Nuclear small modular reactors

1. EXECUTIVE SUMMARY

1.1. A UK consortium, led by Rolls-Royce, has received UK Government backing to re-establish the UK as a leader in nuclear technology with small modular reactor (SMR) technology.

1.2. SMRs are designed to significantly cut Capital Expenditure (Capex) investment requirements compared to traditional large-nuclear by developing the construction base to roll out multiple identical 'units' with common components and design blueprints. The reduction in capex is expected to help achieve levelised cost of energy of £60-£75 per Megawatt Hour (MWh). For comparison, the levelised cost of offshore wind in the UK is now £45 per MWh, but has inherent intermittency issues. Each SMR unit will have up to 400 MW capacity (SMRs as small as 11 Megawatt equivalent (MWe) have been constructed, such as the EGP-6 reactor in Russia), with annual outputs of ~ 3,500 GWh per year. SMRs have improved load-following capability compared to traditional nuclear, with ramp-rates of 5% of maximum load per minute. For comparison, the total annual electric demand in the Isle of Man is 364 Gigawatt Hours (GWh) (2018), whereas demand for all fuels is approximately 1700 GWh per year (2018). A DC interconnector may therefore be required to export surplus electricity to the UK / ROI.

1.3. Nuclear SMR is said to be able to offer baseload supplies to remote areas of the grid. However, nuclear technology is not a renewable source of energy, depending on imports of Uranium- 235 (U_{235}) fuel. The fuel is not an indigenous resource to the Isle of Man and would likely be imported from Central Asia / Australia. The Isle of Man may face significant regulatory, environmental and political barriers to adopting nuclear SMR technology, though from a technical perspective, it offers long term (60 + years) infrastructure to supply stable electrical power in the context of increased electrification of surface transport and domestic heating.

1.4. In the pursuit of reaching net-zero CO_2, nuclear energy may offer a solution to increasing electrical demand in the Isle of Man. It is recommended that a watching brief is maintained on the technology and a national conversation on the technology encouraged to establish whether/how nuclear waste could be dealt with, and then gauge the level of political and public acceptability or support.

1.5. It should be noted that nuclear power is not usually considered compatible with UNESCO Biosphere Reserve designation, so this would be a significant consideration.

2. NUCLEAR: SMALL MODULAR REACTORS (SMRS) OVERVIEW

2.1. In early 2016, the UK Government launched a Small Modular Reactor (SMR) competition and took the first step in acknowledging a potential role of SMRs in the

UK's future low-carbon energy mix. Since then, the UK SMR Consortium, led by Rolls-Royce, has made progress in developing the design of the power station and providing the technical and economic analysis.

2.2. Since 2007, nuclear has played an important role in the UK's energy policy. However, it's a significant task to deliver large new reactors. Firstly, financing new large plants is expensive. Secondly, few organisations are willing to take on the construction risks and thirdly, there is low confidence that large projects can be delivered on time. Nuclear power plants based on SMR technology are claimed to offer an alternative to the uncertainties of the large nuclear new build programme.

2.3. In 1956 the UK opened the first commercial nuclear power reactor at Calder Hall, and for a generation British nuclear energy technology led the world. Policy changes in the 1970s and 1980s gradually led to the erosion of this position, with nuclear energy removed from future policy during the 1990s. This trend was reversed in the first decade of the 21st century and since the 2007 White Paper, 'Meeting the Energy Challenge' (DTI, 2007) nuclear energy has been a cornerstone of the UK's energy policy. This ongoing policy commitment to nuclear has encouraged foreign Governments and companies to make multi-billion pound investments in new nuclear plants, such as the two European Power Reactor (EPR) power plants that Areva and EdF Energy will construct at Hinkley Point. Yet in spite of this, so far there has been limited UK Government support for any redevelopment of UK capability to design, develop and export nuclear products, technology and services.

2.4. Nonetheless, The UK Energy Technologies Institute (ETI) has conducted scenario modelling to show how the UK can achieve the targets set for GHG emissions between now and 2050, which showed around 40 GW of nuclear capacity installed by 2050 as part of a balanced mix of energy technologies under the lowest-cost scenario for decarbonisation. It is likely, given the challenges facing large new-build nuclear reactors, that SMR technology will have a significant capacity delivery.

2.5. Globally, over 70 new reactor designs have been conceived by a wide-range of organisations, from universities to start-ups to engineering multinationals (NNL, 2014). The vast majority of these designs are based on the SMR concept. Such plants are deliberately designed to provide much less power reactor unit than large plants, though could still power around 100,000 homes. Only a handful of SMR designs are based on proven technologies that could be deployed before 2030, one such example being the UK SMR being developed by the Rolls-Royce Consortium. One UK SMR power station will produce 440 MW of electricity (Rolls-Royce, 2019). An artist's illustration of the UK SMR is shown in Figure 1.

Figure 1. The UK SMR (artist's impression).

3. UK SMR CONCEPT

3.1. Whilst SMR energy is low-carbon, it must also be affordable. The UK SMR Consortium design seeks to address the basic economic challenges that larger plants have struggled to overcome in recent years:

- Reduced overall capital cost to enable conventional project financing
- Improved certainty of construction, manufacture and project delivery
- Competitive levelised cost of energy (LCOE).

3.2. The UK SMR is designed based on the requirements of energy utilities and operators. The capital cost of the UK SMR can be reduced from a First-of-a-kind (FOAK) baseline to Nth-of-a-kind (NOAK) over a relatively short period of time, perhaps as little as eight years (Rolls-Royce, 2019). This is less than the time required to construct a single large reactor.

3.3. The levelised cost of electricity (LCOE) generated by a FOAK UK SMR power station is forecast under £75 per MWh and this reduces to a forecast £65 per MWh by station number five. In the medium term the target is even lower at £60 per MWh (Figure 2). The resulting reduced cost of SMR power plants may make them attractive to commercial investors, eliminating the need for Government to financially support construction.

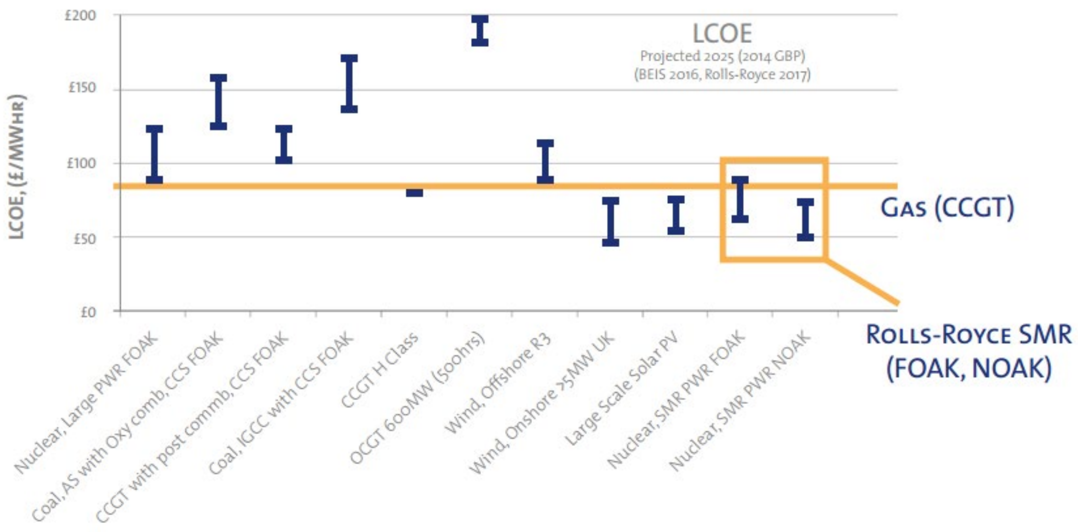

Figure 2. LCOE of various energy generation technologies in 2025 (projected). Figures from BEIS, 2016 and Rolls-Royce 2017.

3.4. In response to the aim of reducing delays to construction and additional cost of borrowing incurred by these delays, which have run into the billions of pounds and are often underwritten by loan guarantees from national Governments, the UK SMR has sought to significantly reduce the amount of on-site construction required by adopting modern deigns principles such as modularity, standardisation and commoditisation. This is achieved by moving activities off-site into a centralised controlled factory environment.

3.5. The UK SMR is a three loop, close-coupled, Pressurised Water Reactor (PWR) and provides a power output circa 400-450 MW (5 times more power capacity than the Pulrose CCGT power station) from 1200-1350 MWth using industry standard U)2 fuel. Coolant is circulated via three centrifugal Reactor Coolant Pumps (RCPs) to three corresponding vertical u-tube Steam Generators.

3.6. The design includes multiple active and passive safety systems, each with internal redundancy. The site layout is based on a modular build, illustrated in figure 3 and 4. The three loop reactor is located in the Nuclear Island (red), adjacent to the Turbine Island (yellow) with the Cooling Water Pump House following (blue). The facilities are protected by a hazard shield. Support buildings and those containing auxiliary services are situated within a berm that sweeps around the sites and provides further protection from hazards.

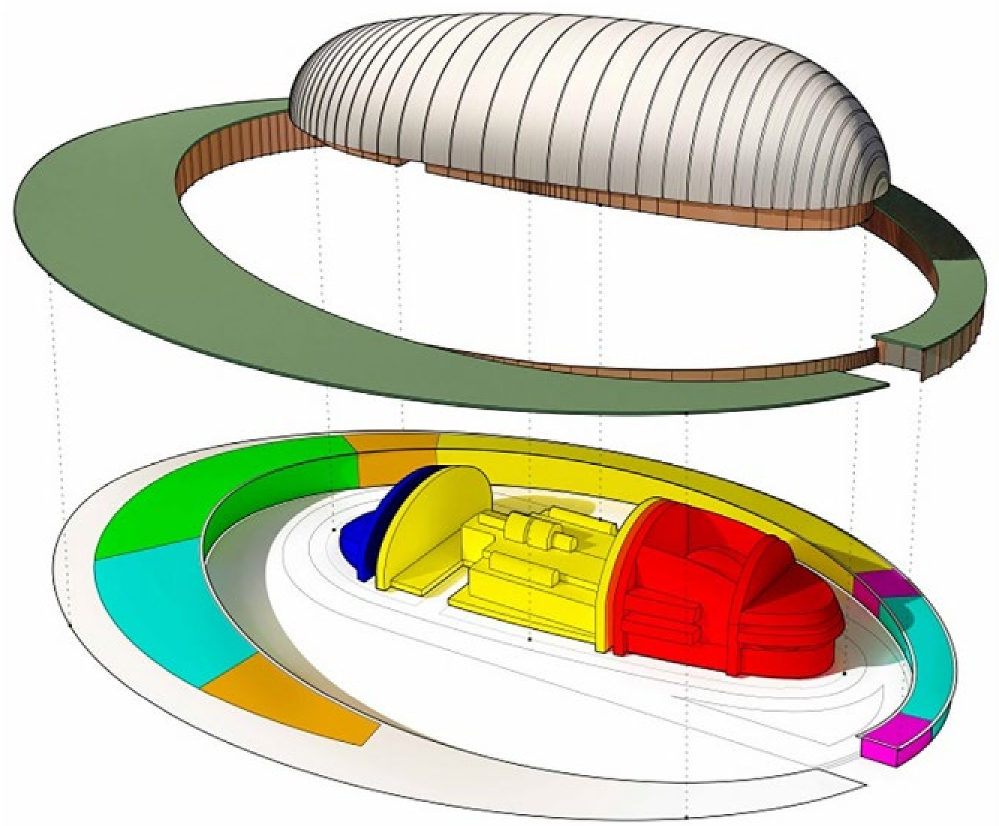

Figure 3. Expanded site view of the UK SMR.

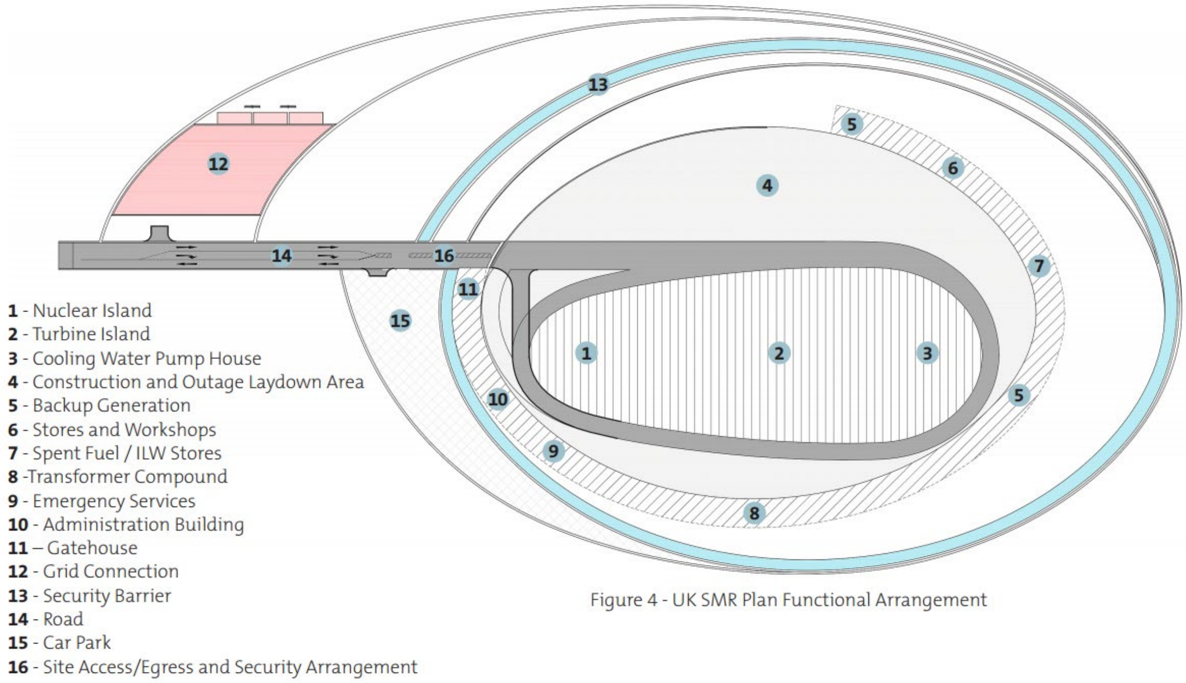

Figure 4 - UK SMR Plan Functional Arrangement

3.7. The first-of-a-kind commercial operation for the UK SMR is planned for 2030, after several years of maturing the design and achieving regulatory Design Acceptance Confirmation and State of Design Acceptability. The major technical parameters are shown below in Table 1.

Table 1. The Major Design Parameters of the UK SMR (Rolls-Royce, 2019)

Parameter	Value
Technology Developer	Rolls-Royce
Country of origin	United Kingdom
Reactor Type	PWR
Electrical Capacity (MWe)	400 – 450
Thermal Capacity (MWth)	1200 – 1350
Expected Capacity Factor (%)	>90
Design Life (years)	60
Plant Footprint (m^2)	TBC
Coolant/Moderator	Light Water
Primary Circulation	Forced circulation
System Pressure (MPa)	15.5
Main Reactivity Control Mechanism	Control rods
RPV Height (m)	11.3
RPV Diameter (m)	4.5
Configuration of Reactor Coolant System	Compact
Coolant Temperature, Core Outlet (°C)	327
Coolant Temperature, Core Inlet (°C)	296
Power Conversion Process	Rankine cycle
Cogeneration Capability	Possible configuration
Passive Safety Features	Yes
Active Safety Features	Yes
Fuel Type / Assembly Array	Industry standard UO_2 fuel in 17x17 array
Fuel Active Length (m)	2.8
Number of Fuel Assemblies	121
Fuel Enrichment (%)	4.95
Fuel Burnup (GWd/Te)	55 – 60
Fuel Cycle (months)	18 – 24
Number of Safety Trains	3 diverse decay heat removal methods, each with multiple trains
Emergency Safety Systems	Passive
Refuelling Outage (Days)	18
Distinguishing Features	• Compact site footprint • Modular approach facilitating rapid and cost effective build • Larger power output than similar SMRs • Highly reliable passive safety systems • Attractive exterior that is robust to hazards
Modules per plant	1
Estimated Construction Schedule (days)	TBC
Seismic Design (g)	0.3
Core Damage Frequency (per reactor year)	<1E-07
Design Status	Mature Initial Concept (termed Basis of Design)

4. TIMELINE FOR GENERATION AND COSTS

- Construction of the first SMR is expected to take three-to-four years, with the first operational plants being planned for 2030.
- The first SMR could be 30% more costly in terms of LCOE compared to a large nuclear reactor (£70 per MWh) but is expected to reduce to £60 per MWh with continued development.
- SMRs could achieve cost-parity with large-scale nuclear after 5GW of deployment, assuming a build rate of 10 units per year.
- Capex: unknown.
- Grid and interconnector upgrades: unknown

5. ISLE OF MAN CONTEXT

5.1. By 2030, the CCGT will be approaching the end of life phase and renewables are expected to grow in the Isle of Man energy mix. This may lead to a requirement for additional means of balancing supply and demand for power, particularly as the most economic sources of renewable energy available are intermittent (wind and solar). Furthermore, as the CCGT is decommissioned and the energy generation market moves towards low-carbon electrical generation, there will be a need to supply the domestic grid with a reliable baseload of energy to protect the commitment for 'security of supply'. It is feasible that a UK SMR could provide this generational capacity, with exports of surplus power to the UK via an additional 500 MW interconnector.

5.2. For large nuclear reactors, load following (i.e. varying the output of a generating unit as the system demand changes over the long and short term) increases the LCOE as nuclear reactors cannot economically load follow within the currently electricity market, which is volatile in terms of price and demand. Whilst SMRs face the same challenges, SMRs can offer improved load following ability in comparison with large reactors with a ramp rate of at least 5% of maximum power per minute due to SMRs having lower core power densities and shorter cores.

5.3. It may be important to firstly, commission a study to assess the feasibility of a UK SMR within the Isle of Man context, particularly as the conceptual design stage progresses to a point where finances and costs can be more thoroughly evaluated. Secondly, it will important to assess how current Isle of Man legislation and regulations may relate to such an activity. Thirdly, and importantly, it will be necessary to gauge the public and political attitude towards nuclear SMR generation on the Island, once a thorough and objective economic, environmental and life-cycle analysis of the project is available. The levelised cost of Nuclear SMR is likely to be significantly higher than technologies than harness indigenous renewable resources, such as wind. It should be noted that nuclear power is not usually considered compatible with UNESCO Biosphere Reserve designation, so this would be a significant consideration.

5.4. The recommendation is therefore to keep a watching brief on the technology, engage with the UK SMR technology at an appropriate time to evaluate the potential within the Isle of Man and look at current public attitudes towards nuclear SMRs as an electrical generation source.

6. REFERENCES

Rolls-Royce, 2019. *UK SMR: A national endeavour,* s.l.: Rolls-Royce.