plausible, in the United States, Federal ownership is implausible beyond one or two demonstration units. Despite Canada's long history in reactor design that resulted in multiple CANDU reactors being built around the world, the design of the SNC-Lavalin CANDU SMR, which can be seen as derived from earlier Canadian designs, is still quite preliminary (McGrath, 2020).

6 | PROSPECTS FOR SMR TECHNOLOGIES

In the past two decades, the United States, the UK, and Canada have all been supportive of nuclear energy technology, in general, and SMRs in particular. To varying extents, they have provided, or are promising to provide, financial support for the development of SMRs. Government funding likely reflects the interests of the nuclear industry while also driving such interest.

Are the inducements offered by these countries to promote SMRs sufficient to create demand for these reactors? To answer this question, we have to first understand the basic economic challenge confronting SMRs. For the non-LWRs, because of the lack of deployment for these designs, the costs for large or small reactors are speculative. For the LWRs, this challenge is a result of the fact that small reactors generate less electricity and less revenue for the owning utility but the costs of constructing them are not proportionately smaller. This is why cost saving in the nuclear industry has usually tried to take advantage of economies of scale (Cantor & Hewlett, 1988; Haldi & Whitcomb, 1967), the idea that it would be cheaper to build a 1.2 GW reactor than a dozen 100 MW reactors.

SMR advocates counter with the argument that this can be compensated through savings from assembly line manufacture. There is good reason to be skeptical of the idea that learning from manufacturing many units will result in declining costs: in the United States and France, the two nations with the highest numbers of nuclear reactors, reactor construction costs have increased with experience (Boccard, 2014; Grubler, 2010, 2013; Hultman et al., 2007; Koomey & Hultman, 2007; Rangel & Lévêque, 2013). In other words, learning across the whole fleet, as measured by economic indicators, has been negative. Even with the optimistic assumption of a positive rate of learning, a very large number of SMRs would have to be constructed before they become competitive with large nuclear reactors (Glaser et al., 2015). And because large nuclear reactors are themselves not economical, it would still leave SMRs incapable of competing in the electricity market.

Furthermore, the high cost to suppliers of setting up SMR assembly lines in the face of an uncertain level of demand would be hard to justify. And because the economics of SMR production will remain unproven until a significant number of orders are placed, it leads us to a circular dilemma. This requirement for adequate orders to justify building a factory is often termed a full order book (Rosner & Goldberg, 2011). To "obtain such a full order book, *de facto* demonstration of SMR construction and operational capacity to time and cost must be proven" (Thomas et al., 2019, p. 8). In this sense, investing in SMRs might be more riskier than investing in proposed large reactors (Cooper, 2014). Any company that seeks "to manufacture and sell SMRs and its suppliers will face a very significant up-front investment that is needed to establish an entire supply chain" (Thomas et al., 2019, p. 8), for it will have to get orders for the many reactors needed to lower costs through proposed economies of replication (Froese et al., 2020; Glaser et al., 2015; Makhijani & Ramana, 2021a; Ramana, 2017).[15]

The other economic penalty due to reducing the output of reactors is in operations and maintenance costs per unit of capacity (kW), or energy produced (kWh). This is widely recognized in the literature (Boarin & Ricotti, 2014; Carelli et al., 2009; Lewis et al., 2016; Mignacca & Locatelli, 2020). Indeed, all else being equal, many elements of cost, for example, those related to security on site, could be no lower for SMRs than for large LWRs.

In addition, there is evidence that SMR developers themselves try to take advantage of economies of scale. A good example is the NuScale design, which has undergone a series of design power increases. NuScale is currently designed to produce 77 MW, which is 28% higher than the earlier design figure of 60 MW, which in turn was a 20% increase over the previous design capacity of 50 MW (NuScale Power, 2018), which was higher than the earlier 45 MW (Landrey, 2012), and which was higher than the earliest announced figure of 40 MW ("Small-Scale Nuclear Co. Hunts For Funds,", 2009). In other words, NuScale has nearly doubled its output, presumably to take advantage of economies of scale. NuScale also wants to build its reactors in clusters of up to 12 units, which might lower costs but raise the question of whether it is really such a small power project if that is done.

Correspondingly, these economic problems lead to nuclear industry demands for significant government funding for SMR development, as was the case with Rolls Royce and its demand for £200 million or more (Pfeifer & Sheppard, 2019). Its subsequent demands of an order of 15 follow-on plants, each estimated at around £2 billion, means, in essence, that it requires a government commitment of more than £30 billion. With the exception of the United States and NuScale, it seems quite clear that governments cannot offer financial support at the scale required for commercialization—namely, in the several hundreds of millions of dollar range. The problem is compounded by the large number of proposed SMR designs vying for government support. Because few have progressed beyond the conceptual design stage (IAEA, 2018, 2020), they will all need hundreds of millions of dollars of public money. Since that kind of money is not forthcoming, it is likely that most of those still at the conceptual stage will progress no further. Non-LWR designs face major technological and materials issues that may mean they are not economically or even technologically viable at any scale (IRSN, 2015; Makhijani & Ramana, 2021a).

Furthermore, any cost benefits of assembly-line module construction relative to custom-build on-site construction may be balanced by additional risks. If there is a generic defect, perhaps because of a mistake in the production line, that would propagate throughout an entire fleet of reactors and would be very costly to fix (Makhijani, 2013). There is a long and troubled history of problems with the manufacture of parts for the nuclear industry.[16]

Experience also suggests that modularity will not be the panacea that SMR vendors have claimed. Such techniques have become widespread in many industrial arenas, including the manufacture of nuclear reactors. Westinghouse engineers routinely emphasized that the AP1000 had adopted "modular construction techniques" (Schulz, 2006, p. 1553). But all AP1000 projects so far have suffered from the problems typical of nuclear construction: cost and time overruns as well as quality problems (Hals & Flitter, 2017; Li & Chaffee, 2011; Smith, 2015; Spegele, 2016; Stanway & Chen, 2016; Yap & Spegele, 2015).

Finally, given that large reactors are not at all competitive with renewables or power plants based on cheap natural gas produced by hydraulic fracturing (fracking), SMRs will have to do much better than just matching the economics of large reactors.[17] Even if the assumption of large cost reductions from use of production line techniques is seen as credible, testing whether it actually applies will require that large numbers of these SMRs are ordered, a massive "bet" that will only be possible if public money underwrites the whole process. NuScale's cost estimates, more than $6 billion for the UAMPS project, are beginning to become comparable to that of a large reactor, but with a smaller power output. This suggests that NuScale will, when it has met regulatory requirements and has been designed in full detail, processes that invariably increase cost estimates, most likely be more expensive than large LWRs per unit of capacity (per kW basis).

The case of NuScale is instructive. It shows that the US government's decades long effort to promote SMRs have not managed to resolve the various problems besetting nuclear power, in particular, those of cost and time overruns that are all too common with nuclear projects (Sovacool et al., 2014a, 2014b). There is little reason to expect SMRs developed in Canada or the UK to fare any better.

Canada is different from the UK and the United States in that SMR promoters also focus on selling units to small and remote communities and mines that are not connected to the electric grid as well as grid applications. The idea is that these communities and mines are largely reliant on diesel generators and the fuel for this has to be transported expensively over long distances (Paraszczak & Fytas, 2012; Standing Senate Committee on Energy, the Environment and Natural Resources, 2014). Therefore, electricity costs and, so, the argument goes, SMRs can be economically competitive.

There are two problems here. First, the cost of electricity from SMRs could be up to 10 times the cost of electricity from diesel and therefore, these remote mines and communities are not likely to order any SMRs (Froese et al., 2020). Furthermore, even if we disregard costs, the electricity demands of these mines and remote communities are too limited and the hypothetical market offered by these would not even justify building a factory. Finally, Canada is unlikely to be able to come up with the kind of government funding available in the United States, amounting to several hundreds of millions of dollars in the case of NuScale. It is implausible that any private sector entity will be willing to invest the amounts needed to translate a paper design into one that can be licensed.

Exports are unlikely to compensate for the lack of domestic markets. Many developing countries do claim to be interested in SMRs, but few are investing in constructing one until the technologies have been fully demonstrated and proven in their home markets. Their interest only goes as far as signing agreements and memoranda of understanding, as illustrated by the cases of Jordan, Ghana, and Indonesia (Cogswell et al., 2017; Ramana & Agyapong, 2016; Ramana & Ahmad, 2016).

There are other problems for SMRs. When normalized for the difference in electricity outputs, SMRs will generate comparable or greater quantities of nuclear waste as large reactors, and they offer the possibility of producing fissile materials for nuclear weapons, particularly, in the case of SMR designs that require spent fuel reprocessing (Glaser et al., 2013). This "implies higher costs of radioactive waste management and safeguarding of numerous SMRs around the world" (Thomas et al., 2019, p. 9).

7 | CONCLUSION

We return to the question we started with: will the rhetorical commitments, policy incentives, and financial investments in those countries that appear to be interested in SMRs suffice to overcome the various challenges faced by these technologies if they are to be commercialized? This article has tried to answer this question by reviewing the SMR programs and policies in the United States, the UK, and Canada, the three countries that have most vigorously pursued these technologies.

Successful commercialization will depend on SMRs overcoming several challenges, in particular economics. Because they generate smaller amounts of power, SMRs lose out on economies of scale, and this makes them even less likely to be economically viable than nuclear power based on large reactors. The other factor that affects prospects for SMRs is the availability of a significant volume of SMR orders in the next two or three decades, and our review suggests that an adequate number of orders are not forthcoming because none of these governments appear to be willing to risk such large amounts of public money.

The private sector is similarly unwilling to put in investments of the scale needed to commercialize even one reactor design. SMR development is being carried out mostly by startup companies with relatively low levels of prior nuclear experience. These companies have largely relied on large amounts of government funding, either provided or suggested. They would also like governments to put in policies that guarantee a large market for their SMRs, but this has not been forthcoming.

It is this set of conditions that, we argued, will come in the way of successful commercialization of the technology.

Given this dire outlook, the puzzle is why these governments are investing in SMR research and development in the first place. A full answer to that question is well beyond the scope of this article but we have briefly discussed the role of extant institutional interests in these countries in propelling SMR programs.

What about other countries? If, as we predict, efforts to commercialize SMRs in the United States, Canada, and the UK—countries with a long history of exploiting nuclear power and with large financial and skills resources—are unlikely to succeed, then the prospects for SMRs to be developed elsewhere will be bleak as well. The larger implication of these conclusions is that SMRs will be unable to rescue nuclear energy from its ongoing decline, or to create a pathway for nuclear energy to contribute significantly to mitigate climate change.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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ENDNOTES

[1] China's first SMR, the HTR-PM (a high-temperature reactor), started construction in December 2012 and has suffered time delays and cost overruns. Plans for constructing a series of such HTRs are uncertain, in part due to the cost of generating electricity at these being significantly more than the generation cost at standard-sized light water reactors (Yu, 2016). Russia's KLT-40S has also been significantly delayed and has been extremely expensive (Schneider & Froggatt, 2020). China's ACP100 appears to be just a signpost, intended as insurance in the event of a large market developing for SMRs.

[2] For example, in 2014, after more than a decade of investment in SMR development, Westinghouse decided to essentially shelve work on their SMR design and its CEO stated: *"The problem I have with SMRs is not the technology, it's not the deployment—it's that there's no customers. The worst thing to do is get ahead of the market"* (Litvak, 2014). Instead, Westinghouse decided to focus on "parts of the company with greater economic potential", for example, "its decommissioning business," which the CEO quantified "as a $1 billion per-year business for us," and characterized as "a growth opportunity on par with new nuclear reactor construction" (Litvak, 2014).

[3] In July 2012, the SMART became the first land-based light water SMR design, without considering the designs from the 1950s and 1960s, to receive regulatory approval anywhere in the world (Dong-joon, 2012). But since then, there have been no orders because it cannot compete economically. As the World Nuclear Association admitted: "KAERI planned to build a 90 MWe demonstration plant to operate from 2017, but this is not practical or economic in South Korea" (WNA, 2017).

[4] Westinghouse has also been owned by non-US companies for more than 20 years.

[5] For a typology of SMRs, see (Glaser et al., 2015).

[6] These include NuScale, SMART, Holtec, and Rolls Royce SMR designs.

[7] The Generation IV Forum was set up as an international cooperative collaboration and included the governments of the United States, the UK, and Canada. https://www.gen-4.org/gif/jcms/c_9502/generation-iv-goals.

[8] An example of a failed project is Elk River, which was widely heralded as "Rural America's First Atomic Power Plant." Analogous to the SMRs currently proposed, it used prefabricated components, and its reactor vessel could be shipped to the site on the smallest standard railroad flat car of the time (Davis, 2013). Commissioning of the reactor was 3.5 years behind schedule, and the construction cost more than doubled in comparison to the initial projection. Elk River operated for a remarkably short three and a half years. The reactor was shut down for good in February 1968 after cracks appeared in the cooling system piping. Faced with replacement costs estimated at $1 million, the cooperative chose not to repair it because the utility "did not feel we wanted to spend the money, especially since the reactor has not been too economical because it is too small" (Bukro, 1971).

[9] The only US utility that had shown interest in the Pebble Bed Modular Reactor was the Philadelphia Electric Company and initial hearings with the NRC took place, but in 2000, it merged with Unicom to become Exelon, and Exelon withdrew from that project in 2002 (Thomas, 2011, p. 2437).

[10] Plans to use nuclear reactors to fuel the oil sands industry have been discussed for over a decade, and between 2007 and 2011, Energy Alberta Corporation and Bruce Power pursued a plan to build four reactors to generate 4000 MW of power. See Reuters, "Bruce Power: Alberta Nuclear Ambitions Shelved," *Financial Post*, December 13, 2011, https://financialpost.com/commodities/energy/bruce-power-scraps-10b-alberta-nuclear-project and Turner, Chris. "The Big Decision." *Alberta Views*, October 1, 2008. https://albertaviews.ca/the-big-decision/.

[11] Ontario Power Generation is also a partner in the Micro Modular Reactor project (OPG, 2020a).

[12] https://www.gov.uk/government/news/pm-outlines-his-ten-point-plan-for-a-green-industrial-revolution-for-250000-jobs and https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/936567/10_POINT_PLAN_BOOKLET.pdf.

[13] The Nuclear Industry Association for the UK, Nuclear Energy Institute for the United States, and the Canadian Nuclear Association.

[14] The November 2020 announcement linking hydrogen production from reactors operating at high temperatures might represent a change in the UK position.

[15] It is to get round this "Catch 22" of the need to demonstrate the technology technically and economically before orders can be placed and that the economics will only be demonstrated when the productions lines have been used to supply large numbers of reactors that Rolls Royce is asking the UK government not only to subsidize design development but to commit to buy about 16 reactors at the same time as the demonstration plant is ordered so the production lines can be set up.

[16] The case of Areva's Le Creusot steel forge in France offers an example, which is particularly striking given France's extensive nuclear fleet.

[17] In the United States, the difference in the generation cost between nuclear energy and solar and wind energy is so large that it allows to economically utilize complementary technologies, such as demand response and storage, to compensate for the variability of output from solar and wind farms (Makhijani & Ramana, 2021b).

AUTHOR CONTRIBUTIONS

Stephen Thomas: Conceptualization (equal); formal analysis (equal); investigation (equal); methodology (equal); writing – original draft (equal); writing – review and editing (equal). **M.V Ramana:** Conceptualization (equal); formal analysis (equal); investigation (equal); methodology (equal); writing – original draft (equal); writing – review and editing (equal).

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How to cite this article: Thomas, S., & Ramana, M. V. (2022). A hopeless pursuit? National efforts to promote small modular nuclear reactors and revive nuclear power. *Wiley Interdisciplinary Reviews: Energy and Environment*, *11*(4), e429. https://doi.org/10.1002/wene.429