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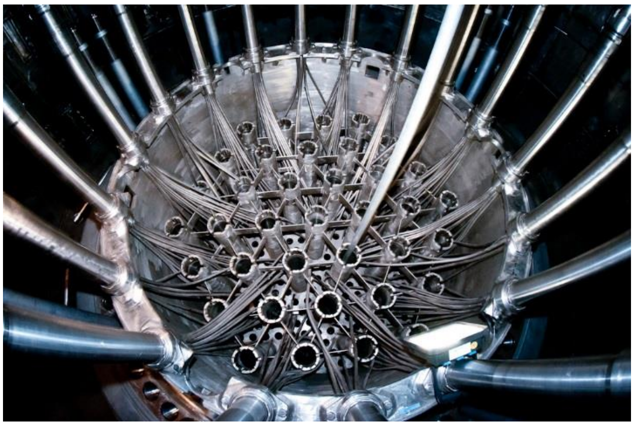
PARLIAMENTARY OFFICE OF SCIENCE & TECHNOLOGY

POSTNOTE

Number 580 July 2018

Small Modular Nuclear Reactors



There is growing UK and international interest in using 'small modular nuclear reactors' (SMRs) to generate electricity. Stakeholders suggest that, compared with conventional reactors, SMRs could offer cost savings to operators and consumers, more flexible energy production and a greater choice of potential sites. This POSTnote examines key aspects of SMR technology, its economics and regulation.

Overview

- Small modular reactors (SMRs) consist primarily of units built in factories and will generate less electricity than conventional nuclear reactors.
- New conventional nuclear build has been challenged by rising costs and delays.
- Proponents suggest SMRs could reduce the financing challenges faced by conventional nuclear power.
- There are many diverse SMR designs. No commercial SMR has been built; the first is expected within ten years. Future cost competitiveness is currently uncertain.
- The 2018 Nuclear Sector Deal prepares for SMR deployment through R&D, supply chain development and regulator support.
- Potential uses of SMRs in the UK and abroad could be limited by access to new sites, and regulatory and planning matters.

Background

In 2017, eight nuclear power stations generated 21% of UK electricity.[1] Nuclear power can supply large amounts of electricity with low greenhouse gas emissions, which are major contributors to climate change.[2] Seven of the UK's nuclear stations are due to close by around 2030, and six new large stations are planned to help meet future demand.[3] The first of these, Hinkley Point C, is under construction and due to start producing electricity in 2025.[4,5] Rising costs and construction delays in Europe and the US have raised concerns about new nuclear power continuing to be a source of cost-effective clean energy.[6-9]

SMRs are small nuclear reactors, made of standardised factory-manufactured parts delivered ready for assembly.[10] SMRs have generated government and industrial interest internationally because designers have suggested SMRs could be a solution to the challenges of conventional nuclear power.[11,12] They may offer lower investment risk, reduced cost and greater compatibility with a flexible electricity network.[13,14] So far, no commercial SMR has been built worldwide and there is considerable uncertainty around their costs, timescales and challenges, partly due to the diversity of SMR designs. SMR designs based on smaller versions of existing Gen III and III+ technology (Box 1) are expected to be commercially available for construction within the next 10 years.[15,16] More advanced Gen IV designs are not expected to be commercially available until after 2030.[17]

The UK Government has not set specific targets for future nuclear power beyond the six new planned large stations.[18] However, National Grid and government modelling suggests that nuclear power capacity may increase further in the future, and SMRs may comprise some of this new capacity.[19,20] UK industry is developing different designs (Box 2), including some supported by the Government's Advanced Modular Reactors (AMR) programme and the 2018 Nuclear Sector Deal (Box 3).[21]

This POSTnote examines SMR technologies in development, their proposed applications and the potential for producing competitively priced electricity. It also explores opportunities for the UK civil nuclear industry alongside planning and regulatory considerations.

Characteristics and Applications of SMRs

The key characteristics of SMRs are their smaller power output and high degree of factory manufacturing.[14,22] The smaller output of SMRs could allow for their use in a wider variety of applications than conventional nuclear reactors.

Box 1. Conventional Nuclear Power
Nuclear reactors produce energy by splitting a heavy atom (the fuel), a process known as fission. The heat from the fission is transported to an electricity-generating turbine by a gas or liquid (the coolant).

Technology
Nuclear reactors are grouped by generation of technology (POSTnote 457). Existing UK nuclear power stations, built in the 1960s-90s, use **Gen II** uranium-fuelled and water- or gas-cooled reactors.[3] **Gen III** are modern versions of water-cooled reactors that are safer and more efficient.[23] **Gen III+** adds 'passive safety' features, which allow them to maintain safe conditions if electrical power is lost, by using natural forces such as gravity rather than back-up generators. Hinkley C will use two Gen III+ reactors. **Gen IV** are advanced designs that use novel fuels and coolants, attempting to address the affordability, efficiency, safety and sustainability issues surrounding nuclear power.[3,17,24]

Construction and Operation of Nuclear Power Stations
Existing UK nuclear stations have a large power output, of 1 gigawatt (GW) or more.[3] Their location is restricted by the need for access to large amounts of water as a sink for excess heat, often on the coast. Construction is complex, usually taking longer than 6 years and using components manufactured specifically for individual reactors.[25] Conventional nuclear construction is often subject to delays; in 2017, two thirds of stations under construction worldwide were behind schedule.[26] Nuclear power stations constantly produce electricity at near maximum output, with relatively low operating cost.[27]

Waste
Uranium-fuelled nuclear power stations generate radioactive waste, including some plutonium which can be extracted for re-use (POSTnote 531). Gen IV designs using novel fuels would generate new waste products that are not yet fully understood.[28]

Box 2. UK and International SMR Designs
Over 50 SMR designs are in development worldwide.[10] A few international designs have reached the licensing or prototyping stage[29], some with UK industry involvement.[30-34] UK designs include:

- **UK SMR** is being developed by a UK industry consortium led by Rolls-Royce. It is a 0.44 GW Gen III water-cooled reactor. The consortium aims to deliver the first unit by 2030.[35]
- **UBattery** is a 'micro' Gen IV SMR being developed by Urenco. It would produce 0.04 GW. Potential applications include use in remote locations and as a back-up generator. Urenco aim for delivery of a demonstrator plant in 2024.[36]
- A Gen IV **Molten Salt Reactor,** designed by Moltex, would use reprocessed plutonium or uranium as fuel and molten salt as a coolant, generating between 0.3 GW and 1.5 GW. Moltex are targeting delivery of a demonstrator plant in Canada for 2028.[37]

SMR Power Output
Small nuclear reactors are already used to power the UK submarine fleet, and were used in the UK's first nuclear power station in 1956.[38,39] Small power output reduces station water requirements and radioactive release in the event of an incident (Box 1).[13,40] The International Atomic Energy Agency (IAEA) definition of an SMR includes an upper power output limit of 0.3 GW (a fifth of one Hinkley C reactor).[10,41] The Department for Business, Energy & Industrial Strategy (BEIS) argues that this definition is too narrow and that it fails to capture the diversity of potential technologies.[42] The AMR competition (Box 3) focuses on novel technologies and applications rather than a specific power output.[43] This POSTnote refers to all reactor designs which come under the IAEA and BEIS definitions as SMRs.

Box 3. UK Government SMR Policy
Since its first expression of interest in SMRs in the 2013 Nuclear Industrial Strategy, the UK Government has supported early-stage SMR research and produced a number of assessments:[44]

- A 2014 study assessed the feasibility of SMRs in the UK, identifying an opportunity for the UK civil nuclear industry.[15]
- A 2016 SMR competition assessed industry interest but did not develop a roadmap for future deployment as intended.[45]
- A 2016 Government-commissioned Techno-Economic Assessment (TEA) examined the economic and technical feasibility of 14 SMR designs.[16]

The 'Nuclear Sector Deal', published in June 2018, seeks to develop the UK nuclear manufacturing industry.[3,21,46] SMR initiatives include:

- A two-stage AMR competition, which will fund feasibility studies for eight Gen IV designs (Stage One).[21] Up to £40 million funding for manufacturing and development is then expected to be made available to successful designers (Stage Two).[42,43]
- £20 million for demonstrating advanced manufacturing in the nuclear sector, including within modular construction.[21]
- An Expert Finance Working Group, examining the effects of different financing models on Gen III/III+ SMR costs.[47,48] It is due to report its findings in summer 2018.[21]

Modular Units and Standard Designs
Unlike conventional nuclear construction (Box 1), SMR designs seek to maximise use of 'modular' systems.[14,22] These are mass manufactured and assembled in factories, then transported to the construction site ready for installation.[22] Some designers include modular infrastructure around the reactor.[49] SMR designers also seek to standardise designs by using single types of component across multiple reactors.[50] This reduces the need to manufacture bespoke parts. Use of modules and standard parts can increase the proportion of construction within factories, reducing on-site challenges like adverse weather conditions to improve construction efficiency.[22,50,51]

Potential Applications of SMRs
SMRs primarily generate electricity, and could be more compatible with the UK's future electricity system than conventional power stations.[14] Some designs could also be used for other applications including heat generation or nuclear waste management.[52,53] The scale of deployment and application of SMRs are subject to developments in the energy system, and operators' future business models.[20,22]

SMRs within a Flexible Electricity System
As with conventional nuclear power, SMRs could provide a 'baseload' source of electricity by constantly supplying power close to maximum output (Box 1). Multiple SMRs situated within a single power station would allow them to produce electricity like a conventional nuclear station.[22]

However, UK electricity demand is increasingly supplied by intermittent renewable sources (POSTnote 464),[54] which require other, more flexible sources of electricity to provide power when supply from renewables is low. Proponents suggest that aspects of some SMR designs allow them to produce electricity flexibly.[53,55] Power stations with multiple SMRs could offer enhanced flexibility: power produced by a number of units could be used for alternative applications during periods of low demand or high renewable supply.[14]

This electricity could be used for desalination or hydrogen production for example (POSTnote 565).[52,56]

Providing Direct Heat to Consumers
All nuclear reactors generate waste heat (Box 1). Heat from SMRs, especially some higher temperature Gen IV designs, could be captured and supplied to residential or industrial users.[13,55,57,58] However, developers of early SMRs in the UK do not plan to provide heat in this way initially.[53,59]

SMRs as a Nuclear Waste Management Option
Some SMR designs under development could use plutonium as a fuel component (Boxes 1 and 2).[60,61] This would provide a method for managing the plutonium stockpile generated by previous generations of nuclear power stations (POSTnote 531).[17]

Commercial Potential of SMRs

To produce cost-competitive electricity, SMR construction costs would need to reduce significantly compared to equivalent costs in conventional nuclear (Box 4).[16,22,40,62,63] The price of electricity from all nuclear power is primarily determined by station construction costs and financing, as operation and fuel are inexpensive in comparison.[25] Considerable cost uncertainties exist as no SMRs have yet been built. SMR designers aim to avoid the financing challenges of conventional nuclear (Box 4) by developing a relatively large number of mass-manufactured reactors with shorter construction times. The extent to which the UK market for SMRs alone could support the commercial viability of a design is unclear.

Reducing Costs and Investment Risk

Unlike conventional nuclear power, which relies on economies of scale to reduce costs (Box 4), SMR designers aim to do so by using standard designs with as much modularisation and in-factory build as possible.[22] This approach has been used to achieve cost savings in the aerospace and construction sectors. The 2016 Techno-Economic Assessment (TEA) (Box 3) suggested productivity gains from in-factory build and mass manufacturing could reduce construction costs by up to 15% every time production is doubled.[16] The higher construction costs of the first SMRs to be built are likely to reduce as more units are manufactured.[16,22] Operators are also evaluating methods to minimise operating costs by sharing services, like security and maintenance, across multiple reactors on one site.[22,64]

Developers suggest that SMR construction could take 2-5 years.[22,63,65] There is wide variety in reactor cost estimates, due to differences in design type, uncertainty due to the lack of completed prototypes and assumptions around savings during subsequent builds.[22,63,65,66] Lower construction time and costs would reduce the financial impact of potential delays that conventional nuclear is subject to (Box 4).[14] They would allow SMRs to generate revenue quicker, which could be used to finance subsequent reactors.[67] Lower investment risk is seen as important to encourage new nuclear build.[40]

Box 4. Economic Challenges of Conventional Nuclear Power
Conventional nuclear power stations are typically costly to construct (£18 billion is estimated for Hinkley C) but relatively inexpensive to operate.[5,27] 60-85% of total costs (such as licensing, land and construction materials) do not increase proportionally when building larger reactors.[25] These 'economies of scale' reduce construction costs per unit of power output, which prompted growth in the output of successive nuclear stations over time from 0.2 GW in the 1950s to 3 GW in 2017.[68] However, larger stations increase complexity and build time. Because of costs and build duration, nuclear construction projects carry a large amount of financial risk.[9,25,27] Financing costs (interest payments and dividends) are sensitive to inflation and delays, and can form more than a third of total capital costs.[22,50,69] This can increase to over half of cost if construction is delayed by 5 years.[69]

The Government Expert Finance Working Group (Box 3) will examine new financing methods.[21,42]

SMR Market Opportunities and Challenges

The Potential UK Market for SMRs
There is considerable uncertainty around the amount of SMR capacity that could be built in the UK.[20,57] The National Nuclear Laboratory uses a central estimate of 7 GW, about 10% of current peak UK electricity demand.[57,70] SMRs are viewed as a commercial opportunity for the UK nuclear industry.[70] The TEA (Box 3) estimated SMR manufacturing in the UK could generate 9,700 jobs and £7 billion in tax income by 2040.[16] However, it is unclear whether the UK market alone would provide sufficient demand to justify investment in a new manufacturing supply chain.[40,71]

Export Market Potential and Uncertainties
Potential global demand for SMRs is valued up to £250-£400 billion.[52,70] Many nuclear newcomer countries, who are yet to develop nuclear infrastructure, have shown particular interest in SMRs.[13,72] However, nuclear technology presents complex safety management considerations and a risk that civil nuclear material could be diverted for military use.[73] Large barriers to access by newcomer countries may exist.[72] IAEA guidelines establish milestones for safely developing nuclear infrastructure.[74] These contain requirements on finance and skills to develop knowledge, regulatory and supply chain infrastructure.

Skills Shortage in the UK Nuclear Industry
Stakeholders from the nuclear industry have raised concerns over a shortage of skilled and experienced UK workers.[75] The Nuclear Skills Strategy Group, a joint venture between Government and industry, aims to address the issue and a number of new training schemes have been launched.[76] Gen IV designs would also require new skills but their later potential delivery date provides more time to develop skilled labour.

Safety, Regulation and Planning

The UK nuclear regulatory framework (Box 5) requires vendors to demonstrate their safety case, rather than apply prescriptive standards as is the case in many other countries.[77] The UK approach is considered better adapted than a prescriptive approach to address the regulation of

SMRs.[78] The framework for existing nuclear technologies (POSTnote 457) will apply to SMRs, but some novel features are likely to require additional regulatory considerations.[56,79] The UK Government is actively considering siting for SMRs and aims for mature designs to begin the licensing process in late 2018.[21]

Assessing Novel Safety Features

The greatest safety risk associated with conventional nuclear power is release of radioactive material due to loss of cooling and reactor core meltdown.[80] SMR designs aim to mitigate this risk with passive safety (Gen III+) or the use of novel fuels and coolants (Gen IV).[56] These features could either ensure a longer safe period if an incident occurs or remove the possibility of meltdown and radioactive release.[13] However, they also introduce new potential hazards, like toxic and corrosive liquid metal coolants.[14,28]

Novel technology could require a higher burden of proof and scrutiny during Generic Design Assessment (GDA) (Box 5). Assessing the safety of Gen III/III+ designs would likely be similar to recent new build reactors, as expertise exists on established nuclear technologies. The novelty of Gen IV technology and lack of regulatory expertise is however viewed as a challenge by regulators internationally.[17,81]

Siting Considerations for SMRs

Deploying Standard Units across Different Sites

Characteristics of potential construction sites, such as local seismic activity or flood risk, could lead to modifications to individual reactors during the Site Specific Assessment (SSA).[82] This would present challenges to maximising standardisation across reactors, which is seen as a necessary condition for SMR cost reduction.[52,83] Moreover, different national regulatory frameworks could become an export barrier if significant design modifications are required for each market. The World Nuclear Association views SMRs as an opportunity to increase harmonisation of international nuclear regulation in future.[56,84]

Co-Siting and Shared Services across Multiple Units

Some potential SMR operators have suggested building multiple units on a single site and using shared or centralised operational and control facilities to reduce operating costs.[13,22,52] Current operating nuclear stations in the UK only host up to two reactors.[3] Following the 2011 Fukushima accident, the IAEA issued new guidelines calling for operators to better consider how different units could affect each other in the event of an incident.[85]

Challenges for Flexible Siting of SMRs

Proponents argue that SMRs' potential for increased safety, smaller footprint and lower water-cooling needs mean they could be accommodated on a wider range of sites than conventional nuclear could.[13,40] Flexibility in siting would allow SMRs to generate electricity for industrial sites or heat for nearby residential areas. However, it is unclear whether siting close to population centres or hazardous chemical industrial facilities would be approved.[56,72] As part of the licensing process, an emergency planning zone (EPZ) currently up to 7km is defined around reactor sites in the UK.[94] This puts safety protocols such as evacuations in place in the case of an incident. EPZs are set on the basis of potential radioactive exposure levels.[95]

Box 5. UK Nuclear Licensing

Nuclear build in the UK requires regulatory and planning approval. The UK Government identifies potential sites and ultimately grants planning consent. The regulatory process may take six or more years pre-construction.[40] It comprises three elements:[86,87]

- During pre-licensing, the GDA is carried out by the Office for Nuclear Regulation (ONR) and Environment Agency (EA). The safety case made by vendors of a reactor design is assessed to ensure risk is reduced to as low a level as reasonably possible for the safety and security of the public and the environment.[88,89]
- The SSA, which determines whether a site is suitable, is done by the ONR, EA (in England), Scottish Environment Protection and Natural Resources Wales. Northern Ireland does not have nuclear infrastructure.[90-92]
- The regulators conduct further monitoring during construction.

In 2017, the UK Government announced it would provide regulators £7 million to build capability and capacity for advanced technology assessment and licensing.[21,93]

Public Opinion

The UK planning process takes into account local public opinion, which could be a challenge to deploying SMRs to new sites. People close to existing nuclear sites are thought to be supportive due to local social and economic benefits, but evidence is limited.[96] The wider population is less supportive. A 2017 survey reported that 62% of respondents did not want to live near a nuclear power plant.[97] Developers in the UK are presently only considering locations that currently host or have hosted nuclear sites.[81]

Nuclear Non-Proliferation

Governments and nuclear operators are required to consider the need to prevent civil nuclear material being diverted for military purposes (known as proliferation).[73,98] High-risk periods of proliferation are fuel production, reactor re-fuelling and waste disposal (transport and storage).[66] The UN Treaty on the Non-Proliferation of Nuclear Weapons (NPT) aims to prevent the spread of nuclear weapons and promote peaceful use of nuclear energy.[99] Compliance with the NPT is monitored by the IAEA.[100] The EU also applies additional safeguards to its members, monitored by Euratom.[101] The UK is introducing its own safeguards system ahead of withdrawal from Euratom.[102]

Establishing an international fuel and waste supply chain for SMRs has been suggested as a method to manage and monitor proliferation risk.[103] There is uncertainty over the extent to which widespread SMR use might increase or decrease non-proliferation risk.[66,81,103] Some SMRs require less frequent refuelling than conventional nuclear, reducing high risk periods.[66] However, more integrated designs may be more challenging to inspect, and some designs use more highly enriched uranium than conventional nuclear. Both of these aspects could increase proliferation risk.[66,104]

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POST is an office of both Houses of Parliament, charged with providing independent and balanced analysis of policy issues that have a basis in science and technology. POST is grateful to Marie-Laure Hicks for researching this briefing, to EPSRC for funding her parliamentary fellowship, and to all contributors and reviewers. For further information on this subject, please contact the co-author, Jack Miller.