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Prospects for Small Modular Reactors in the UK & Worldwide

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Executive Summary

Over the past few years in the UK, and in a number of other countries with nuclear power programmes, there has been a growing clamour of support within government and from the nuclear industry to develop a programme of 'Small' Modular Reactors' (SMRs). This has been part of a wider attempt to make nuclear power part of the 'low carbon' energy solution and stabilise the nuclear sector from an apparently terminal decline.

Much of this focus arises from the failings of the large reactor sector. In the UK alone, in 2018 both the Sellafield Moorside and the Wylfa B projects were effectively abandoned as Japanese reactor vendors pulled out because they were unable to attract the scale of finance required. Globally, even the home markets of China and Russia for large reactors have stalled and, there is little appetite for them, due to such projects being prohibitively expensive to develop and deliver.

The nuclear industry has put forward SMRs as a panacea to these problems of high cost and the difficulty of financing; an ostensibly ready-made alternative that can fill the gap. However, as this report outlines in detail, there are huge obstacles to overcome. Some of these are technical issues, others are around building up an effective supply chain, while the financing of such schemes will only be possible with significant subsidy from the public purse.

Report after report, usually from the nuclear industry or its supporters, has made grandiose claims for SMRs and their importance in delivering a low carbon future. In the UK, the site of Trawsfynydd in Gwynedd, Wales, which hosts a former Magnox plant, is being heavily trailed by the industry and the UK and Welsh Governments as being ideal for SMRs. In Canada and the United States, sites have also been put forward. But is this confidence brittle-deep, style over substance, words rather than action?

This report has been initiated and developed by the Nuclear Consulting Group (NCG) to provide a rational, technical and independent analysis of the prospects for SMRs being developed in the UK and around the world. Whilst the original 'small' nuclear reactors had a military application in nuclear powered submarines, this report focuses on, and takes in turn, each of the different SMR proposals that have been put forward by the nuclear industry – Light Water Reactors, Rolls Royce's SMR designs and Non-Light Water Reactors (such as sodium fast reactors and high temperature reactors). In each case the authors conclude that it remains likely that no substantive deployment of the technology will be realised, with just a very few reactors built, at most.

This will be the case despite large amounts of public money being invested in these projects and, worse, the neglect of other more viable non-nuclear options. It provides another example of the industry talking a good game but delivering little.

The report also outlines in some detail UK Government policy on SMRs. It notes that after some considerable early promotion of the technology, interest has markedly cooled. The report notes the extraordinary set of conditions set out by Rolls Royce to be met by the UK Government if it is to invest significant amounts of money in its own SMR design, which the authors argue could and should not be committed to at a time when serious doubts remain about the economic viability of the technology.

At a global level, the report concludes that, as with the much-heralded ‘nuclear renaissance’ of recent times, SMRs will not be built in any significant scale. The authors note that the two main rationales for SMRs – promised lower overall project costs and lowering the risk of cost overruns by shifting to an assembly line approach – are more than offset by the loss of scale economies that the nuclear industry has pursued for the past five decades. Indeed, many of the features of the SMRs being developed are the same ones that underpinned the latest, failed generation of large reactors. Reactor cost estimates will remain with a large degree of uncertainty until a comprehensive review by national nuclear regulators is completed, the design features are finalised and demonstration plants are built. Whether the economies claimed from the use of production line techniques can be achieved will only be known if reactors are built in very large numbers, and at significant cost.

Spending so much time and effort pursuing such an uncertain technology, at a time when the ‘climate emergency’ has now reached the political and public lexicon and seen as requiring urgent attention, does not appear to be an effective use of taxpayer resources. Abundant evidence shows that renewable energy supply, storage, distribution and management technologies are being developed ever cheaper and swifter at a time when real urgency is required across society and government. SMRs are no answer to creating low-carbon economies by 2030 or close to that date. Governments should consider this report carefully and not be diverted by an unproven technology inherent with much of the failings of its large reactor ‘big brother’.

In the overall view of the report authors, the prospects for SMRs in the UK and Worldwide is limited and not worth the huge levels of effort or finance being proposed for them.

1. Introduction

In 2014, the UK government, co-funded by seven nuclear industry organisations including Rolls Royce, commissioned the National Nuclear Laboratory (NNL) to carry out a feasibility study on Small Modular Reactors (SMRs), reactor designs that produce much less electricity in comparison with designs that are currently being constructed in the UK and elsewhere.[1] Rather optimistically, the resulting study projected a potential world market of 65-85 GW by 2035 with 7-21 GW installed in the UK, suggesting that the market would be worth £250-400bn, implying a construction cost of about £4000/kW. Given how the large reactor program that was launched with ambitious goals has come crashing down as the high costs of Hinkley Point have become apparent, these claims about a global SMR market and a large build-up in the UK should be critically examined, especially since plans envision funnelling significant amounts of public funding to various nuclear organizations, especially Rolls Royce.

In this report, therefore, we examine the prospects for Small Modular Reactors (SMRs) worldwide and in particular in the UK. In Section 2, we look at the factors contributing to the recent push for SMRs - primarily the inability of large reactor designs to reduce costs or make the construction process more manageable. In Section 3 we critically examine the form, function and relative economics of SMR deployment. In Section 4, we review the main designs that have been proposed, dividing them into Light Water Reactors (LWRs) and non-LWRs - the former claiming to be closer to commercial deployment. In Section 5 we discuss unfolding UK government SMR policy. Finally, we draw conclusions about the relative probability of SMR deployment worldwide, and particularly in the UK. Some SMR developers claim safety advantages over current designs. These claims are theoretical and untested and while we note these claims, we make no judgement on their validity

2. The Economic Failure of Large Reactors

The latest set of large reactor designs,[2] were supposed to be safer and address the economic problems of earlier designs. The idea was that they would be simpler, and therefore cheaper, easier to build, and less prone to cost and time overruns than their predecessors. Optimistic forecasts were made of overnight construction costs of $1000/kW to $2000/kW, and construction times of 3-4 years.[3] These were based on use of many of the features that now underpin most of the Light Water Small Modular Reactor designs, in particular reliance on passive safety, and the use of factory manufactured modules so that only module assembly was required on site. The nuclear industry predicted that deployment of the new large designs would lead to a ‘nuclear Renaissance’.

[1] http://www.nnl.co.uk/media/1627/smr-feasibility-study-december-2014.pdf
[2] The net capacity of the current large nuclear reactors range between 1085 to 1660MWe. With Westinghouse-Toshiba’s AP-1000 rated at 1117MWe, Areva EPR at 1660MWe, Hitachi-GE ABWR at 1350MWe and CGNPC-CNNC HPR-1000 rated at 1090MWe and Rosatom AES-1200 rated at 1085MWe.
[3] Tony McConnell and Louis Long, “A Roadmap to Deploy New Nuclear Power Plants in the United States by 2010” (Washington, D. C.: United States Department of Energy Office of Nuclear Energy, Science and Technology, October 31, 2001), https://www.energy.gov/sites/prod/files/ntdroadmapvolume1.pdf; UC, “The Economic Future of Nuclear Power” (Chicago, U.S.A.: University of Chicago, 2004); Stephen Ansolabehere et al., “The Future of Nuclear Power” (Massachusetts Institute of Technology, 2003), http://web.mit.edu/nuclearpower/.

In fact, the experience has been the opposite. A ‘Renaissance’ has not happened and, 15 years after the new large designs were offered, only a handful of them are in operation, with a further 15 at varying stages of increasingly lengthy construction. The main three novel large reactor designs are the Westinghouse AP1000, the Areva EPR, and the Rosatom AES-1200. Without exception, all reactor builds using these designs are significantly late and, where costs are known, far over budget. The construction cost appears to be on the order of $8000/kW. Reactor construction has taken up to 15 years, and some plants will cost more than three times their expected cost. It seems that far from being simpler and easier to build, these new designs are far more complex and vastly more expensive.[4]

Market analysis by Citibank has identified five significant technical and financial risks associated with ownership of nuclear power plants, including: risks during planning, construction, operation, decommissioning and from the market power price.[5] Citibank also noted that equity investment in nuclear poses core challenges, suggesting that it may be extraordinarily difficult to get non-recourse debt into new nuclear. And given the opportunity costs of nuclear combined with the proven tendency to significant cost increases and overruns, initial industry cost estimates for new-build have proven major under-estimates. For example, in the USA, the construction of two AP1000 Westinghouse nuclear reactors at the Summer site was abandoned after 4 years’ work due to significant construction cost overruns with estimated costs more than doubling to US$23bn, the expectation of further escalation, and completion delay of at least 5 years. This project has left consumers facing heavy costs as the utility has been allowed to recover some of its costs from consumers. Another US project, Vogtle, comprising the construction of two AP1000s, although still ongoing, remains vulnerable to abandonment, has experienced a cost ramp from US$14bn to the latest estimate of US$25bn, and the project is already at least five years behind schedule.[6] Likewise, the cost estimate for the UK’s Hinkley Point C project for two EPR reactors, even before construction started in December 2018, had increased from £12bn in 2012 to £20bn in 2017. China is no exception, with at least half of the 16 units under construction, including all the reactors using new imported designs (i.e., AP1000 and EPR), experiencing significant delays.

In Europe, the Areva EPR new-build in Olkiluoto, Finland has not gone well. Originally planned to go online early by 2009, the 1.6 GW Areva designed reactor was a ‘first of a kind’ (FOAK). Latest estimates suggest completion will not be before 2020. Originally priced at €3bn, the project is now estimated at more than three times that level of costs and rising. The fixed price turn-key contract was subject to a prolonged dispute between the French manufacturer Areva and the Finnish nuclear corporation TVO, with the latter claiming costs for delays. The settlement saw Areva meeting all the extra costs (excluding finance) over the €3bn contract price, estimated at €5.5bn, as well as paying an additional €450m in compensation.[7] Similarly, in France, EDF’s EPR Flamanville project has experienced

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[4] S D Thomas (2019) ‘Is it the end of the line for Light Water Reactor technology or can China and Russia save the day?’ Energy Policy, 125, p 119-125.

[5] Citi (2009): New Nuclear – The Economics Say No, UK Green Lights New Nuclear – Or Does It? 9 Nov 2009. http://npolicy.org/article_file/New_Nuclear-The_Economics_Say_No.pdf

[6] Schneider M., Froggatt A., Hazemann J., Katsuta T., Ramana M.V., Stirling A., Johnstone P., von Hirschhausen C., Wealer B. (2018): The World Nuclear Industry Status Report 2018, Mycle Schneider Consulting, Paris, 2018.

[7] Nuclear Intelligence Weekly ‘End in Sight After Settlement on €11.4 billion-Plus OL3’ March 16, 2018.

escalating delays and cost increases, dating back to the start of construction and pouring of first structural concrete. Originally scheduled to start operating in 2012, EDF now hopes that the reactor may be operational by 2021, but there could be delays of a further two years due to safety concerns associated with the repair of sub-standard welds. Originally priced at €3.3bn, the reactor completion was estimated at €10.9bn by 2018.[8]

Because of the economic implications of the ongoing and cumulative construction cost and time over-runs associated with new nuclear projects, utilities are now only be able to pay for new plants if governments guarantee their income will almost certainly cover their costs.[9] In other words, costs and risks associated with nuclear construction mean that plants can only be built with explicit and substantial public subsidy, including loan guarantees, and long-term power purchase agreements or guarantees that cost overruns can be recovered from taxpayers and consumers. In the UK, despite significant public subsidies, plans for five new nuclear power plants have been subject to significant recalibration. Only one plant, Hinkley Point C, has started construction (in December 2018) - *circa* eight years later than planned - whilst four other NPP construction projects have been abandoned or are in serious doubt. Following the bankruptcy of Toshiba's US nuclear arm, Westinghouse, the Japanese conglomerate has withdrawn from its Moorside project for three reactors citing expanding costs. Fellow Japanese corporation, Hitachi, has also recently suspended development of its Wylfa plant in Anglesey, Wales, with a proposed second Hitachi plant in Oldbury, England, also likely to be abandoned. Similarly, significant uncertainty remains concerning the proposed Framatome EPR reactors planned for Sizewell.

Further doubts have been cast over the UK's new nuclear programme following the UK Parliamentary National Audit Offices' review of the economic case for the EDF EPR Hinkley Point C project, which concluded that HPC was both 'risky and expensive' for the UK taxpayer and electricity consumer.[10] The UK Parliamentary National Infrastructure Commission (NIC) also reported that Britain should not back more than one new nuclear plant after Hinkley Point before 2025, noting that new renewable energy represented least-cost for consumers.[11]

3. Small Modular Reactors

In response to the construction and cost difficulties associated with the most recent designs of large reactors, a step-change in emphasis associated with research and development of small

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[8] A significant quality-control scandal at the French nuclear construction corporation Areva's nuclear forge at Le Creusot further eroded confidence, resulting in share-value erosion and downgrading by credit-rating agencies. This was swiftly followed by a fiscal rescue and Areva was renamed Framatome.

[9] World Nuclear Association (WNA) (2017): Nuclear Power Economics and Project Structuring - 2017 Edition Produced by: World Nuclear Association Published: January 2017 Report No. 2017/001.

[10] NAO (National Audit Office) (2017): Hinkley Point C, Report by the Comptroller and Auditor General, Department for Business, Energy & Industrial Strategy, https://www.nao.org.uk/wp-content/uploads/2017/06/Hinkley-Point-C.pdf

[11] NIC (National Infrastructure Commission) (2018): National Infrastructure Assessment, July 2018. https://www.nic.org.uk/wp-content/uploads/CCS001_CCS0618917350-001_NIC-NIA_Accessible.pdf; NIC also noted that it was now possible to conceive of a low-cost electricity system that is principally powered by renewable energy sources. Perhaps tellingly, Sir John Armitt, Chair of NIC, stated: "*Where, in the past, I've been a strong supporter of nuclear – I think that we are in a different world today. We don't have to be as dependent on a nuclear solution as maybe we thought we needed to be 10 years ago*" (Carbon Brief, 2018).

modular reactors (SMRs) has been suggested.[12] SMRs are nuclear reactors, generally understood to comprise net capacity of 300MWe equivalent or less, designed with modular technology.[13] Proponents suggest that SMRs can drive construction costs to more competitive levels through assembly line reactor manufacture of the constitutive modules. However, there are serious concerns with this theory.

All recent nuclear design has been based around the concept of economies of scale. This is because, for example, normal engineering metrics forecast it would be far more economic to build one 1.2 GW unit than a dozen 100 MW units. Economies of scale have been exploited with offshore wind power generation, where costs have significantly decreased due to larger unit construction, increasing turbine size from about 3MW to 15MW. Scale economies imply that SMRs will be more expensive to build than large reactors per unit of capacity.[14]

As mentioned, SMR advocates claim that they can compensate for this loss of economies of scale through savings introduced by assembly line manufacture. However, setting up SMR assembly lines is costly, and the relative economics of SMR production may remain unproven until very many SMR units have been produced - which, paradoxically, cannot happen until a significant number of orders are placed, a circular dilemma. This requirement for a significant number of orders is sometimes called a full order book. In order to obtain such a full order book, *de facto* demonstration of SMR construction and operational capacity to time and cost must be proven. In this sense, SMR investment risk seems very great, perhaps even bigger than that of proposed large reactors.[15] The company seeking to manufacture and sell SMRs will face a very significant up-front investment that is needed to establish an entire supply chain to sell scores of reactors needed to replace the lost economies of scale with the proposed economies of replication.[16] Correspondingly, this dynamic has resulted in demands for significant government assistance for SMR development. For example, in the UK, Rolls Royce is asking for £200m or more of public money to develop its SMR design.[17] Thus, to date, the relatively poor economics of SMR deployment has been the key determinant of SMR market dynamics. Two main US nuclear corporations, Westinghouse and Babcock & Wilcox, have already pulled out of SMR development because of lack of interest from utilities.

Further, potential cost benefits of assembly line module construction relative to custom-build on-site construction appear overstated. One reason is that production line mistakes may lead to generic defects that propagate throughout an entire fleet of reactors and are costly to fix,

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[12] World Nuclear Association (WNA) (2015): Facilitating International Licensing of Small Modular Reactors, Cooperation in Reactor Design Evaluation and Licensing (CORDEL) Working Group of the World Nuclear Association, August 2015; BEIS (UK Dept. Business, Energy and Industrial Strategy) (2018): Advanced Nuclear Technologies, Policy paper, Updated 17 December 2018, BEIS. https://www.gov.uk/government/publications/advanced-nuclear-technologies/advanced-nuclear-technologies
[13] BEIS (UK Dept. Business, Energy and Industrial Strategy) (2018): Advanced Nuclear Technologies, Policy paper, Updated 17 December 2018, BEIS. https://www.gov.uk/government/publications/advanced-nuclear-technologies/advanced-nuclear-technologies
[14] Sovacool B K, Ramana M.V (2014): Back to the Future: Small Modular Reactors, Nuclear Fantasies, and Symbolic Convergence, Science, Tech and Human Values. https://doi.org/10.1177/0162243914542350
[15] Cooper M. (2014): Small modular reactors and the future of nuclear power in the United States, Energy Research & Social Science, Vol 3, Sept. 2014, pp. 161-177.
[16] Ramana M.V. (2017): Small Modular Reactors for Nuclear Power: Hope or Mirage? Energy Studies Institute Bulletin, Vol 10, Issue 6, December 2017, pp. 10-11.
[17] Sylvia Pfeifer and David Sheppard, 'Rolls-Royce Leads Drive for Small Nuclear Sites: Energy' *Financial Times*, January 28, 2019.

and experience with production-line manufacture of parts for the nuclear industry has proved troubling.[18]

SMRs produce comparable or greater amounts of nuclear waste as conventional reactors per kWh, and any SMR roll-out among present non-nuclear states provides break-out proliferation potential.[19] This implies higher costs of radioactive waste management and safeguarding of numerous SMRs around the world.

4. Main SMR Designs

In this section, we review those SMR designs that have undergone significant development; we do not deal with those that are just design concepts.[20] Because of its special position in the UK, we deal with the Rolls Royce's plans for SMR development in more detail. We use the categorisation adopted by the World Nuclear Association (WNA), updated in March 2019, regards designs they regard as ready for near-term deployment, and designs at earlier stages or which have been shelved.[21]

There are three main applications proposed for SMRs: as part of a national grid; as part of a local isolated grid; and, to produce process heat for industrial uses such as hydrogen production. We focus mainly on the first application. The other two often entail use of small reactors, sometimes just a few MW of capacity. Different countries emphasize different applications; there is particular interest in Canada for the second application (see Annex). We therefore include only designs with an electrical output of at least 30MW (or expected to be scaled up to at least 30MW), and do not cover Russian designs. Although 33 SMR designs have been designated by the UK government in 2017 as 'eligible participants'[22] in the competition to identify 'the best' SMR option for the UK, most of these have seen little progress and we do not consider those. We look in greater detail at the Light Water Reactors (LWRs) because they are potentially closer to deployment than non-LWRs.

Note, there is ambiguity about the term modularity within the SMR concept. Some developers, such as Rolls Royce, interpret it as being built in factory-made modules, leaving assembly on-site. Others, such as NuScale, refer to factory-made modules, but also the scope to install the reactors in clusters of up to a dozen reactors with some interdependency on-site. UK government publications concentrate on the requirement for factory-made modules rather than clusters of interdependent reactors.

4.1. A Short History of Small Reactors

While discussion of small reactors has become more prevalent from 2010 onwards, there were signs from the 1980s onwards, that the old model of ever-larger reactors was being

[18] Ramana M.V., Ahmad A. (2016): Wishful thinking and real problems: Small modular reactors, planning constraints, and nuclear power in Jordan, Energy Policy 93, pp. 236–245. An example of problems at the manufacturing site affecting multiple reactors is the ongoing concern about Areva's Le Creusot steel forge.

[19] Glaser A., Hopkins L.B., Ramana M.V. (2013): Resource Requirements and Proliferation Risks Associated with Small Modular Reactors, Nuclear Technology 184 (2013): 121–29.

[20] https://aris.iaea.org/publications/smr-book_2018.pdf

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

[22] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/665376/List_of_Eligible_Participants_in_Phase_One_of_the_SMR_Competition.pdf

questioned by some sections of the nuclear industry. (We ignore the first phase of small reactor construction in the 1960s that ended in such reactors being shut down early because they were not economically competitive.[23]) Most prominently, Westinghouse began development of the AP600 (600MW) in 1985. In 1989, a Westinghouse executive, explaining the decision to scale down, stated 'the economies of scale are no longer operative'.[24]. Ironically, by the time the design had completed its regulatory review, Westinghouse found it was not competitive and nearly doubled its output - resulting in the 1150MW AP1000 reactor design in an attempt to make it economic. Subsequently, its Chinese licensee has scaled it up to 1400MW, presumably to gain further scale economies.

Other small designs developed in the 1980s included: the Siemens/ABB HTR-Modul, the GE SBWR, the ASEA-Atom PIUS and the ABB/Rolls Royce SIR. The HTR-Modul design was a 95MW helium-cooled, graphite moderated reactor licensed to Chinese and South African licensees (see below). The GE Simplified Boiling Water Reactor was a 600MW BWR that was submitted to the US safety regulator but withdrawn, the Process Inherent Ultimate Safety Reactor (PIUS) was a 600MW PWR developed in Sweden, and the Safe Integral Reactor (SIR) was a 300-400MW PWR developed jointly by a number of nuclear vendors, including ABB Combustion Engineering and Rolls-Royce. None of the latter three was pursued. Nevertheless, these designs had many of the features that underpin current SMR designs: smaller scale, passive safety and simplification.

4.2. Light Water Reactors (LWRs)

Most LWR SMRs comprise 'integral designs', with the reactor core, primary cooling loop, and steam generators contained within a single reactor vessel (see Table 1). Integral reactor designs are claimed to have safety advantages although these claims are untested. The major exception appears to be the Rolls Royce SMR, which is designed with steam generators manifestly outside the reactor pressure vessel.[25] That Rolls Royce chose not to offer an integrated design is surprising given that submarine reactors are often integral designs - and that Rolls Royce was one of the prime movers in the design of a Safe Integral Reactor (SIR) concept, developed in the 1980s.[26]

All designs claim a high degree of reliance on passive safety systems under which, in an accident situation, it is hoped that the reactor can be brought back under control by processes such as convection - rather than relying on engineered systems like Emergency Core Cooling Systems (ECCSs).

While most of the developers give estimates of construction costs and times, expected lifetimes, and expected date of commercial availability - given their early stage of development, these are of limited value and therefore are not included in our analysis.[27]

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[23] M. V. Ramana (2015): 'The Forgotten History of Small Nuclear Reactors', IEEE Spectrum, http://spectrum.ieee.org/energy/nuclear/the-forgotten-history-of-small-nuclear-reactors
[24] Outlook on advanced reactors. *Nucleonics Week* Special Report, March 30 1989, 3.
[25] See page 67 in https://aris.iaea.org/publications/smr-book_2018.pdf
[26] R Matzie, J Longo, R B Bradbury & K R Teale (1992): 'Design of the Safe Integral Reactor', Nuclear Engineering & Design, Vol. 36, 1-2, pp. 73-83.
[27] https://www.york.ac.uk/media/physics/ypi/docs/SMR%20Joint%20Nuclear%20CDT%20Event%20York%20MAY%202017.pdf

In the following, we briefly list and discuss the form and function of LWRs currently under development. We do so in order to provide a broad over-view of the evolving SMR situation, in order to locate the UK RR SMR in context. Of the LWR SMRs covered, all were included in the UK government's 2017 list of 33 eligible participants in its SMR competition except the Argentinian CAREM-25 and the GE-Hitachi BWRX-300, which had not then been announced.

4.2.1. NuScale SMR

The NuScale SMR has a relatively long development history.[28] It is a pressurized water reactor (PWR), currently designed to produce 60MW. That figure was increased by 20 per cent in 2018 from 50MW, which was itself increased from 45 MW in 2014, an indirect testimony to its desire to achieve economies of scale. The other scale advantage that NuScale seeks to obtain is building its reactors in clusters of up to 12 units. In 2008 NuScale requested a pre-application review by the US Nuclear Regulatory Commission (NRC), and in 2011 the Fluor Corporation (a large US-based engineering and construction firm) became the primary investor. NuScale claims the reactor is suitable for a variety of uses including desalination, and process heat as well as power generation and NuScale makes strong, but unsubstantiated, claims for its load-following capabilities.

In 2013 NuScale received US$217m from the US Department of Energy to develop the design and secure NRC generic approval. In the same year, RR joined the NuScale development programme. In 2017, NuScale submitted its design certification application to the NRC - the only company that has taken that step as of June 2019.[29] There is no forecast date from the NRC when it would receive final approval although NuScale has claimed it would be in 2021.[30] However, the design submitted is the 50MW version and NuScale will have to resubmit the 60MW design to the NRC, once the first design has been certified. It is not clear how long the new review would take but the power upgrade is significant. Its design is under preliminary review by the Canadian Nuclear Safety Commission (CNSC).[31]

As of the end of 2017, Fluor claimed it had invested over $475m in NuScale.[32] By 2018, NuScale claimed it would need to spend a further US$600m to bring it to commercial availability.[33] So despite its long development history, it is still far from being ready for commercialisation. The lead project appears to be for a cluster of to be owned by Utah Associated Municipal Power Systems (UAMPS), but which will be constructed in Idaho, within the national laboratory in that state. However, by July 2019, less than 40 per cent of output of the plant had been sold and construction will not start until all the capacity is sold. UAMPS hopes the plant can still be online in 2027 but this estimate may prove unrealistic. The federally-owned utility, the Tennessee Valley Authority has received an early site permit to build SMRs at its Clinch River site where the NuScale design is seen as the frontrunner.[34] The UAMPS and TVA orders are far from firm and it is worth noting that both

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[28] https://www.nuscalepower.com/en/about-us/history
[29] https://www.nrc.gov/reactors/new-reactors/design-cert/nuscale.html
[30] Inside NRC 'NuScale expects NRC certification of SMR design in 2021: company official' May 14, 2018
[31] https://nuclearsafety.gc.ca/eng/reactors/power-plants/pre-licensing-vendor-design-review/index.cfm
[32] https://www.nuscalepower.com/about-us/faq
[33] SNL Power Daily 'NuScale's compact nuclear design completes 1st review phase by US regulators' May 1, 2018
[34] Inside NRC 'NRC board recommends TVA be given early permit for work on SMR project' Jan 21, 2019.

utilities are publicly-owned and, unlike investor-owned utilities (IOUs), the rates they charge consumers are not independently regulated - so additional costs can be passed on to consumers.

In 2016, NuScale confirmed its intention to compete in the UK's competition to select the best SMR design for the UK. In 2016, the UK company, Sheffield Forgemasters joined the NuScale development team, which already included Rolls Royce.

Other markets that have expressed an interest in the NuScale SMR include: Jordan through an agreement with the Jordan Atomic Energy Commission, apparently superseding an earlier agreement with Rolls Royce;[35] Romania through an agreement with Romania's nuclear generating company, Nuclearelectrica;[36] Canada, through an agreement with the Canadian nuclear power operators, Ontario Power Generation and Bruce Power.[37] These are all far from firm orders and, as with the RR agreement with Jordan, can easily be abandoned.

NuScale is claiming construction costs would be $4200/kW, about half the level of large reactor projects in the USA, the UK, France and Finland.[38] However, the NuScale design is still far from finalised, so current estimates must be seen as promotional. The NuScale design is much smaller than its main competitors, so the lost scale economies compared to large reactors will be correspondingly harder to make up through savings that might accrue from using assembly line manufacture.

4.2.2. Holtec SMR-160

The SMR-160 is a 160MW PWR under development in the USA since 2010.[39] The developers talk about clusters of up to ten reactors. Holtec is collaborating with Mitsubishi Electric (Japan), SNC Lavalin (Canada) and the US utility, Exelon, in the development of the reactor's design. In 2019, Holtec signed an MOU with Ukraine planned to lead to production and deployment of the SMR-160 in Ukraine. Its design is under preliminary review by the CNSC and is collaborating with the Ukraine State Nuclear Inspectorate in its review.[40] These expressions of interest are far from being firm orders.

4.2.3. CNNC ACP100

The China National Nuclear Corporation ACP100 is a 100MW PWR that has been under development for a decade as a reactor intended to provide power, heat and desalination. It is claimed it will be able to be built in clusters of up to eight modules. Start of construction of the first unit has been expected every year from 2014 onwards but as of 2019, no construction had begun. In March 2019, it was forecast the first reactor, now scaled up to 125MW, would start construction by the end of 2019.[41] While CNNC claims it has had discussions in a number of countries about sales of this design, there is little evidence of interest in this design outside China.

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[35] http://www.world-nuclear-news.org/Articles/NuScale-SMR-to-be-considered-for-use-in-Jordan
[36] http://www.world-nuclear-news.org/Articles/Romania-to-explore-NuScale-SMR-deployment
[37] Nuclear News 'OPG to support NuScale Power's SMR efforts' December 2018
[38] US Official News 'NuScale reports 20 percent boost in SMR output' June 8, 2018
[39] https://smrllc.com/about/
[40] https://nuclearsafety.gc.ca/eng/reactors/power-plants/pre-licensing-vendor-design-review/index.cfm
[41] http://www.world-nuclear-news.org/Articles/December-construction-start-for-Chinese-SMR

4.2.4. KAERI SMART

The SMART (System-integrated Modular Advanced ReacTor) has been under development by the Korea Atomic Energy Research Institute (KAERI) since 1997.[42] It is a 100MW PWR. In 2014, it was transferred to a new company, SMART power Co Ltd, and in 2015, an MOU was signed with the Saudi Arabian King Abdullah City for Atomic and Renewable Energy (KA-CARE) with a view to constructing the first two SMART reactors in Saudi Arabia. These reactors would also be planned to provide desalination services.

4.2.5. Argentine CNEA CAREM-25

CAREM-25 was designed by the Argentine Atomic Energy Commission (CNEA).[43] It is a 32MW PWR and construction of a prototype started in 2014 after more than a decade of development. It was planned to be complete by 2018, but by June 2019 was still not in operation. A planned follow-on plant in the Formosa province of Argentina is expected to be 120-300MW but no order has been placed. There appears little interest in this design outside Argentina and the reactor under construction in Argentina is much smaller than the proposed commercial designs - so despite the construction work, it may be further from commercial deployment than some of its competitors.

To this list, we should add two LWR designs that have been shelved or at a very early stage.

4.2.6. Westinghouse SMR

The Westinghouse SMR is a 225MW PWR that began development more than a decade ago.[44] It is based on Westinghouse's large reactor, the AP1000 - a design certified by the US NRC in 2011. The first reactor of four AP1000 reactors entered service in China in 2018 and two reactors are under construction in the USA. However, construction experience has been very poor with high costs and long construction times, and these were largely responsible for Westinghouse filing for bankruptcy protection in 2017.

In 2012, Westinghouse formed the NexStart SMR Alliance along with Ameren Missouri and other utilities "to licence and deploy the Westinghouse SMR by 2022".[45] This Alliance applied for Department of Energy (DOE) funding "to support the initial licensing and construction" of its SMR design.[46] When DOE chose Babcock and Wilcox and NuScale during its two rounds of funding in 2012 and 2013, Westinghouse decided to essentially shelve the project in early 2014. In February 2014, the CEO of Westinghouse 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'*[47]. Since then, little further work has been done on the Westinghouse SMR.

[42] http://www.smart-nuclear.com/tech/d_history.php
[43] http://www.world-nuclear-news.org/NN-Argentina-reaches-generator-milestone-for-CAREM-25-08051801.html
[44] http://www.westinghousenuclear.com/new-plants/small-modular-reactor
[45] https://www.world-nuclear-news.org/NN-Westinghouse-SMR-progress-slows-210214ST.html
[46] https://www.nucnet.org/all-the-news/2012/05/18/westinghouse-forms-nexstart-alliance-to-bid-for-smr-funding
[47] Pittsburgh Post Gazette 'Westinghouse backs off small nuclear plants' February 2, 2014

4.2.7. GE-Hitachi BWRX-300

The 300MW BWRX-300 was only announced in 2018 and is basically a scaled-down version of the 1500MW GE-Hitachi ESBWR.[48] The ESBWR design was given generic approval by the US NRC in 2014 but has won no orders, not least due to its high expected cost - and no orders are in prospect. US utilities Dominion and Exelon are providing financial support for the design work for BWRX-300 and it has support from the US Department of Energy but is clearly a long way from deployment.4.2.5.

4.3. Summary

The LWR SMRs being developed are generally based on the principles that inspired some of the recent large reactor designs, especially the Westinghouse AP1000 and the GE-Hitachi ESBWR. These large reactor designs have also incorporated modularity, factory production, and passive safety. None of these factors have helped the AP1000 and the ESBWR become cheaper and there is no reason to believe scaling them down, as is the case with the Westinghouse SMR and BWRX-300, will do anything but increase costs.

4.4. Rolls Royce's SMR

We now turn the UK's candidate to the list of LWR SMRs. Announced in 2017, the 450MW Rolls Royce (RR) design was a latecomer compared to other SMR designs. Using its experience of supplying PWRs for submarine propulsion units and its strong position in the UK, RR is also associated with the NuScale SMR.[49] RR has been involved in SMR development since 2013 - the time when the UK government began to show interest in SMRs, and particularly since the government announced its intention to fund a competition to identify an SMR design for the UK market in 2014.

Separately, but perhaps not entirely unconnected to its involvement in SMRs, RR was awarded a contract in 2012 to supply reactors for a new generation of UK nuclear powered submarines.

4.4.1. Rolls Royce's Submarine Reactor Experience

Rolls Royce has supplied all the UK nuclear submarine propulsion units with no serious consideration of alternative suppliers, the first entering service in 1965.[50] There have been three basic designs used: the 1965 PWR1, based on a Westinghouse design; the 1985 PWR2, a development of the PWR1 design; and the PWR 3, which was chosen in 2011, but is not expected to enter service until 2028.

The PWR3 was chosen from three options, all of which would be supplied by RR. The first two were PWR2 and PWR2b (an upgraded PWR2), while the third, PWR3, was based on a US design. The government said the main reasons for choosing the US design were: *'Through simpler design it is easier to operate, has a longer in-service life and lower through-life maintenance costs. In addition the introduction of the new design means that it is*

[48] https://nuclear.gepower.com/build-a-plant/products/nuclear-power-plants-overview
[49] In 2013, RR announced it was joining the team led by NuScale to commercialise the NuScale SMR.
[50] Note, submarine reactors have a much smaller output than civil reactors with perhaps only 10% of their output. They are also necessarily compact and may need refuelling, if required at all in their lifetime, once a decade.

practicable to implement further improvements to safety'.[51] This appeared to be a rejection of the UK design-based options.[52] The PWR2 design had been criticised by the military nuclear safety regulator for safety deficiencies, which were found to be: *'potentially vulnerable to a structural failure of the primary circuit'*.[53] The apparent unquestioned monopoly of Rolls Royce in submarine reactor supply was probably only feasible because of the more secretive nature of defence work and would be seen as unjustifiably anti-competitive in other sectors.

4.4.2. The RR SMR Design[54]

Details of the RR design on their website remain sketchy and it appears closer to a reasonably large and conventional PWR than other SMR competitors such as NuScale and Holtec.

RR SMR Development History[55]

In March 2016, Rolls Royce submitted a bid to the UK government for the SMR contest although details of the design were very vague, with the reactor size forecast between 220MW and 440MW.[56] By October 2016 it was making a strong pitch for 7GW of UK SMR orders billed as 'the only option' with UK Intellectual Property (IP). RR went on to claim that: Based on a theoretical world market of 65-85GW of which RR claimed they could win 9GW, via a consortium of primarily UK based companies, they assumed rather optimistic potential benefits of £100bn to the UK economy and 40,000 jobs from UK and export sales.[57] The consortium included Amec Foster Wheeler, Nuvia and Arup as well as the UK government's Nuclear Advanced Manufacturing Research Centre. Given the lack of interest in the RR SMR outside the UK, these estimates seem unrealistic. In June 2017, RR settled on a rather large reactor size of 440MW, claiming the plant would still be fully transportable by road.[58] SMRs are defined as having a net capacity of 300 MWe equivalent or less. Correspondingly, the size of RR's design took it outside the bounds of the UK government's SMR Competition.

In January 2019, the Financial Times reported that the RR consortium was seeking 'a sum "in the low hundreds of millions"' of UK government money, which it would match, in order to take the design to the later stages of the UK regulator's Generic Design Assessment process.[59] The very significant cost of setting up the associated manufacturing facilities would presumably be in addition to this. If RR forecasts there is further *circa* £400m of design work to be undertaken, that suggests that the design is at a very early stage of development. RR was reported as estimating the construction cost of one of their SMRs

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[51] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/27399/submarine_initial_gate.pdf
[52] https://fas.org/wp-content/uploads/2015/03/2015-FAS-UK-NNPP-HEU-final2.pdf
[53] https://www.theguardian.com/world/2011/mar/10/royal-navy-nuclear-submarine-reactor-flaws
[54] https://aris.iaea.org/publications/smr-book_2018.pdf
[55] https://www.rolls-royce.com/~/media/Files/R/Rolls-Royce/documents/customers/nuclear/smr-technical-summary.pdf and https://aris.iaea.org/publications/smr-book_2018.pdf
[56] Nucleonics Week 'Several companies express interest in UK SMR competition' March 24, 2016
[57] *The Telegraph*, 'Buy British to reap benefits of mini-nuclear power plants, Rolls Royce tells ministers' October 1, 2016. *The Telegraph*, 'Mini-nuclear plants could create 40,000 jobs and trigger export bonanza, says Rolls-Royce', November 7, 2016.
[58] Nucleonics Week 'Rolls Royce SMR would have up to 440-MW capacity, company says' June 22, 2017
[59] Peggy Hollinger and Sylvia Pfeifer, 'Rolls-Royce Threatens to End 'Mini-Nuke' Project for Lack of Support' *Financial Times*, July 22, 2018.
https://www.ft.com/content/ba08f298-8b6e-11e8-b18d-0181731a0340; A GDA comprises a detailed and prolonged (up to 5 year) regulatory review by UK Office for Nuclear Regulation of any proposed reactor design.

would be £2.5bn or £5700/kW ($7400/kW). Given the early stage of development of the design, these cost estimates can have little credibility. While the construction cost estimate is less than the most recent Hinkley cost estimates (£6200/kW) given the early stage of design development and the historic tendency for costs to escalate substantially during design development, the economic case seems weak. The UK government is reported to be promising a response to the RR consortium's request in 'spring 2019'. By June 2019, this reply had not been published. However, in January 2019, *The Times* of London reported that Rolls Royce has "approached China General Nuclear (CGN) to propose using its control systems at the Bradwell plant instead of the Chinese company's own kit" and this "marks a change of tack in its UK nuclear strategy after its efforts to develop smaller reactors, dubbed "mini nukes", foundered".[60]

Rolls Royce SMR claims

In February 2017 Rolls Royce revealed more details of its strategy in evidence to a House of Lords (HoL) Committee Inquiry, *'Nuclear research and technology: Breaking the cycle of indecision'*, by detailing the conditions that would need to be fulfilled to go ahead with SMR development.[61] These were:

- *'Choosing one preferred technology preferably with input from a selected UK team to deploy and maximise 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 7GWe;*
- *Sustainment of a national nuclear supply chain capability across both Defence 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.'*

RR told the committee that they believed SMRs could be as large as 500MW, leaving the door open for them to scale up their design even further if the economics proved poor.

RR went on to suggest that it should be considered as Government's industrial partner of choice in a UK SMR programme. Correspondingly, the HoL Committee leant heavily on Rolls Royce's evidence. For example, on required SMR market size, quoting David Orr (Senior Vice-President, Future Programmes and Technology at Rolls-Royce Nuclear), it said that *'there is not a large enough market in the UK for more than one design to be commercially viable'*, noting that since *'Rolls-Royce told us that 7GW of power would "be of sufficient scale to provide a commercial return on investment from a UK-developed SMR, it*

[60] Emily Gosden, 'Rolls-Royce Vies for British Nuclear Role' *The Times (London)*, January 22, 2019.
[61] https://www.parliament.uk/business/committees/committees-a-z/lords-select/science-and-technology-committee/news-parliament-2015/nuclear-research-technology-report-published/

would not be sufficient to create a long-term, sustainable business for UK plc." The implication being, *'any SMR manufacturer would have to look to export markets to make a return on their investment.'*

In further evidence to the HoL Committee, RR became critical of delays in announcing the results of the government's SMR competition, and the failure to publish a 'SMR Roadmap'. RR also claimed the government's priority should be on LWR SMRs rather than the non-LWRs, arguing that LWRs were potentially *'closer to deployment'*.

RR went on to make some very optimistic statements about the benefits an SMR programme would bring, claiming its design would be deployable by 2028-30, and insisting that it could be the *'first [SMR] to market'* – despite the fact that RR later informed the IAEA that any first power from a first unit could only be expected by 2030. RR gave a vision of the benefits of adopting their SMR technology, stating that *"A UK SMR programme will create many highly skilled jobs in both the near and longer term and also re-establish the UK as a leading global nuclear nation. Rolls-Royce estimates that a regular production schedule of one SMR per annum would generate >10,000 jobs within the supply chain, which could increase to c.40,000 jobs on the basis of two UK plants per annum and secured export opportunities of c.9GW"*.[62]

These claims and demands were reiterated in evidence to the UK Parliamentary Business, Energy and Industrial Strategy Select Committee.[63] RR added strong claims for the load-following capability and the potential use for Combined Heat and Power: '*Therefore, a significant opportunity exists for dispatchable, low-carbon energy generation that can support electricity and heat production at an affordable price. SMR has the potential to do this.* .'. Load following would raise safety issues that would need to be carefully assessed by the safety regulator but which, by reducing the output the plant, would inevitably increase the cost of the power. RR confirmed its overnight construction cost estimate of £4000/kW and added a demand for the provision of export credit guarantee.

There are strong allusions in its submission to the need for government to play a major role in financing production facilities and guaranteeing orders: *'It is likely that the first of a kind (FOAK) project will command a higher risk premium than follow on (or nth of a kind – NOAK) projects, and therefore careful considerations should be made of how Government can assist in helping industry manage risk for the FOAK unit so that industry can invest, and further plants be constructed. This is particularly important for SMRs as factory-based volume production of systems and components is one of the key ways that cost can be reduced and timescales for build certainty improved.'*

There are repeated claims of the need to speed up licensing processes and of the need to overcome the market failure that hampered the deployment of nuclear technologies: *'SMR has the potential to do this [provide dispatchable low-carbon energy generation], if it can be helped to overcome current market failure driven by the lengthy up-front regulatory and licensing processes that impact route and time to market.'*

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[62] https://www.parliament.uk/business/committees/committees-a-z/lords-select/science-and-technology-committee/news-parliament-2015/nuclear-research-technology-report-published/
[63] http://data.parliament.uk/writtenevidence/committeeevidence.svc/evidencedocument/business-energy-and-industrial-strategy-committee/financing-energy-infrastructure/written/98880.pdf

These claims cannot be justified. The idea that the safety review of a new reactor design, claimed to be innovative, could be anything other than exhaustive is hard to justify and there seems no reason why, for this case, local planning procedures should be essentially bypassed. The safety regulator's Generic Design Assessment for all three large reactor designs planned for the UK was completed largely within the four-year time frame promised. The claim of a 'market failure' betrays a lack of understanding of the term. The fact that a technology has not been deployed, which is not economically competitive and is seen by financiers as too risky to support is a market success, not a failure. The failure of the projects for large reactors in the UK had nothing to do with delays in licensing or regulation, it was the result of their high costs and the absence of anyone prepared to provide the necessary finance.

One element of the RR report that has gained visibility is the interface with military submarine technology. The report's section headed '*Advantages to the UK's nuclear deterrent programme'* clearly implied that costs that would otherwise be borne by the military would fall on electricity consumers - thus reiterating the point it had made earlier to the Lords Committee.

RR suggested that the low estimated cost of power produced by their SMR (compared to Hinkley Point C, which in 2017 pounds, would generate at about £100/MWh) was attributable to enhanced 'learning' from development of a large number of modules, factory production, and minimised on-site work - claiming that a GDA by the UK ONR could be completed by 2024. However, the lack of specific commitment in the UK's June 2018 Nuclear Sector Deal led to reports that RR would abandon SMR development unless further UK government support was offered.[64]

Failure in Jordan and Nuclear Sell-off

Meanwhile, in November 2017, RR signed a memorandum of understanding (MOU) with Jordan in order to conduct a technical feasibility study concerning a potential SMR program for power generation and water desalination.[65] However, by January 2019, it appeared there were serious difficulties in the relationship between RR and Jordan, in part due to the apparent unwillingness of the UK government to allow the latter access to the RR SMR technical details.[66]

In March 2019, RR announced it was selling the majority of its civil nuclear businesses, hoping to raise £200m. The sale would exclude the SMR division, the work associated with the Hinkley Point project, and the nuclear submarine business. By July 2019, there had been no offers from potential buyers.

To summarize, the RR design is a latecomer to the field of LWR SMRs. It was launched two decades after NuScale and KAERI SMART, and a decade after CNNC ACP-100. It is unclear how advanced the design is. The RR design is 50% larger than the upper size limit for SMRs. As the only UK-based option, it will have some public support, but there is no indication that the government is looking favourably on it. Rolls Royce is making demands for its continued development only if the UK government guarantees significant funding, assured markets, and

[64] Peggy Hollinger and Sylvia Pfeifer, 'Rolls-Royce Threatens to End 'Mini-Nuke' Project for Lack of Support' *Financial Times*, July 22, 2018.
[65] Nuclear Engineering International 'Jordan – Rolls Royce to undertake SMR study' December 2017
[66] Nuclear Intelligence Weekly 'NuScale a finalist in SMR competition' January 18, 2019, p 5-6

grants RR a key position as government's key partner in SMR development. As of June 2019, it was not clear whether these extraordinary demands would be met.

The UK government's decision to choose the US-developed PWR3 design for future UK submarines rather than RR's own designs suggests that the UK government would not choose the RR SMR design option just because it is British. How far the UK government's cutting back of its LWR SMR commitment is due to reservations about Rolls Royce is hard to tell. It is not clear what, if any, the next steps in the UK government's SMR programme will be for LWRs, but until and if it comes under detailed scrutiny by the UK safety regulator, the costs of the Rolls Royce SMR will be highly speculative. Importantly, with the apparent collapse of the agreement with Jordan, there appears to be no interest in the RR SMR outside the UK, undermining RR's claims of a large world market.

5. Non-Light Water SMRs

The non-LWR reactors under development include a range of very diverse technologies. These fall into four main types:

- Helium-cooled graphite moderated high-temperature reactors (HTGR);
- Sodium-cooled fast reactors (FBR);
- Molten salt reactors;
- Lead-cooled fast reactors.

The first two types have been built in very small numbers up to commercial scale but with poor results.[67] Despite decades of development, the second two have not been built even to prototype power reactor scale.

One of the attractions of HTGRs that has led to attempts to commercialise the technology stretching back over six decades is that they operate at much higher temperatures than LWRs. If the outlet temperature can be increased to 1000+C as is proposed for Very High Temperature Reactors, this opens the way to produce hydrogen by a much more efficient process than the conventional electrolytic method.[68] However, it is hard to see why, after decades of failed attempts to commercialise the technology, these new attempts should be any more successful than their predecessors, especially if even higher reactor temperatures than have so far been attempted are sought.

Sodium-cooled fast reactors have also been under development for more than six decades because of their potential to use much more of the naturally occurring uranium than LWRs.[69] The interest resulted from fears that uranium reserves would be quickly depleted if only LWRs were used. Fast reactors require the reprocessing of spent fuel to isolate the plutonium fast reactors use as fuel, but reprocessing has been expensive, and countries have been

[67] 'Fast Breeder Reactor Programs: History and Status,' Princeton: International Panel on Fissile Materials, 2010; Thomas B. Cochran, Harold A. Feiveson, Zia Mian, M. V. Ramana, Mycle Schneider, and Frank N. von Hippel, 'It's Time to Give Up on Breeder Reactors' *Bulletin of the Atomic Scientists* 66, no. 3 (2010): 50–56; M. V. Ramana, 'The Checkered Operational History of High Temperature Gas Cooled Reactors' *Bulletin of the Atomic Scientists* 72, no. 3 (2016): 171–79. https://doi.org/10.1080/00963402.2016.1170395.
[68] https://www.gen-4.org/gif/jcms/c_42153/very-high-temperature-reactor-vhtr
[69] https://www.gen-4.org/gif/jcms/c_42152/sodium-cooled-fast-reactor-sfr

gradually ceasing that practice.[70] The isolation of plutonium leads to concerns about weapons proliferation and sodium burns explosively if it comes into contact with water. As with high temperature reactors, it is hard to see why renewed efforts to commercialise the technology would be any more successful than their predecessors.

In molten salt reactors, the fuel is dissolved in molten fluoride salt.[71] Molten salt reactors can be used in various modes, often as fast reactors. The technology is still very much 'in development', and significant technology and materials advances would be needed to bring the design anywhere near market.

Lead-cooled fast reactors also use a technology that requires very significant materials and technology advances and remains very much 'in development'. Like sodium-cooled reactors, separated plutonium with all the issues that raises, would be needed.[72] While a number of lead-cooled reactor developers were amongst the 33 'eligible participants' in the UK government's SMR competition, the designs appear to be no more than conceptual designs.

5.1. Non-LWR SMRs under Construction: The Case of the HTR-PM

The HTR-PM is a High Temperature reactor cooled by helium gas and is being developed in China by a consortium involving China Huaneng, China Nuclear Engineering Corporation, and Tsinghua University. The design has a long history dating back to the late 1980s when a joint venture of Siemens and ABB developed the 80MW HTR-MODUL design. This was never marketed but the technology was licensed to Russia, China and South Africa. It was not pursued in Russia. In South Africa, the technology was developed from 1992-2010 with a view to series ordering of a design, the Pebble Bed Modular Reactor (PBMR) partly in South Africa but primarily for export.[73] However, the project was constantly delayed and subject to massive cost escalation. By the time of its abandonment in 2010, the reactor's output had increased to 170MW without changing the physical size of the plant. While the technology still has its supporters in South Africa, the chances of renewed development there, and elsewhere, appear very low.

In China, there were also long delays in development of the technology. For example, in 2004, construction of the first plant was forecast for 2007 with completion planned for 2010. The expected size of the reactor varied from 105MW to up to 200MW, but construction on the first unit only finally started in 2012, with a pair of reactors at the Shidao Bay site each of 105MW connected to one turbine. The design was less ambitious than the proposed South African design, which has an output of 170MW, a coolant gas temperature of 850C, and was powered directly by the helium coolant using a novel helium-driven gas turbine. The Chinese design is planned to operate at 750C and may use a much less challenging steam circuit in which the helium gas will heat steam in a heat exchanger to power a conventional steam turbine. These differences may well have been the result of the difficulties South Africa encountered developing the gas turbine and the safety concerns about overheating of the

[70] 'Plutonium Separation in Nuclear Power Programs: Status, Problems, and Prospects of Civilian Reprocessing Around the World', Princeton: International Panel on Fissile Materials, 2015, http://fissilematerials.org/library/rr14.pdf.
[71] https://www.gen-4.org/gif/jcms/c_42150/molten-salt-reactor-msr
[72] https://www.gen-4.org/gif/jcms/c_42149/lead-cooled-fast-reactor-lfr
[73] S D Thomas (2011): 'The Pebble Bed Modular Reactor: An obituary' Energy Policy, vol 39, 5, 2431-2440

core.[74] MOUs to build HTR-PMs were signed with Indonesia and Saudi Arabia in 2016 but there appears to have been little progress towards construction since then.[75]

As discussed, construction started at Shidao Bay in December 2012, with completion was expected in 2017. However, by 2019, the plant was not on-line and completion was not expected until 2020 at the earliest.[76] A further problem was that the cost of the reactors appears to be nearly $6000/kW, about 2.5 times the expected construction cost of the indigenous large Chinese PWR, the Hualong One. This might explain the changes in future plans.

When construction of the HTR-PM power plant began, there were plans for eventually constructing a further 18 units of the same type at the same site.[77] That no longer seems to be the case.[78] As a result, promoters of the HTR-PM design are now pushing for future projects to involve clusters of six reactors giving an output of 600 MW. The hope is that constructing in multiples will reduce the cost to reduce by 25 percent, and eventually become on par with the cost of the Hualong reactor. Whether this will be achieved remains to be seen, but the clear conclusion that can be drawn from the experience in South Africa and China is that the pebble bed design of high temperature reactors is not economically viable as an SMR.

6. Non-LWRs for near-term Deployment

6.1. GE-Hitachi PRISM

The GE-Hitachi PRISM design is a sodium-cooled fast reactor that was first discussed in the 1980s and has been under sporadic development since then.[79] Its output is planned to be about 300MWe and it is designed to be installed as cluster of up to six reactors. Given the poor track record of fast neutron reactors, the developers of PRISM started advancing it as a means of ‘burning’ plutonium and other high-level spent fuel products rather than as an economic method of power generation. It has been considered by officials in the USA and the UK for this purpose. In the USA, the first unit has been under examination for installation at the US Department of Energy’s Savannah River site. However, by April 2019, there had been no solid progress in ordering a reactor there. Nevertheless, there appears to be some support for the PRISM design as the basis for the US Department of Energy’s Versatile Test Reactor (VTR) which may be used to test materials that could be used in advanced nuclear technologies.[80]

In the UK, PRISM was one of three options chosen in 2012 by the UK government’s Nuclear Decommissioning Authority (NDA) for investigation as a way to deal with the UK’s large stockpile of plutonium. However, in March 2019, after missing projected decision dates from

[74] https://www.theengineer.co.uk/nuclear-safety-pebble-bed-reactors/
[75] Nucleonics Week ‘China signs agreement with Saudi Arabia to build high temperature reactor’ January 28, 2016
[76] Nuclear Intelligence Weekly ‘Progress on HTGR’ April 26, 2019.
[77] NucNet, “China Begins Construction of First Generation IV HTR-PM Unit,” The Communications Network for Nuclear Energy and Ionising Radiation, January 7, 2013, http://www.nucnet.org/all-the-news/2013/01/07/china-begins-construction-of-first-generation-iv-htr-pm-unit.
[78] WNN, “First Vessel Installed in China’s HTR-PM Unit,” *World Nuclear News*, March 21, 2016, http://www.world-nuclear-news.org/nn-first-vessel-installed-in-chinas-htr-pm-unit-2103164.html.
[79] https://nuclear.gepower.com/build-a-plant/products/nuclear-power-plants-overview/prism1
[80] http://www.world-nuclear-news.org/Articles/US-launches-test-reactor-project

2015 onwards, the NDA published an update on the process that appeared to postpone a decision again. Nevertheless, NDA's verdict on the PRISM option was damning.[81] It stated:

> *'the studies undertaken by NDA with GEH over the past few years have shown that a major research and development programme would be required, indicating a low level of technical maturity for the option with no guarantee of success.'*

6.2. Advanced Reactor Concepts ARC-100

Advanced Reactor Concepts is a private company founded in 2006 in Delaware.[82] It qualified in the UK government's list of 33 'eligible participants.' It is a 100MW sodium-cooled fast reactor based on the 20MW EBR-2 fast reactor, designed by Argonne National Laboratories, that operated from 1965-2005. However, ARC-100 is advertised as having a 20 year refuelling cycle, which is unlike many other fast reactor designs, including the PRISM.[83] Nevertheless, in 2017, GE Hitachi Nuclear Energy (GEH) and Advanced Reactor Concepts LLC (ARC Nuclear) signed a Memorandum of Understanding to "collaborate in the development and licensing of an advanced small modular reactor… based on mature Generation IV sodium-cooled reactor technology".[84]

The reactor's best prospects appear to be in Canada. The company submitted its design to the Canadian Nuclear Safety Commission for pre-licensing vendor design review in 2017. In 2018 it opened an office in the Canadian province of New Brunswick following an agreement with the province's primary electric utility to explore the possibility of building its reactors in New Brunswick.

To this list, we should add some Non-LWR designs that are at earlier stages or shelved.

6.3. Terrestrial IMSR

Terrestrial Energy was established in 2013 in New York.[85] It is attempting to develop a 195MW molten salt reactor, which it is claiming could be deployed by the late 2020s. Its design is under preliminary review by the CNSC and Terrestrial has pre-qualified as a potential technology to be built by Canadian Nuclear Laboratories.[86]

6.4. Moltex SSR

The Moltex Stable Salt Reactor (SSR) was developed in the UK by a new company, Moltex.[87] Each reactor is designed to produce 150MW, but the company seems to promote joining these in clusters of up to eight reactors to produce 1200 MW. In other words, it will not be that small in its output.

It qualified in the UK government's list of 33 'eligible participants' and it has attracted interest in the province of New Brunswick, Canada (where it has set up its North America

[81] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/791046/Progress_on_Plutonium.pdf
[82] https://www.arcnuclear.com/technology
[83] https://www.arcnuclear.com/technology
[84] https://www.arcnuclear.com/arcnews/ge-hitachi-nuclear-energy-geh-and-advanced-reactor-concepts-arc-announce-agreement-to-collaborate-in-the-development-and-licensing-of-the-arc-100
[85] https://www.terrestrialenergy.com/technology/
[86] http://www.cnl.ca/en/home/facilities-and-expertise/smr/progressupdate.aspx
[87] https://www.moltexenergy.com/

headquarters).[88] Its design is under preliminary review by the CNSC and it is under consideration in Estonia.[89]

6.5. SMR Design Summary

While a large number of SMR designs have been announced, only a handful have reached what the WNA describes as 'ready for near-term deployment'. Most of those in that category are LWRs and will require a decade or more of development before they might be ready for commercial deployment. Many of the designs are offered by small companies that would not have the expertise to design a whole nuclear power station and will need strong partners to bring their designs to the market. It is significant that some of the larger, more credible, suppliers like Westinghouse and Babcock & Wilcox have effectively abandoned development.

Interest in SMRs is concentrated in just five countries, Canada, the USA, the UK, Russia and China and in all five cases it is primarily the significant sums of public money that have been promised that seems to be driving the process. Only Canada (see Annex) and, to a lesser extent, the USA have shown any interest in non-LWR designs. For the UK, there is a perception that the process is designed to allow Rolls Royce, the only substantial UK developer, to win the competition as the designated design for the UK. Indeed, the UK government's 'Small Modular Reactor Competition' was renamed the 'Advanced Nuclear Technologies Framework' so that the Rolls Royce offering, whose output is 50% more than the conventional upper limit for SMRs could compete. However, the UK government programme has missed several deadlines and the most recent announcements suggest a shift in emphasis towards non-LWR designs. Despite Rolls Royce's aggressive marketing statements, its design has undergone significantly less development than its competitors and appears significantly less advanced.

7. UK Government SMR Policy

The 2014 feasibility study on Small Modular Reactors (SMRs) co-funded by seven nuclear industry organisations including Rolls Royce.[90] Rather optimistically, the study projected a potential world market of 65-85GW by 2035 with 7-21GW installed in the UK, suggesting that the market would be worth £250-400bn, implying a construction cost of about £4000/kW. It adopted the IAEA definition of SMRs as being less than 300MW, and it considered designs they expected to be deployable within ten years.

Four designs were said to meet these criteria: APC 100+ (CNNC, China), mPower (B&W/Bechtel, USA), Westinghouse SMR (USA), and NuScale (Fluor, USA). All of these were Pressurised Water Reactors (PWRs) with no Boiling Water Reactors (BWRs) meeting the criteria and no reactors of a more radical design. The analysis claimed that a FOAK 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.

[88] Nuclear News 'Westinghouse exits bankruptcy; other news' September 2018.
[89] http://www.world-nuclear-news.org/Articles/Estonia-to-study-siting-of-Moltex-advanced-reactor
[90] http://www.nnl.co.uk/media/1627/smr-feasibility-study-december-2014.pdf

The subsequent few years have demonstrated the limits of NNL's assessment of deployability. Within a couple of years of the report, the companies responsible for two of the four designs, mPower and the Westinghouse SMR, had both stopped work on these.[91] No Rolls Royce option was offered, and the Rolls Royce design being considered from 2017 onwards would have been excluded on size grounds. The scenarios appeared highly optimistic even when published in terms of the world market size and none of the four options examined would meet the NNL's forecast of being deployable by 2024. In terms of cost the forecasts are also optimistic: the latest cost estimate for Hinkley is 50% more than the assumed SMR cost of £4000/kW.

7.1. The SMR Competition

In UK government's November 2015 Budget, the government announced it would spend at least £250m by 2020 on 'innovative nuclear technologies.' This appears to have been almost exclusively for SMRs, including a competition to identify 'the best SMR for the UK'.[92] No details of nuclear technologies other than SMRs were mentioned, so it must be assumed the vast majority of funds were expected to be offered for SMRs.

In March 2016, the government launched the competition with a call for expressions of interest in supplying SMRs. The first phase of this competition was expected to be complete by late 2016 when an 'SMR Delivery Roadmap' would be published.[93] Phase One was severely delayed and was not completed until December 2017 when a list of 33 'eligible participants' was published.[94] The criteria for designs included a requirement that the capacity be 300MW or less and that the design *'will be designed for manufacture and assembly, and that will be able to achieve in-factory production of modular components or systems amounting to a minimum of 40% of the total plant cost.'*

The 33 eligible participants did not represent 33 technologies that met these criteria. About half of these participants were no more than one of several partners in a consortium offering a design or were deemed to have the skills necessary to participate in the development of an SMR design. Of those with a design, only a handful appeared to be any more than a reactor concept as of the time of this report.

In the following we discuss reactors that appear to have undergone some development work and that have made progress outside the UK. We also focus on the Rolls Royce design, which appears to be at a much earlier stage of development.

Despite the requirement on size, a Rolls Royce design of 450MW announced in 2017 was deemed eligible, as were all four of the options noted in the NNL feasibility study, despite the termination of the mPower venture and the end of the Westinghouse SMR programme.

[91] http://ansnuclearcafe.org/2017/03/16/mpower-consortium-halts-project/; http://www.post-gazette.com/business/2014/02/02/Westinghouse-backs-off-small-nuclear-plants/stories/201402020074
[92] https://www.theguardian.com/environment/2015/nov/24/mini-nuclear-reactors-answer-to-climate-change-crisis
[93] http://www.world-nuclear-news.org/Articles/UK-government-launches-SMR-competition and https://www.gov.uk/government/publications/small-modular-reactors-competition-phase-one
[94] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/665376/List_of_Eligible_Participants_in_Phase_One_of_the_SMR_Competition.pdf

A House of Lords Select Committee findings, published in May 2017, was highly critical of the delay in completing phase one of the SMR programme.[95] It noted that SMRs could be divided into two groups: Light water reactors (LWRs) – that is PWRs and BWRs – and non-LWR technologies.[96] PWRs and BWRs make up the vast majority of commercial reactors in operation in 2019 (372 of the 451 reactors defined as being operational in the International Atomic Energy Agency's PRIS database). The non-LWR technologies are new designs that have not been deployed commercially or based on designs that have been commercial failures. Reflecting on this, the Committee stated that non-LWR designs could not be deployed before 2030 and *'would need significant further R&D before deployment.'*

Perhaps tellingly, in December 2017, the UK government effectively abandoned the UK SMR competition, publishing an independent report that suggested power from the first reactor would cost £101/MWh, as much as power from Hinkley Point C and far higher than RR's forecasts for their SMR.[97] The £250m competition was replaced by a £44m 3-year Advanced Modular Reactor (AMR) Design Competition aimed at non-LWR reactor designs[98].

7.2. The Nuclear Sector Deal

Progress in 2018 continued to be slow and the SMR Delivery Roadmap appeared to have been forgotten. In June 2018, the UK government published its 'Nuclear Sector Deal' promising £200m to develop new nuclear technologies.[99] However, the largest element, £86m, was for fusion technology, while the next largest element was £56m for AMR design development, including the £44m previously announced in December 2017. The remaining £62m was split between an *'advanced manufacturing and construction programme'* and a *'new national supply chain programme'*. There appeared to be nothing specifically for LWR SMRs and no timeframe was specified for the money to be spent. This appeared to anger RR, who were reported to be threatening to abandon their SMR development unless government support was forthcoming. In January 2019, the Financial Times reported that the RR consortium was seeking more than £200m from the UK government (which it would match) to develop the design to the point where it could receive approval from the UK safety regulator.[100]

In July 2019, the UK government published details of further support for SMRs.[101] It offered up to £18m to RR to be allocated by autumn 2019, but with no details about what this money would pay for. It gave no indication that it was willing to find the £200m RR had asked for to fund a demonstration plant. It did confirm that the earlies a demonstration plant would be

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[95] https://www.parliament.uk/business/committees/committees-a-z/lords-select/science-and-technology-committee/news-parliament-2015/nuclear-research-technology-report-published/
[96] The Committee called the non-LWR designs Generation IV. By comparison, large reactors like the EPR planned for Hinkley Point are often designated design Generation III+. However, the definition of the design generations is too vague to be useful
[97] The Times 'Double setback casts big shadow over mini reactors' December 8, 2017
[98] https://www.gov.uk/government/publications/advanced-modular-reactor-amr-feasibility-and-development-project
[99] https://www.gov.uk/government/news/new-deal-with-industry-to-secure-uk-civil-nuclear-future-and-drive-down-cost-of-energy-for-customers
[100] Sylvia Pfeifer and David Sheppard, 'Rolls-Royce Leads Drive for Small Nuclear Sites: Energy,' Financial Times, January 28, 2019.
[101] https://www.parliament.uk/business/publications/written-questions-answers-statements/written-statement/Commons/2019-07-22/HCWS1789/

operating would be the '*early 2030s*' reinforcing the impression that the design is still at a very early stage. The £18m offered is in stark contrast to the £44m allocated in November 2018 to the much more speculative advanced modular reactors (see below).

7.3. Advanced Nuclear Technology Framework

In November 2018, at a "Commercialisation of Small Nuclear in the UK" event held at the Trawsfynydd, expected to host the first UK SMR, the Energy Minister Richard Harrington announced an intention that ONR's nuclear regulatory GDA process would be open to review SMR designs.[102] Harrington opined that the existing SMR definition was too narrow to encompass all relevant technologies (including larger designs and non-LWR designs) and stated the programme would henceforth be termed as the 'Advanced Nuclear Technology Framework'. He further announced an intention to launch a fund for *'the development of the Advanced Manufacturing and Construction programme.'* A call for expressions of interest for this fund was published in January 2019.[103] The aims were stated to be:

- *'By 2021 to have established a strong manufacturing & materials R&D base to support the UK nuclear supply chain.*
- *By 2030 provide underpinning technology support to the UK manufacture of components for SMR and other reactor types.*
- *By 2050 facilitate UK industry developing a position as a significant global player in the deployment of SMRs and other advanced reactor technologies. Support BEIS in achieving its objectives.'*

In March 2019, a government minister told Parliament: *'The Nuclear Sector Deal published last year outlines the government's ongoing commitment to nuclear innovation, including a new framework to support the deployment of small modular reactors. Up to £56m is available to support the development of advanced modular reactors, including up to £44m for a Feasibility and Development Project and £12m for the Office of Nuclear Regulation and Environment Agency to build the necessary capability.'*

Thus, the plan to spend £250m on SMR (or advanced nuclear) development by 2020 has clearly been abandoned, as has the commitment to publish an SMR Delivery Roadmap. A potential explanation can be drawn from a statement by then energy minister, Greg Clark, in response to the effective collapse of one of the projects for a large nuclear power plant (Wylfa), where he stressed that nuclear had to be cost-competitive with low-carbon alternatives, noting *'no technology will be pursued at any price'*[104].

Some government officials also seem to have learnt to be sceptical of the promises of new nuclear reactor designs to solve the problems of the technology. National Infrastructure Commission chief economist James Richardson, for example, warned 'You have to have a degree of caution with new nuclear technology…We have been promised things time and time again and typically the industry tends to be more expensive and take longer than

[102] https://www.gov.uk/government/publications/advanced-nuclear-technologies/advanced-nuclear-technologies
[103] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/770941/Advanced_Manufacturing_and_Materials_Phase_2_Guidance_Notes.pdf
[104] https://www.gov.uk/government/speeches/statement-to-parliament-on-horizon-project-at-wylfa-newydd

planned. I would be cautious against SMRs, they are a question for the 2030s'.[105] Given the problematic dis-economies of scale implicit in SMR deployment, the technologies' future remains open to question.

7.4. UK SMR Programme Summary

Progress with the UK's SMR programme has been slow and erratic with little clear direction. The apparent early attention on LWR SMRs has disappeared with the focus appearing to shift from 2017 onwards to a concentration on the more distant and speculative non-LWR technologies. Funding has also been drastically cut from the original intention in 2015 to spend £250m by 2020 to a commitment to spend a little over £100m but with no timescale for this expenditure and with no funds for LWR SMRs.

8. Conclusions

The conclusions fall into two parts. In the first part, we review UK SMR development policy. In the second, we draw generic conclusions concerning SMR technology. We focus on LWR SMRs as other designs are far away from any potential market deployment.

8.1. The UK Programme

The UK government's interest in SMRs became apparent from about 2014 onwards. By then the high costs of power from the UK's large reactor programme (specifically the deal for power from the Hinkley Point C project), had become apparent. In 2015, the government announced a large sum of public money (£250m) would be available to be spent by 2020 to identify 'the best' SMR design option for the UK. Since then, costs of large reactors have continued to rise and finance has become increasingly difficult, leading to the collapse in 2018 of three of the five new UK nuclear projects projected to be on-line by 2030.

However, although SMR proponents hoped to profit from large reactor failure, UK government interest in SMRs appears also to have cooled. The £250m SMR programme was abandoned after serial delays, with little of the money spent. The considerably reduced new budget subsequently allocated to SMR development has been targeted at more speculative non-LWR designs.

The strong support UK government has shown for new nuclear since 2006 appears to be evaporating, with a government minister saying in a clear reference to nuclear power: 'no technology will be pursued at any price'.[106] While this pursuit of economic functionality seems obvious, it does represents a very different emphasis to previous statements on the central importance of nuclear power to the UK's energy future.

RR is widely perceived as the likely recipient of any UK SMR development funding because it is the only large UK candidate, because of the prestige of the RR brand, and because of its long history in exclusive supply of submarine reactors to the UK. The submarine reactors are considered a relative success, despite the lack of detailed cost and performance evidence, and despite safety concerns arising in the past decade. The RR design is a very late-comer to the process, only being announced in 2017 - long after its main competitors. At 450MW, the RR

[105] Connor Ibbetson, 'Caution Urged over Modular Nuclear Reactors,' New Civil Engineer, June 9, 2019. https://www.newcivilengineer.com/latest/caution-urged-over-modular-nuclear-reactors/10042995.article.
[106] https://www.gov.uk/government/speeches/statement-to-parliament-on-horizon-project-at-wylfa-newydd

PWR design is significantly larger than its competitors, and far too large to be designated an SMR. The RR reactor also appears closer to an older generation PWR design. RR estimates that it will cost £400m to complete the design and a comprehensive safety review - reinforcing the impression that development will be costly, and the design is a very far from market deployment. It claims the safety review could be complete by 2024 and the design available to order by 2028, although given the early stage of development of the design, but these estimates appear unrealistic.

RR has set out an extraordinary set of conditions to be met by UK government if it is to invest significant amounts of its own money in design development. These include government paying for more than half of the design development costs, exclusive access to the UK market for their design and a guaranteed UK market of 7GW (16 reactors). If the Rolls Royce design is not chosen, it is demanding that it be the UK partner company for whatever design is chosen.

Whether these demands represent naivety on the part of Rolls Royce or whether they simply represent how it has historically done business with the Defence Ministry is hard to determine. However, no government could or should 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.

8.2. World-wide Development of SMRs

The non-LWR designs use concepts that have been discussed for many decades. For some concepts (such as sodium fast reactors and high temperature reactors), small numbers of reactors have been built and, in most cases, have failed badly. In others (such as molten salt reactors), the concepts have not even reached the prototype power reactor stage and would generally need significant materials advances to be commercialised. Given this poor record, it is hard to justify further public money being spent on non-LWR SMRs, and if these concepts are to be advanced, it should be exclusively through private capital.

The entire history of nuclear power has been characterised by large public subsidies and failed promises of reduced costs. As well, we do not have any demonstrated solutions to major problems associated with nuclear power, such as waste disposal and nuclear weapons proliferation. As a result, governments should be highly sceptical of claims by the nuclear industry that yet another new set of technologies will solve these problems especially where there is a requirement for large sums of public money to bring these technologies to market.

SMRs would require a particularly large commitment of public money. Whereas previous reactor designs could be proved by building one or two demonstration plants, the economics of SMRs can only be tested by building up a large number of reactors, possibly hundreds or thousands, requiring expensive investment in component production line facilities and commitment to large numbers of orders. Utility interest in SMRs, particularly where utilities would be required to risk their shareholders' money, has been minimal.

There are two main rationales for SMRs: lower overall project costs (total cost of reactor); and lowering the risk of cost overruns by shifting as much work from construction sites, which are notoriously difficult to manage effectively, to the much more controlled environment of a factory. But these advantages are more than offset by the loss of the scale economies that the nuclear industry has pursued for the past five decades.

Use of standard engineering metrics to estimate scale economies and economies of number suggests that economies from building large numbers of small reactors will not be sufficient to counterbalance the loss of scale economies. The smaller the reactor, the more difficult it will be to counterbalance the lost scale economies, and this is especially relevant to the NuScale design. Scale economies have not produced the cost reductions hoped for, but it may well be that the scale economies were there but were more than swamped by other factors such as the greater scope and complexity that increased safety requirements brought.

Many of the features of the SMRs being developed are the same ones that underpinned the latest, failed generation of large reactors. Until a comprehensive review by a regulator is completed and the design features required are finalised, reactor cost estimates will have a large degree of uncertainty.

Experience with the most recent large designs, especially the AP1000, which is highly modular, is not encouraging. Quality control problems and severe delays remained at all four sites where AP1000s were being built.

There is every likelihood that, as with the previous nuclear renaissance, SMRs will be still born with few reactors built. This will mean that public money will again have been wasted on nuclear technology, but, as previously, the main cost will be the opportunity costs of the options not pursued and properly funded because resources have been pre-empted by the nuclear sector.

Annex Canada's SMR Programme

Canada is pursuing one of the most aggressive programmes of development of Small Modular Reactors (SMRs) and in 2018, 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 produce a 'roadmap' for the deployment of SMRs.[107] There is interest in SMRS in Canada for three somewhat different applications: for use in normal grids; very small reactors for use in meeting the electricity needs of isolated communities and mines; and to provide high temperature process heat, mostly aimed at processing tar sands.[108]

Five reactor designs with output greater than 30MW are undergoing preliminary review by the Canadian Nuclear Safety Commission (CNSC).[109] These are:

- Terrestrial Energy 200MW IMSR molten salt reactor;
- NuScale 60MW PWR;
- Advanced Reactor Concepts ARC-100 100MW sodium-cooled fast reactor;
- Moltex SSR 150MW molten salt reactor;
- Holtec SMR-160 160MW PWR, although there appear to be no active plans to deploy this design in Canada.

Four main separate organisations pursuing their own strategies to build SMRs:

- Canadian Nuclear Laboratories (CNL), 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 (NB Power), itself owned by the provincial government;
- Ontario Power Generation, a Corporation owned by the province of Ontario
- Bruce Power, a consortium of several private corporations that operates eight nuclear reactors

Canadian Nuclear Laboratories

CNL has set itself the goal of demonstrating the commercial viability of SMRs by 2026 and to become a world-leader in SMR technology. In April 2018, it issued a call to potential vendors to site a small modular reactor (SMR) demonstration unit at a CNL managed campus. Three designs were being evaluated by February 2019[110] although only one of these, Terrestrial Energy's 195MW IMSR molten salt reactor was larger than our 30MW cut-off point. The IMSR is undergoing a preliminary review by the CNSC. The other two designs are the 14MW Starcore and the 5MW Global First Power reactors, both high temperature gas-

[107] https://www.nrcan.gc.ca/energy/funding/icg/21084

[108] 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/.

[109] http://nuclearsafety.gc.ca/eng/reactors/power-plants/pre-licensing-vendor-design-review/index.cfm

[110] http://www.cnl.ca/en/home/facilities-and-expertise/smr/progressupdate.aspx

cooled reactors. The Starcore reactor is said to suitable for mines and isolated villages,[111] while the Global First Power (GFP) reactor is targeted at process heat with scope for power generation.[112] In April 2019, the GFP design was the first to be submitted to the CNSC for full safety evaluation.[113] Other designs could also be added to the evaluation process.

New Brunswick Energy Solutions Corporation

New Brunswick Energy Solution Corporation was formed in 2017 and plans to have its first SMR in operation by 2030 as well as positioning itself as a world leader in SMR technologies. Two technologies, both undergoing preliminary review by the CNSC, are being pursued, the ARC-100 sodium-cooled fast reactor and the Moltex molten salt reactor.[114]

Ontario Power Generation and Bruce Power

The two owners of Candu reactors in Ontario, the provincially-owned OPG (that owns the Pickering and Darlington sites) and the privately-owned Bruce Power (the Bruce site) are both independently pursuing SMRs, primarily the NuScale SMR. OPG is also supporting the 5MW Global First Power high temperature reactor through preliminary evaluation by the CNSC. There is no time-line yet for completion of the first reactor.

Canada SMR Summary

While there appears to be significant interest from the Federal and provincial governments and from private companies, especially SNC Lavalin, in developing and deploying SMRs in Canada, the plans are some years from placement of the first firm order. Three out of four of the designs being pursued are for more radical non-LWR types, usually seen as unlikely to be deployable before 2030.

http://www.world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/small-nuclear-power-reactors.aspx

[111] http://starcorenuclear.ca/#!/welcome/
[112] https://www.globalfirstpower.com/project-description
[113] https://www.world-nuclear-news.org/Articles/First-Canadian-SMR-licence-application-submitted
[114] http://www.world-nuclear-news.org/Articles/Moltex-partners-in-New-Brunswick-SMR-project and http://www.world-nuclear-news.org/NN-First-partner-announced-for-New-Brunswick-SMR-project-1007187.html

Table 1 **SMR designs: LWRs**

Supplier	Name	Technology	Size MW	Country origin	Status
Bechtel/BWXT[115]	mPower	PWR	125-195	USA	Abandoned March 2017
CNNC[116]	ACP100/100	PWR	100	China	Passed IAEA safety review 2016
GE-Hitachi	BWRX-300	BWR	300	USA	Sponsored by US Dept Energy
KAERI	SMART	PWR	90	Korea	Licensed by NSSC in 2012
Holtec Int	SMR-160	PWR	160	Canada	
NuScale Power	NuScale	PWR	60	USA/UK	
Rolls Royce	UK SMR	PWR	450-500	UK	
CNEA	CAREM-25	PWR	32	Argentina	Prototype construction start 2014
Westinghouse	SMR	PWR	225	USA	Work suspended 2014

Table 2 **SMR designs: Non-LWRs**

Supplier	Name	Technology	Size MW	Country origin	Status
Advanced Reactor Concepts	ARC-100	Sodium-cooled fast reactor	100	USA	Review by CNSC, proposed New Brunswick
GE-Hitachi[117]	PRISM	Sodium-cooled fast reactor	311	USA	
Hydromine Nuclear Energy	LFR-AS-200	Lead-cooled fast reactor	200	USA	
LeadCold Reactors[118]	SEALER	Lead-cooled fast reactor	55	Sweden	
Moltex Energy	SSR	Molten salt cooled reactor	150	UK/Canada	Review by CNSC. Interest in New Brunswick & Estonia
Nuclear Cogen Indl Initiative	GEMINI	High Temperature gas cooled reactor	?	USA/Europe	Sponsored by EURATOM
Terrestrial Energy	IMSR	Molten salt cooled reactor	195	USA/Canada/UK	Review by CNSC
Chinergy	HTR-PM	High Temperature gas cooled reactor	105	China	Prototype construction start 2012

Notes: No detailed information was found or the companies listed are not pursuing an independent design on the following designs that the BEIS review listed as 'eligible participants': Algometrics Ltd Advanced Hybrid SMR, Amec Foster Wheeler, Costain, Critical Path Energy Limited, EDF Energy, Empresarios Agrupados Internacional, Ernst & Young, Frazer-Nash Consultancy, Nuclear Advanced Manufacturing Research Centre, National Nuclear Laboratory Limited, Nuvia Ltd, Penultimate Power UK Ltd, Sainc Energy Ltd, Sheffield Forgemasters, Tokamak Energy Ltd., Small Modular Fusion Power, TWI Ltd.

115 https://www.bechtel.com/newsroom/releases/2016/03/bwxt-pursue-small-modular-nuclear-reactor-project/
116 http://en.cnnc.com.cn/2016-04/28/c_51725.htm
117 https://nuclear.gepower.com/build-a-plant/products/nuclear-power-plants-overview/prism1
118 https://www.leadcold.com/sealer.html

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