Programme Area: Nuclear

Project: System Requirements for Alternative Nuclear Technologies

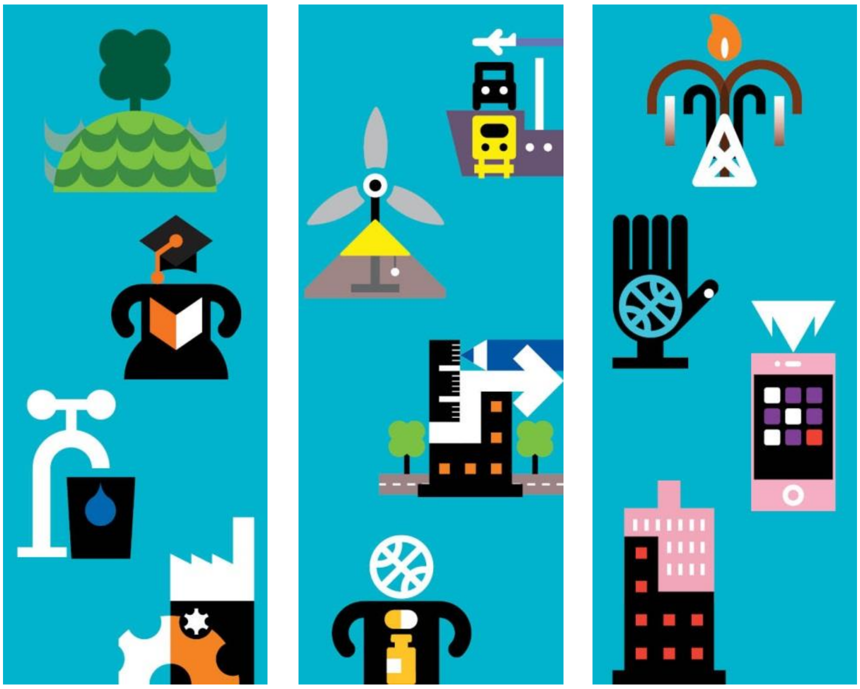
Title: Project Summary Report

Abstract:

The purpose of the System Requirements for Alternative Nuclear Technologies (ANT) project is to frame the UK energy system requirements for a small generic nuclear power plant with an output up to 300MWe. In practice this means defining the broad technical and economic parameters for an SMR to be of value to the UK's energy system in the future. This Project Summary Report presents the main findings of the ANT project. It begins with an overview of how the UK's energy system might develop over the coming decades. It is then split into two main parts. The first describes the functional requirements work stream; the second the business case work stream. Each provides a summary of the key findings followed by an outline of the relevant tasks undertaken. Together these sections frame the UK energy system requirements for small nuclear reactors under 300MWe.

Context:

The purpose of the System Requirements for Alternative Nuclear Technologies project was to capture the high level technical performance characteristics and business-case parameters of small thermal plants, which will be of value to the potential future of the UK's energy system. The project included small nuclear reactors, enabling comparison with other small-scale plants, such as those powered by bio-mass. The project outputs will help enable the subsequent contrast of a range of specific technologies.



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Energy Technologies Institute

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A	Dec 2014	Sam Friggens Guy Doyle Ian Scott Bob Ashley David Dodd (RR) Martin Goodfellow (RR)	Guy Doyle	David Holding	Draft Phase 1 Summary Report
B	Jan 2015	Sam Friggens David Dodd (RR) Martin Goodfellow (RR)	Guy Doyle	David Holding	Final Phase 1 Summary Report
C	Apr 2015	Sam Friggens Bob Ashley Martin Goodfellow (RR)	D23,D24 & D25 separately checked	D23,D24 & D25 separately reviewed	Updated with D23, D24, D25 (phase 2)
D	Jun 2015	Sam Friggens Guy Doyle Martin Goodfellow (RR)		Guy Doyle	Updated after 1st phase peer review & with new data
E	Aug 2015	Sam Friggens		Guy Doyle	Final version of Summary Report (after 2nd phase peer review)

Information Class: Standard

Contents

1 Introduction

Small Modular Nuclear Reactors (SMRs) are defined as nuclear power reactors with a maximum electrical output below 300MWe. They are generally considered to have distinct characteristics that make them different from conventional large reactors (LRs), such as modular design with pre-fabrication in offsite factories and the potential to deploy multiple reactors at the same site to form larger power plants. Many SMRs are also being designed as ‘integral’ units, where all key primary system components are integrated within a single pressure vessel and surrounded by a containment structure. A number of countries and companies are at different stages in the design and development of SMR technology.

If the technology is successfully developed, proponents claim that SMRs have the potential to offer a number of benefits to the UK’s future energy system. These benefits include the reliable provision of low-carbon electricity and heat, flexible deployment and the opening up of additional sites closer to demand. There could also be economic benefits to countries that establish themselves at the forefront of technology development and export. But despite this potential, there are currently significant uncertainties relating to the future costs and performance of SMR technologies and the suitability of different designs for the UK.

This is the background context for the System Requirements for Alternative Nuclear Technologies (ANT) Project, commissioned by the Energy Technologies Institute (ETI).

Project purpose

The purpose of the ANT project was to frame the UK energy system requirements for a small generic nuclear power plant with an output of up to 300MWe. In practical terms this meant defining the technical and economic parameters for an SMR to be of value to the UK’s energy system in the future. The ETI appointed Mott MacDonald to undertake this work with Rolls Royce as subcontractor to Mott MacDonald.

The project was primarily aimed at understanding what SMRs will ultimately need to ‘achieve’ in order to be deployed in the UK. Whether or not the UK has a role in technology development is not directly relevant in this context, although some aspects of technology development were considered during the project.

Links with wider work

Alongside the ANT project, the ETI commissioned the Power Plant Siting Study (PPSS) to identify potential sites for new power plants in Great Britain (including plants under 300MWe). The ANT and PPSS projects were closely interlinked with a joint workshop held early on and information shared throughout.

In 2014 the National Nuclear Laboratory completed an SMR Feasibility Study for the UK Government. It provides a review of the future global market for SMRs, a technical review of SMR technologies, and an assessment of SMR cost reduction potential. The ANT project builds on and complements this work.

At the time of writing in 2015, the Department of Energy and Climate Change (DECC) is undertaking work to define the criteria for a techno-economic assessment of different SMR concepts. The ANT project is available to form part of the evidence base for this wider work.

Project scope

The project included a functional requirements workstream and a business case workstream, and each of these workstreams was made up of a number of discrete but interrelated tasks defined by the ETI. The functional requirements workstream focussed on exploring what SMRs will need to do from a technical perspective to be of value to the UK's future energy system; the business case workstream on what SMRs will need to do from an economic perspective.

Report structure

This Project Summary Report presents the main findings of the ANT project. It begins with an overview of how the UK's energy system might develop over the coming decades. It is then split into two main parts. The first describes the functional requirements workstream; the second the business case workstream. Each provides a summary of the key findings followed by an outline of the relevant tasks undertaken. Together these sections frame the UK energy system requirements for small nuclear reactors under 300MWe in size. The report concludes with commentary on the overall contribution of the ANT project.

Assumptions

The ANT project analysis relied on a number of assumptions about future markets, technologies and economics. Some of these were set by the ETI at project inception, such as the nature and pace of the UK's approach to decarbonisation. Others were established by the ANT project team during the course of the project, such as those relating to the future performance of SMR power plants. The impact of changing some of these key assumptions was explored within the economic appraisal.

In terms of nuclear licensing, the ANT project assumed that the UK's current regulatory and licensing regime will be applied to SMR technologies and that UK SMR licensing could be achieved in a timely manner. We generally consider the GDA process to be robust and flexible and note that it is currently being successfully applied to commercial large Boiling Water Reactor (BWR) technology as it has been previously to large Pressurised Water Reactor (PWR) technology. This provides some confidence that the goal and evidence based approach taken to design assessment and licensing in the UK will be appropriate for SMR deployment too. The topic of licensing has been addressed in recent academic and industry literature, with barriers and drivers discussed in detail.[1] Given the significance of licensing for the deployment of nuclear technologies, further consideration of this issue may be warranted.

SMR terminology

The term 'SMR' is used throughout this report to refer to the broad category of SMR technology. However we also use the following specific terms and meanings where necessary:

- *SMR (power) module* – a single small nuclear reactor and associated components within the 'integral' unit that is produced in a factory.
- *SMR (power) plant* – all the physical elements of a power (and heat) generation plant, including multiple SMR power modules deployed together at a single site, associated electrical plant, steam turbines, electrical generators, civil works, balance of plant and connection to local substations.
- *SMR service offering* – the type of service an SMR plant provides to the UK's energy system, for example baseload electricity or Combined Heat and Power (CHP).
- *SMR project* – the development, construction and commissioning of an SMR power plant.

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[1] See for example: Sainati et al. (2015) Small Modular Reactors: Licensing constraints and the way forward; and World Nuclear Association (2015) Facilitating International Licensing of Small Modular Reactors.

Throughout the report we refer to the maximum electrical output of a power plant in mega-watts (electrical), or MWe. We refer to the maximum thermal output of a CHP plant in mega-watts (heat), or MWth. In the latter case MWth is as a measure of useful heat output, not a measure of the reactor’s core energy output.

In some sections we also refer to 100MWe SMR modules. 100MWe was defined as a representative SMR size for the purposes of analysis, such as identifying potential DH network locations. In reality a wide range of SMR module sizes are under development (from <5MWe to ~300MWe rated capacity) and it is anticipated that multiple modules will be deployed together to form power plants of different sizes.

All prices and costs in this report are in 2014 real terms unless otherwise stated.

Further reading

In this summary report, where necessary, we provide references to other documents that are directly relevant to the issue being discussed. We have also listed some of the key literature relating to SMRs in Appendix A, for the interested reader. The full range of wider literature drawn on for the ANT project is referenced in the Full Report.

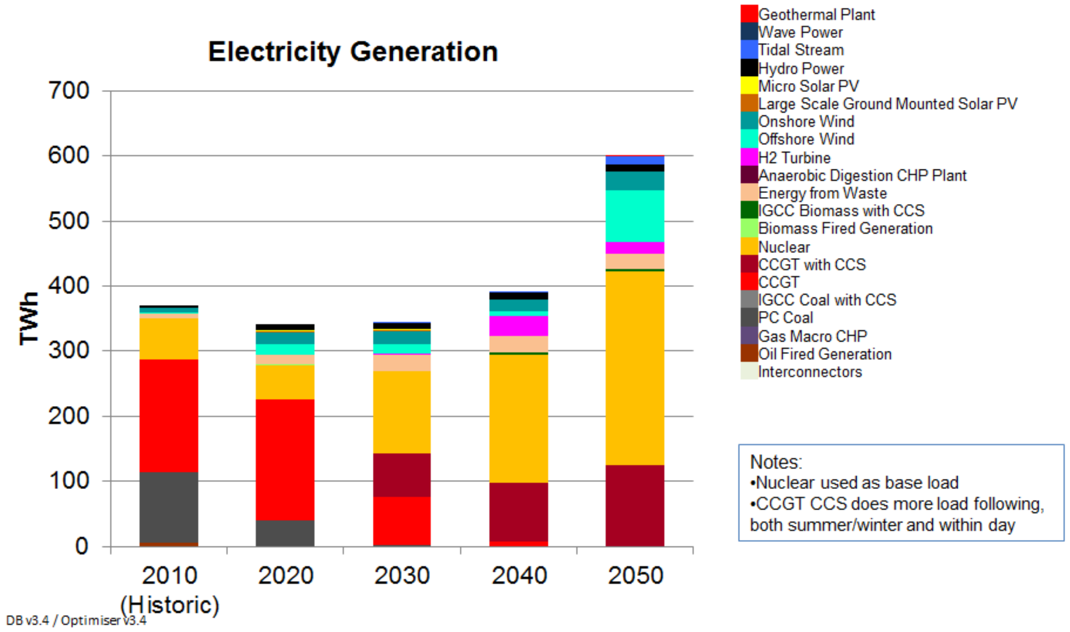
2 The UK’s future energy system

The UK’s energy system is expected to change in fundamental ways over the coming decades. As new technologies emerge and action to decarbonise the economy expands and deepens, unabated fossil fuel power generation and gas-fired central heating systems will need be phased out and replaced. Increased deployment of variable renewables technologies such as wind and solar will create a need for new forms of storage, flexible dispatch and other non-kWh services. New forms of heat generation will need to be deployed. This is the context for exploring the potential future role and requirements of SMRs in the UK.

2.1 Electricity generation

Figure 2.1 shows a scenario for electricity generation through to 2050, from the ETI’s ESME model. It shows virtually all electricity generation as low-carbon by 2040 with demand increasing over time as the heat and transport sectors become more reliant on electricity and less on the direct burning of fossil fuels.

Figure 2.1: Power generation scenario from the ETI’s ESME model



Notes:
- Nuclear used as base load
- CCGT CCS does more load following, both summer/winter and within day

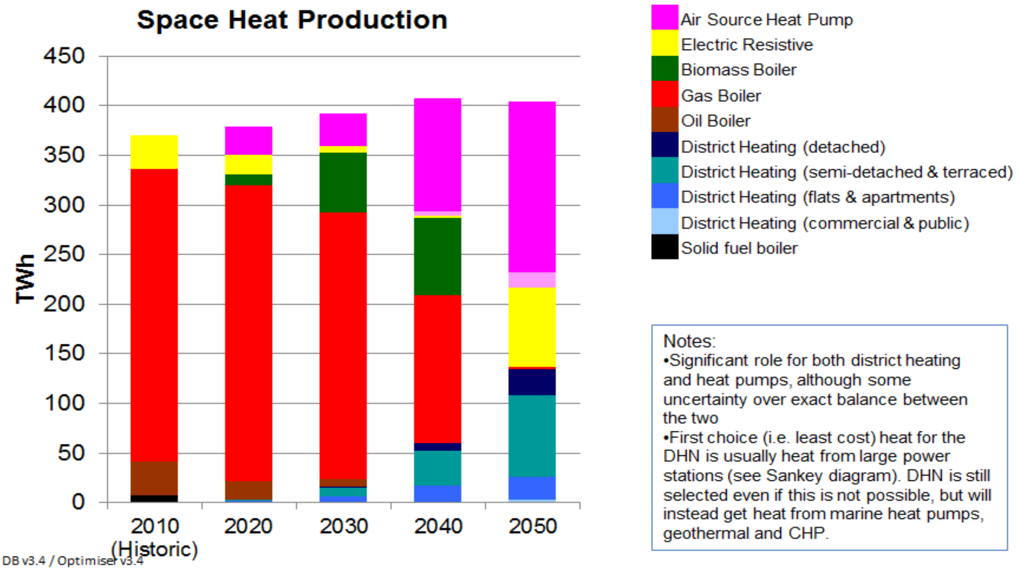
Source: Energy Technologies Institute (ESME scenario)

In this scenario around half of all electricity is produced from nuclear power by 2050, with a quarter coming from renewables and a quarter from Carbon Capture and Storage (CCS). Nuclear is assumed to be the pre-eminent technology for providing baseload electricity, and its deployment here is restricted by assumptions relating to the availability of suitable sites for large thermal power plants (an issue further investigated in the PPSS). In such a context there could be an opportunity for SMR technologies with in-built passive safety and lower cooling water requirements to open up more sites closer to demand and contribute in a cost-effective way to the generation of low carbon electricity.

2.2 Heat production

Figure 2.2 shows an ESME scenario for space heat production for commercial and residential premises through to 2050. It shows heat production taking longer to fully decarbonise than electricity generation and overall levels of space heat demand increasing only marginally compared to today.

Figure 2.2: Space heat production scenario from the ETI's ESME model



Notes:
- Significant role for both district heating and heat pumps, although some uncertainty over exact balance between the two
- First choice (i.e. least cost) heat for the DHN is usually heat from large power stations (see Sankey diagram). DHN is still selected even if this is not possible, but will instead get heat from marine heat pumps, geothermal and CHP.

Source: Energy Technologies Institute (ESME scenario)

The biggest implication for SMRs from this scenario is the significance of district heat (DH) networks in 2050 – projected here to supply over one-third of all space heat. It is a core assumption of the ANT project that decarbonising heat production in the UK will require large city-scale DH networks. This in turn would require a substantial roll-out of technologies capable of supplying low-carbon heat to these networks.

2.3 Flexibility

For the ANT project we defined three categories of flexibility related to electricity generators:

Load-following generation usually refers to the provision of 'mid-merit' electricity to meet varying demand, by plants capable of operating economically with some flexibility. Here the term refers to flexible generation covered by the day-ahead and intra-day markets. Currently in the UK gas plants provide the primary form of load-following generation. In a decarbonised future, we would expect new storage and demand side technologies to be an important source of this flexibility. In terms of generation the most likely candidates may be less capital intensive plant such as reciprocating engines and gas turbines using zero-carbon fuels.

Energy balancing is the near real-time matching of demand and supply. In Great Britain (GB) it is managed through the Balancing Mechanism (BM), where National Grid (NG) calls for increments and decrements to bring the system to balance over rolling 90 minute periods. Currently this is mostly provided by CCGT, coal, and pumped storage. Nuclear plant can provide increments/decrements but its costs are unaffected by small deviations so it has no economic incentive to de-load. In the future demand for energy balancing is likely to increase. We would expect this to be met via new flexible solutions and interconnectors.

Ancillary services are procured directly by NG to resolve transmission constraints and ensure the security and quality of electricity supply across the Transmission System. We expect demand for many of these – such as frequency response, reactive power and reserve – to increase in the future, especially in scenarios with higher penetrations of variable renewables.

3 SMR functional requirements workstream

The functional requirements workstream focussed on determining what SMRs will need to do from a technical perspective to be of value to the UK's future energy system. It involved a wide range of project tasks. Some were aimed at understanding what SMRs might realistically offer in terms of energy services, commercial readiness and long-term deployment rates. Others explored the needs of the energy system in more detail, such as low-carbon heat for DH network energisation, technology capable of being located on a diverse range of sites close to demand, and the compatibility of nuclear power plant fuel cycles with existing UK infrastructure. These pieces of analysis, supported by additional expert input, fed into the development of a list of SMR technical requirements.

Each of the main functional requirement workstream tasks is outlined in this section, with a focus on presenting the principle outputs and conclusions. A summary of the key findings is also presented upfront.

3.1 Summary of key findings

- It is likely to be technically feasible for SMRs to offer a range of different energy services, including baseload electricity, load-following electricity, heat for DH networks, and – if integrated with new storage technologies – energy balancing and other ancillary services.
- Development of a low risk evolutionary Light Water Reactor (LWR) type SMR from initial basis of design to the point of FOAK commissioning could take ~17 years and cost a minimum of ~£1.3bn (excluding FOAK capital costs). This assumes no full-scale design demonstrator plant is required. Many SMR concepts are already some way along this timeline.
- More radical SMR concepts would probably require a full-scale design demonstrator to prove the technological case for the design in question, adding ~£1bn to these development costs, with timescales as high as 26 years.
- From a technology development perspective, it is reasonable to assume that the first commercially deployed SMR power plants could be operating in the UK in the early 2030s. However if SMR concepts are selected that take longer to develop, there is a risk that the market opportunity will be lost.
- From the early 2030s, it is possible to envisage a regular deployment drumbeat that could lead to multiple gigawatts of deployed SMR capacity by 2050. This would require substantial challenges relating to supply chain development, investment and public acceptability to be overcome. The ANT project did not include an assessment of these issues.
- Our analysis of heat demand data suggests there are around 50 conurbations in GB potentially suitable for hosting SMR energised DH networks. The theoretical SMR capacity needed to energise all these networks is 22.3GWe/40.1GWth.
- It is unlikely SMRs will meet a DH's heat load in its entirety. Heat storage and low CAPEX technologies are likely to be used for meeting periods of peak load, whilst SMRs will be competing with other high CAPEX low carbon technologies to provide 'baseload' and 'mid-merit' heat. Reliable long-term offtake arrangements will be needed to secure upfront investment in these high CAPEX plant.
- The PPSS study, which was not exhaustive, has identified a significant number of site locations in England and Wales that are potentially suitable for small thermal plants like SMRs. The total 'stand-alone' electrical capacity that could be hosted by these sites is 66.9GWe. Less than 10% of this capacity is 'lost' when water cooling availability due to shared watercourses is taken into account. It should be noted that the PPSS represents the first stage of a multi stage assessment process for new

nuclear power plants. Actual plant capacity deployed on the identified sites will be lower once the full assessment process has run its course.

- The proximity of the PPSS site capacity to the identified DH networks suggests there could be a potential market for SMR heat in the England and Wales. This strengthens the conclusion that SMRs in the UK should be able to produce heat for DH networks.
- All of the existing siting criteria set out in the UK's National Policy Statement for Nuclear Power Generation (2011) are relevant to SMRs. However some may need to be applied flexibly, as they were in the PPSS, to account for the unique characteristics of SMR technologies and unlock the full range of potential sites.
- It is feasible for a small number of standardised SMR modules and plug-in systems configured at the site level to be deployed in a diverse range of contexts. This is important because it is a prerequisite for realising the economic benefits of factory production and standardised processes that SMRs could offer.
- In practice, for SMRs to produce heat as well as electricity, the reactor will need to run at a near constant rate (maintaining a relatively stable core power) whilst throttling heat production up and down to meet demand. There are a variety of technical solutions to achieve this but to date it appears that vendors have given little consideration to this requirement.
- From a technical perspective, SMRs could be deployed in areas with a limited cooling water supply provided that an engineered ultimate heat sink can be made available, for example by utilising forced draft cooling towers. Turning SMRs off for scheduled maintenance in summer when cooling water is unavailable may facilitate such deployment. However there are regulatory and safety challenges that will need to be overcome to allow this.
- The deployment of a fleet UK SMRs will add to the UK's national nuclear infrastructure requirements. In particular, additional capacity for all levels of nuclear waste handling and disposal is likely to be required. The cost of these 'back-end' infrastructure upgrades could be lower if deployment is based on LWR designs rather than more novel technologies. In addition, SMRs that require changes to Government policy on waste management to accommodate alternative fuel cycles and waste-forms may face additional delays to deployment whilst such policy matters are concluded. The capability and skills to service novel fuel cycles also need to be considered.
- We identified a list 98 technical requirements relevant to SMRs if they are to meet the needs of the UK's future energy system. These cover technical readiness, infrastructure compatibility and the capability to provide heat and flexibility as well as baseload electricity. A number of stringent standards relating to safety, performance, and design will also need to be met – factors that will likely have a significant impact on the public and political acceptability of large-scale SMR deployment in the UK.

3.2 Energy service offerings

To understand at a broad level the energy services that SMRs could potentially provide to the UK's future energy system, we defined a number of representative SMR 'service offerings'. These offerings are essentially different physical configurations and operating modes for SMR power plants, and they were used as units of analysis for much of the subsequent ANT project tasks. The three most important service offerings are set out in Table 3.1 below, along with key base-case performance assumptions.

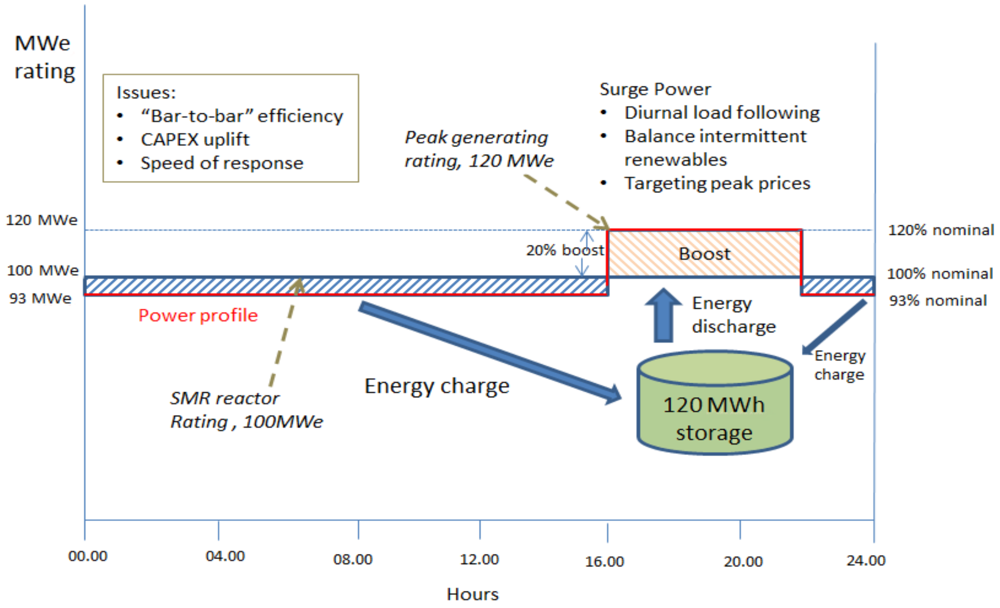
Table 3.1: Main representative SMR service offerings defined for the ANT project

Service offering	Description	Base-case performance assumptions
Electricity-only SMR (baseload)	An SMR power plant configured and operated to generate baseload electricity.	85% electricity annual capacity factor (ACF), based on 85% annual availability.
Combined Heat & Power (CHP) SMR	An SMR power plant configured for the cogeneration of heat and electricity. Operated to provide baseload electricity and heat on a load-following basis (by 'dumping' excess heat when not needed).	75% electricity ACF (to account for de-rating of electrical capacity). 40% heat ACF. 1.8 heat:power ratio.
Extra-flex SMR (electricity-only)	An electricity-only SMR power plant with combined energy storage and extra surge electricity generation capacity. The core plant would run continuously, as if providing baseload electricity, but operating the Extra-flex facility would allow the provision of load-following electricity and other energy balancing and ancillary services.	Type of storage facility not specified. 85% electricity ACF (i.e. minimal efficiency losses in a storage system operating on a diurnal basis). 20% additional capacity boost (maximum discharge rate).

Source: Mott MacDonald

Figure 3.1 is an example schematic for Extra-flex plant operation over a 24 hour period. The plant is shown storing ~7% of its output for 18 hours and using this to boost capacity by ~20% over the remaining 6 hours.

Figure 3.1: Example schematic of Extra-flex operation, showing diurnal electricity output*



Source: Mott MacDonald

* 20% boost capacity is representative only. Other options would be possible.

3.3 Technical development

Achieving long-term decarbonisation objectives will require the UK to be rolling out low-carbon technologies at increasing scale across all sectors of the economy by the 2030s. New technologies not ready for commercial deployment by this point may miss their market opportunity. In this context the timing of SMR technological development is likely to be important, both for the success of the technology itself in the UK and, potentially, in terms of the UK achieving a least-cost decarbonisation pathway.

To understand the potential of SMR technologies to meet these energy system timescales, we explored the activities and timescales associated with bringing SMR concepts to the point of commercial readiness. We then developed a high-level generic framework tool to assess the technological maturity of different SMR concepts and estimate the remaining time and cost to reach 'in service maturity' (which we consider to be the point of 'FOAK' plant commissioning). Whilst this framework could be used to establish UK based SMR development, it could equally be applied to SMRs being developed overseas (whilst acknowledging that there may be some international variation depending on local conditions).

3.3.1 A note on the terms 'design demonstrator', 'FOAK' and 'NOAK'

SMRs are likely to have a different development pathway to most power generation technologies, since one of the main features of the technology is that it will be largely manufactured in a controlled factory environment. In advance of these factory facilities being developed, however, different approaches to the technical and commercial demonstration of SMR technology are possible.

During the technology development process, it is likely some form of prototype reactor module will need to be built and tested. This is referred to as a 'design demonstrator' in this report and would be required to prove the technological case for a given SMR design. It is likely to be a single module, and may or may not be full-size. It could be tested in a purpose built test-rig or potentially on-site.

There are different perspectives as to whether it would then be necessary to build a 'First-of-a-kind' (FOAK) commercial demonstration plant.

In this report we principally use the term FOAK to denote the first fully operational plant for a given SMR design, regardless of jurisdiction. It would be custom-built and based on the design that would ultimately be built in a factory. We would expect its construction to require more on-site activity than subsequent commercial plants, but to also include significant pre-assembly off-site. It could be comprised of one or multiple modules; designed to operate for a commercial lifetime, and be significantly more expensive than subsequent plants. The intention behind the FOAK plant would be to demonstrate the real-life operation of an SMR plant and prove the commercial case for the SMR concept in question.

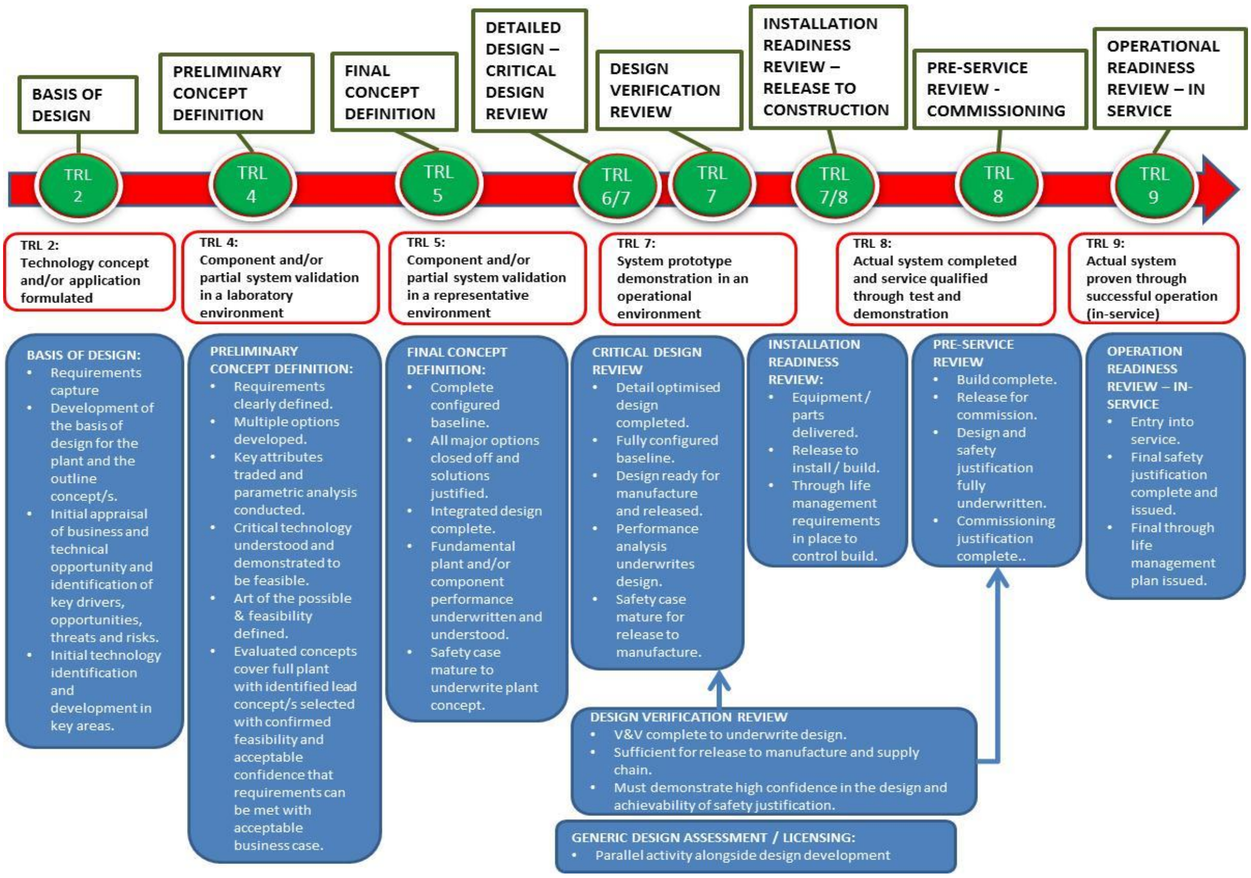
An alternative perspective – favoured by some SMR developers – would be to move straight from an acceptable design to factory production without a FOAK plant. This approach would be quicker and could allow an SMR developer or early investor to establish itself as a market leader, potentially gaining a large share of any future market. However this approach also implies significant barriers to investment can be overcome in financing the factory ecosystem in advance of commercial demonstration.

Once factory facilities and a supporting supply chain ecosystem are built, a regular production drumbeat could be established. SMR plants built at this stage are considered in this report to be fully commercial and are referred as ‘Nth-of-a-kind’ (NOAK). We would expect a large proportion of SMR cost reduction potential to be realised with this shift to factory production.

3.3.2 SMR development lifecycle stages

Figure 3.2 shows the generic SMR development lifecycle framework developed for the ANT project. The main stages of SMR technical development are shown along the top. The corresponding technology readiness level (TRL)[2] and a description of the main activities and outputs associated with each stage is provided in the columns below. This framework can be used to assess the level of maturity of key system components of an SMR concept under development and to indicate its overall lifecycle stage.

Figure 3.2: Development Lifecycle stages for SMR technical development assessment



Source: Rolls Royce

3.3.3 Cost and duration estimates

Figure 3.3 shows our estimates for the total cost and duration of taking a single SMR design from initial basis of design to ‘in service maturity’, as well as the remaining cost and duration for an SMR already at a given TRL. In each case a range of values is provided. These ranges represent different levels of technological novelty. Generally speaking, we would expect an SMR design with systems and components

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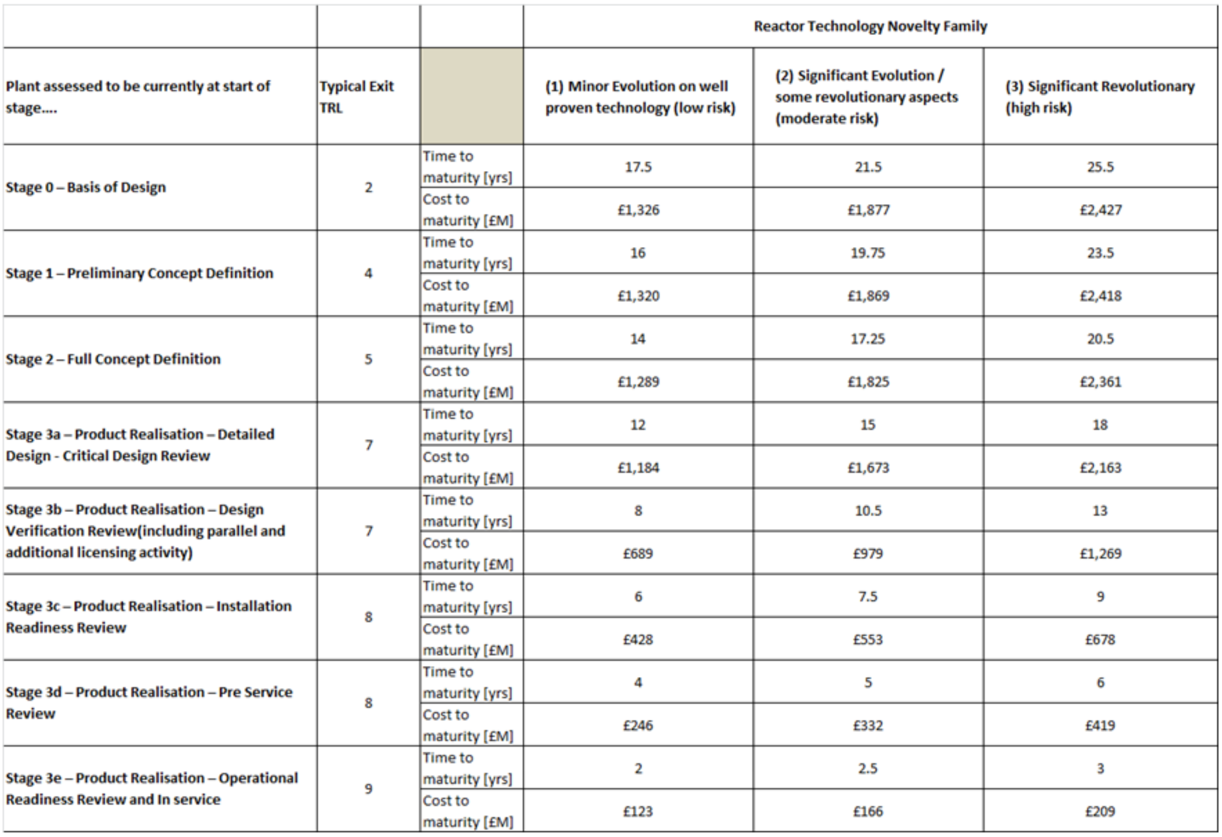
[2] The TRL framework was originally utilised by NASA in the 1980s but is now used across many industries and organisations.

that use proven principles and require only minor evolution to cost the least and be fastest to develop; and we would expect more revolutionary designs with systems, components and approaches that vary significantly from prior knowledge and experience to cost the most and take longest to develop.

Figure 3.3: SMR development cost and duration matrix



			Reactor Technology Novelty Family		
Plant assessed to be currently at start of stage….	**Typical Exit TRL**		**(1) Minor Evolution on well proven technology (low risk)**	**(2) Significant Evolution / some revolutionary aspects (moderate risk)**	**(3) Significant Revolutionary (high risk)**
Stage 0 – Basis of Design	2	Time to maturity [yrs]	17.5	21.5	25.5
		Cost to maturity [£M]	£1,326	£1,877	£2,427
Stage 1 – Preliminary Concept Definition	4	Time to maturity [yrs]	16	19.75	23.5
		Cost to maturity [£M]	£1,320	£1,869	£2,418
Stage 2 – Full Concept Definition	5	Time to maturity [yrs]	14	17.25	20.5
		Cost to maturity [£M]	£1,289	£1,825	£2,361
Stage 3a – Product Realisation – Detailed Design - Critical Design Review	7	Time to maturity [yrs]	12	15	18
		Cost to maturity [£M]	£1,184	£1,673	£2,163
Stage 3b – Product Realisation – Design Verification Review(including parallel and additional licensing activity)	7	Time to maturity [yrs]	8	10.5	13
		Cost to maturity [£M]	£689	£979	£1,269
Stage 3c – Product Realisation – Installation Readiness Review	8	Time to maturity [yrs]	6	7.5	9
		Cost to maturity [£M]	£428	£553	£678
Stage 3d – Product Realisation – Pre Service Review	8	Time to maturity [yrs]	4	5	6
		Cost to maturity [£M]	£246	£332	£419
Stage 3e – Product Realisation – Operational Readiness Review and In service	9	Time to maturity [yrs]	2	2.5	3
		Cost to maturity [£M]	£123	£166	£209

Source: Rolls Royce

Overall, we estimate that full development of low risk evolutionary LWR type technology could take in the region of 17 years and cost a minimum of £1.3bn up to the point of FOAK plant commissioning (excluding FOAK capital costs). This assumes no full-scale design demonstrator plant is required. A more likely scenario, particularly for more radical technological options, is that a full-scale design demonstrator plant would be required, adding around £1bn to these costs, with timescales as high as 26 years. Costs for a SMR technology development programme will grow significantly as the technology is developed through the TRL levels. It is worth noting that for a number of existing SMR concepts a significant amount of design and development effort has already been applied.

The timelines presented here provide an indicative ‘top-down’ outline of the process required to move from concept through to fully realised and licensed detailed design with physically validated systems and components. They are based on reactor development experience in many different nations. It should also be noted however that in certain jurisdictions, particularly where reactor designer and energy utility are state controlled, it may be possible to accelerate some phases of the development program.

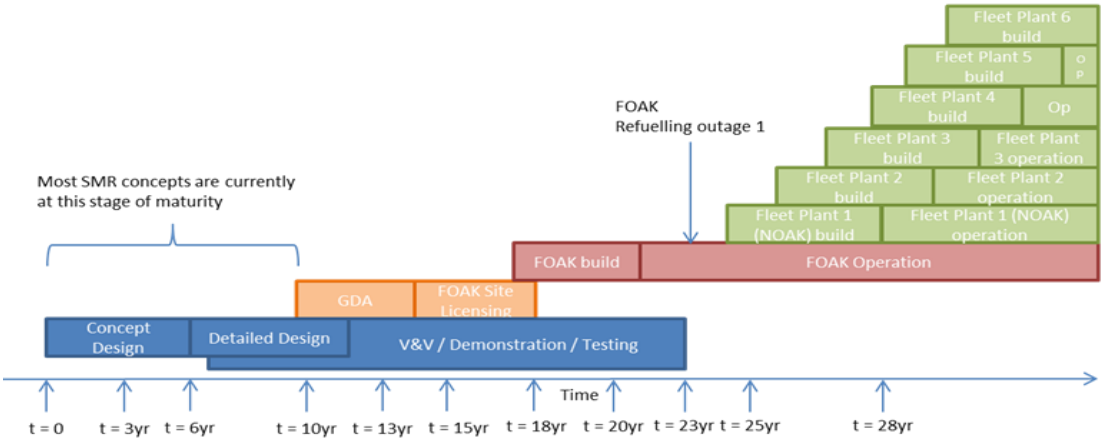
3.4 Deployment schedule

Using these indicative timescales for SMR technological development and assumptions about the subsequent rate of commercial deployment, we mapped out three deployment scenarios for SMR power plants in the UK. These scenarios are based on supply-side assumptions and do not directly consider market demand. However we note that other parts of the ANT project suggest that future heat demand (section 3.5) and site availability (section 3.7) are both potentially compatible with the levels of deployment outlined here.

3.4.1 Technology development and early deployment

Figure 3.4 shows an indicative schematic for the technology development and early deployment phases of a LWR type SMR design. It covers design, testing, licensing and the build and operation of a full-scale FOAK commercial demonstration plant. It is assumed here that the final investment decision for factory production facilities and NOAK plant build is taken only after the first FOAK plant refuelling cycle. Given that many SMR concepts are some way along this programme (such that 2005 could be considered year zero) it is reasonable to assume the first NOAK SMR power plants could be operating in the early 2030s.

Figure 3.4: Simplified build schematic for LWR type SMR technology



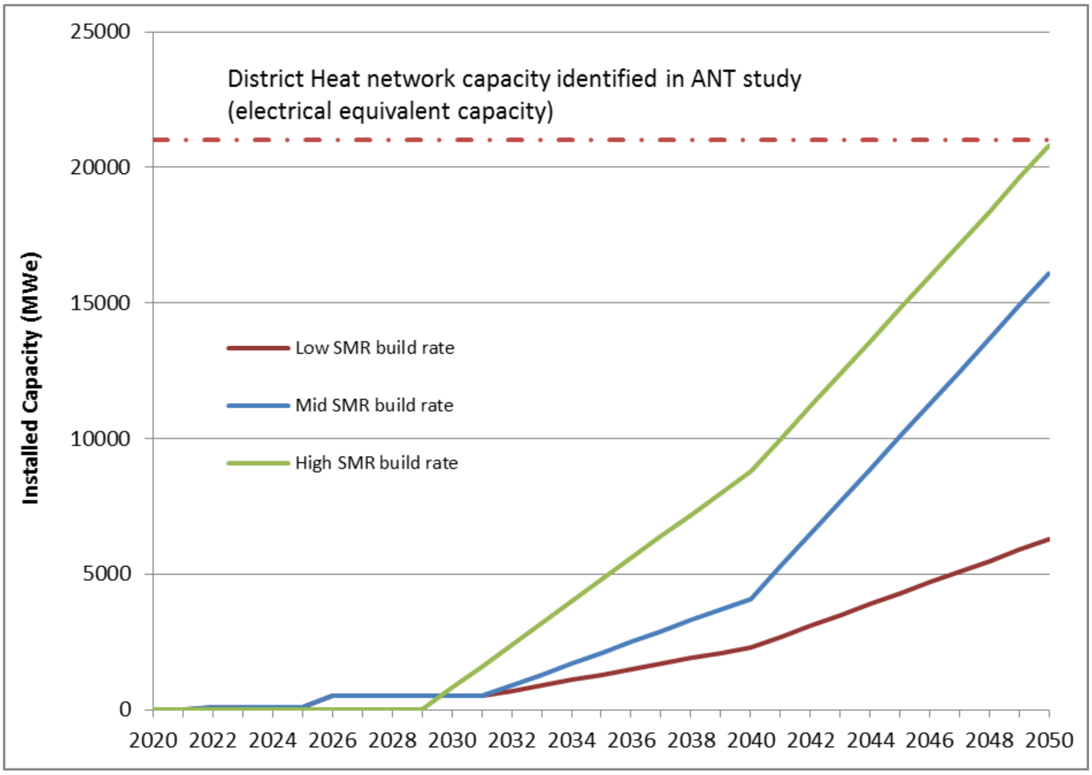
Source: Rolls Royce

There are implications here for SMR technology selection. If the UK Government chooses to support the development of SMR technology, the question of whether a given concept is likely to meet this timetable may be a material consideration in deciding which concept(s) to support. More radical non-LWR options may be attractive, but may also take longer to develop, with the risk that the market opportunity is lost.

3.4.2 The commercial drumbeat

Once SMRs reach commercial readiness, the rate of NOAK deployment will depend on a wide range of factors. On the supply side these include investor attitude and the pace of supply chain development. Both our ‘low’ and ‘mid’ deployment scenarios (see Figure 3.5) assume a FOAK plant is built in the UK followed by a rapid move to factory production facilities, then NOAK deployment from 2032 and a production drumbeat of 2x100MWe and 4x100MWe modules per year respectively. Our ‘high’ scenario, which we consider unlikely in all but exceptional circumstances, assumes that no technology demonstration is needed in the UK, and that NOAK deployment begins in 2030 with a production drumbeat of 8x100MWe modules per year in the 2030s, rising to 12 per year in the 2040s.

Figure 3.5: Installed cumulative UK SMR electrical capacity in the three scenarios

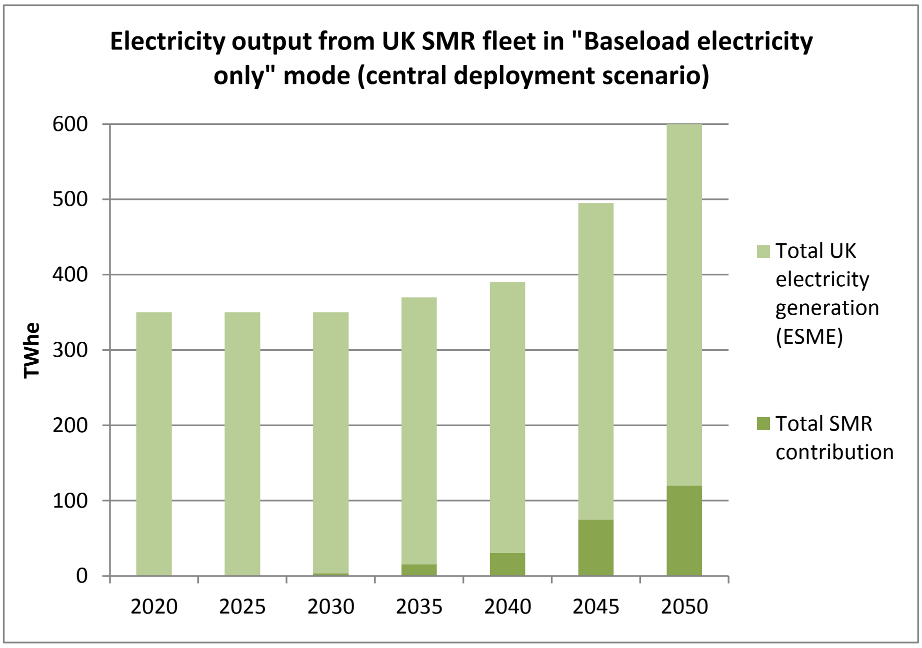


Source: Rolls Royce

Attracting the substantial investment required to realise any of these scenarios represents a significant challenge. This challenge is driven by two constraints: the long up-front timescale (20+ years) involved in design, licensing and demonstration ahead of final investment decisions for NOAK plants; and the financing of a factory supply chain ‘eco-system’ capable of manufacturing multiple sets of reactor and plant modules per year.

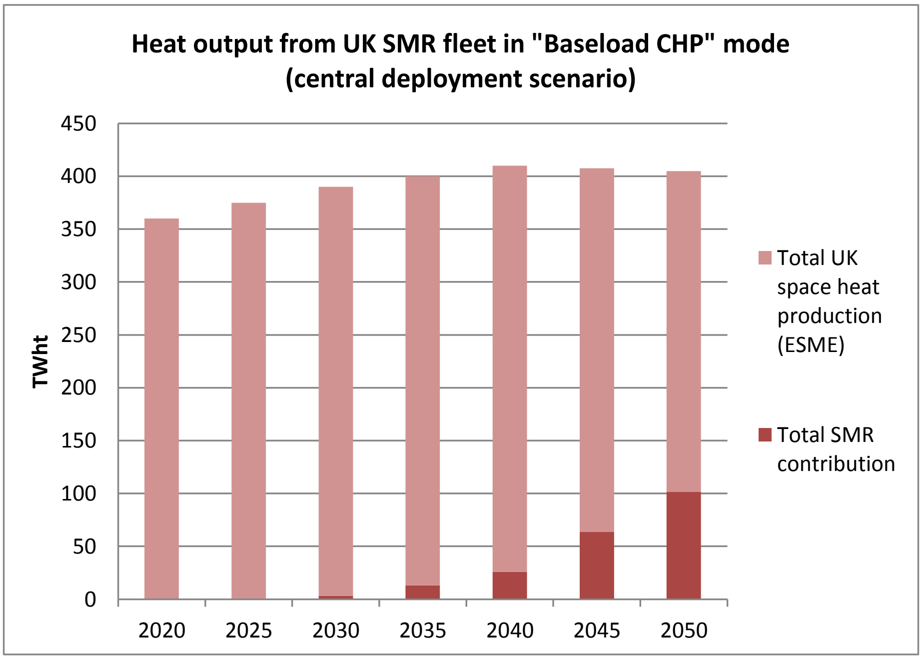
An SMR fleet of 16GWe (our mid scenario) could provide in the region of ~20% of the UK’s total electricity generation and (if CHP) ~25% of total UK space heat production in 2050 (using the ETI ESME scenario that informed the ANT project as a baseline) – see Figures 3.6a and 3.6b.

Figure 3.6a: Indicative electricity output from a fleet of electricity-only SMRs (2020-50)



Source: Mott MacDonald (based on EMSE scenario)

Figure 3.6b: Indicative heat output from a fleet of CHP SMRs (2020-2050)



Source: Mott MacDonald (based on EMSE scenario)

3.5 District heat networks

A central proposition of the ANT project is that future city-scale DH networks will need to be energised by sources of low-carbon heat and that this could in turn be a key driver of SMR deployment. To test this proposition, we first undertook analysis of local heat demand data to identify locations in GB that may have a suitable heat load to host SMR-energised DH networks. We then undertook further investigation into the potential role of SMR heat in these networks, mapping out technology and operating temperature options.

3.5.1 DH network target locations

The approach to identifying potential future DH networks was based on an assessment of contemporary residential and tertiary sector heat demand. The data for this was provided by ETI, and covered every Mid-level Super Output Area (MSOA) in GB. No analysis of the feasibility of installing DH networks was undertaken beyond using heat load and heat load density as proxies for economic viability. We used GIS to identify MSOAs where the following criteria could be met:

- Sufficient heat load in the surrounding area to utilise 40% of the heat output of a 100MWe SMR power plant, i.e. a 40% heat ACF (assuming the DH network has a 75% penetration rate);
- A heat load density within this area that is at least equivalent to the minimum known heat load densities found in Swedish DH networks.

Our results indicate there are around 50 conurbations in GB potentially suitable for hosting SMR energised DH networks. The theoretical capacity needed to energise all these networks is 22.3GWe/40.1GWth.

It should be noted that detailed optimisation was not carried out for this analysis. The number of networks and fleet capacity should be considered broad estimates only, and should be expected to change in the future as assumptions vary and when more detailed work is carried out.

3.5.2 Options for DH network energisation

3.5.2.1 The nature of the heat load profile

There will be a range of technology and operating temperature options for SMR energised DH networks. A key factor underpinning the selection of these options will be the nature of a network's heat load profile, and to better understand what a typical load profile looks like we analysed half hourly residential and tertiary heat load data for GB in 2010. This data showed that on a diurnal timeframe, heat demand is extremely varied with peaks in the mornings and evenings. On a seasonal timeframe the load profile shows a 'U-shape' profile with much higher demand in winter than summer.

This is important because an important question for SMR energised DH networks is how the SMR plant should be 'sized' against the network (i.e. the plant's maximum thermal output in relation to the network's peak demand). Based on the 2010 data, our analysis suggests that an SMR plant sized to meet 40% of peak load could meet ~90% of total demand and operate at a 40% heat ACF.[3]

The fluctuating nature of heat demand on both diurnal and seasonal timescales means it is unlikely SMRs will meet a network's heat load in its entirety. Heat storage and low CAPEX technologies are likely to be

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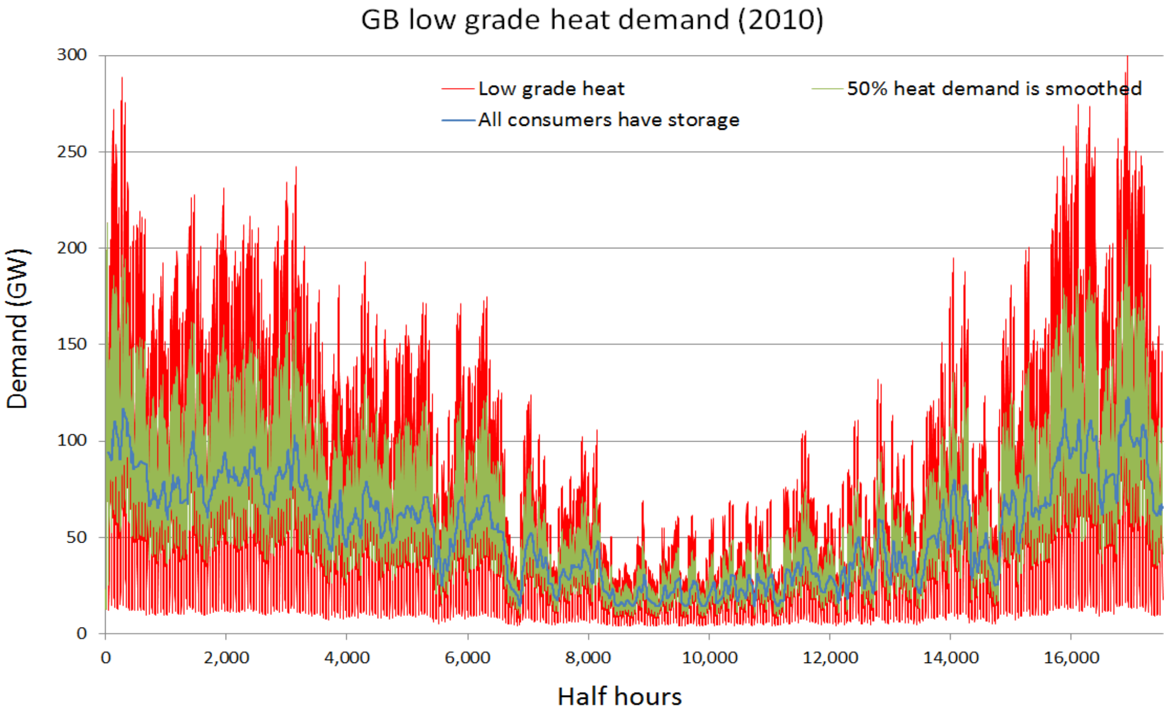
[3] It is a coincidence resulting from the heat load profile used that a ~40% sizing equates to a ~40% heat ACF.

used for meeting periods of peak load, whilst SMRs will be competing with other high CAPEX low carbon technologies to provide 'baseload' and 'mid-merit' heat.

3.5.2.2 Technology options

A key approach used to manage demand in current DH networks is water storage tanks. Well-insulated tanks are proven low cost solutions and will likely be a key component of future DH networks. According to our analysis, if end-users had tank storage to 'smooth' their daily profiles by 50%[4], then peak demand periods would be substantially lower over the course of a year – see the green line profile in Figure 3.7.

Figure 3.7: The impact of diurnal water tank storage on the GB heat load profile



Source: Mott MacDonald, based on data from Imperial College London (R Sansom)

In terms of generation technologies, a wide range of current and future low carbon solutions will be available beyond SMRs, each with advantages and disadvantages in ensuring supply can meet demand in a reliable and economic way. These technologies include gas CCS, biomass, solar thermal and waste process heat from industrial processes. A number of factors will affect which technologies are used for any given network, including local context, economics, policy incentives and 'contractability' (the framework in place for long-term heat offtake arrangements – particularly important for high CAPEX plant like SMRs).

Figure 3.8 shows how heat load could be met throughout the year under an illustrative scenario where a CHP SMR plant is contracted to supply baseload heat (it is assumed here to have the lowest cost of heat when operating at high levels of utilisation). 'Mid-'merit' heat is met by other thermal plants (such as biomass) and peak demand by alternative future sources such as hydrogen fuelled plant.

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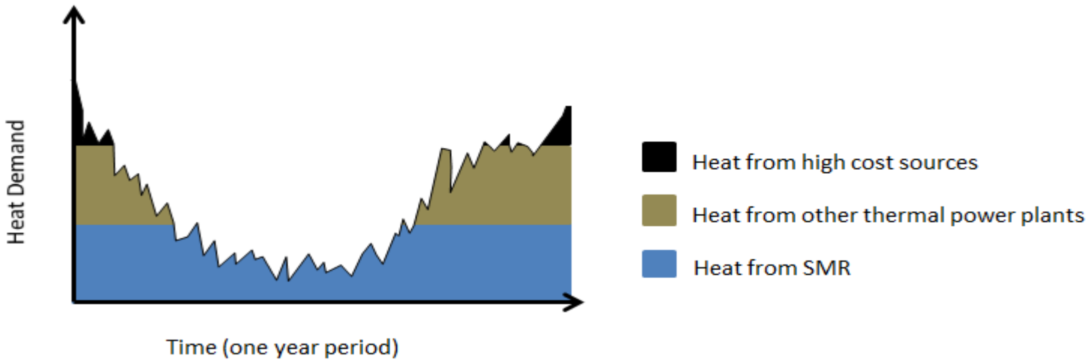
[4] I.e. reduce the gap between minimum and peak demand by 50%.

Figure 3.8: Indicative SMR priority heat supply scenario



Source: Mott MacDonald

3.5.2.3 Key issues SMR energised heat networks

Table 3.2 summarises the key issues identified that are relevant to the development of future low-carbon DH networks energised (at least in part) by SMR plants.

Table 3.2: Issues identified affecting future low-carbon DH networks and SMRs

Issue	Relevance to all heat DH energisation technologies	Relevance to SMRs specifically
Heat demand profiles currently have large fluctuations and high demand peaks	A high heat generation capacity will be needed to meet peak demand. In a low-carbon future this capacity will be expensive, as low carbon heat sources tend to be high CAPEX technologies. This will lead to an economic incentive to reduce peaks.	SMRs may be one of a number of high CAPEX low carbon heat technologies competing for contracts to provide baseload or mid-merit heat in the future.
Storage buffers to smooth demand	Hot water storage tanks are expected to play a major part in low-carbon DH networks. By 'smoothing' demand profiles they will be an effective way to reduce overall system capacity and CAPEX.	None
Meeting peak seasonal demand	Lower CAPEX heat technologies are expected to supply periods of peak demand that remain after the implementation of demand smoothing.	Unlikely that SMRs will be cost effective options for peak heat (unless already locally deployed for electricity generation).
Back-up heat provision to address unit unavailability	Less back-up capacity is likely to be required where core heat source plants are small or comprised of a number of smaller modules.	If an SMR for electricity generation is required anyway, the incremental CAPEX for CHP will be small and the short-run marginal cost attractive even for back-up.
Contractability	High CAPEX technologies will require a contractual framework capable of providing reliable heat offtake arrangements and/or capacity payments.	No significant differences between high CAPEX technologies.
Dispatch priority	Technologies available to dispatch low carbon heat will have been determined by prior award of long-term heat offtake contracts. Following this, we would expect contractual arrangements to allow for the lowest short run marginal cost technologies to provide the heat required at any given time.	SMRs are likely to have a low short run marginal cost. Therefore once built it is likely an SMR plant would be amongst the top priorities for heat dispatch.
DH network operating temperatures	The choice of outflow and return temperatures is a complex issue. In general, low temperature (40/20°C) will have advantages for heat suppliers and higher temperatures (110/60°C) advantages for heat users.	No significant differences between technologies.

Source: Mott MacDonald

3.6 Potential siting locations

The Power Plant Siting Study (PPSS) ran alongside the ANT project. It was based on the application of siting criteria developed for the UK's National Policy Statement (NPS) for Nuclear Power Generation, and it identified site locations in England & Wales that are potentially suitable for small thermal plants like SMRs.

The PPSS estimated that the total 'stand-alone' electrical capacity that could be hosted by these sites is 66.9GWe (i.e. before reduced water-cooling is taken into account due to multiple sites sharing the same watercourse). For the ANT project we carried out further analysis using GIS to reveal the diversity of these potential SMR locations and to illustrate their ability to energise the identified DH networks.

In interpreting these site capacity figures, it is important to note the following:

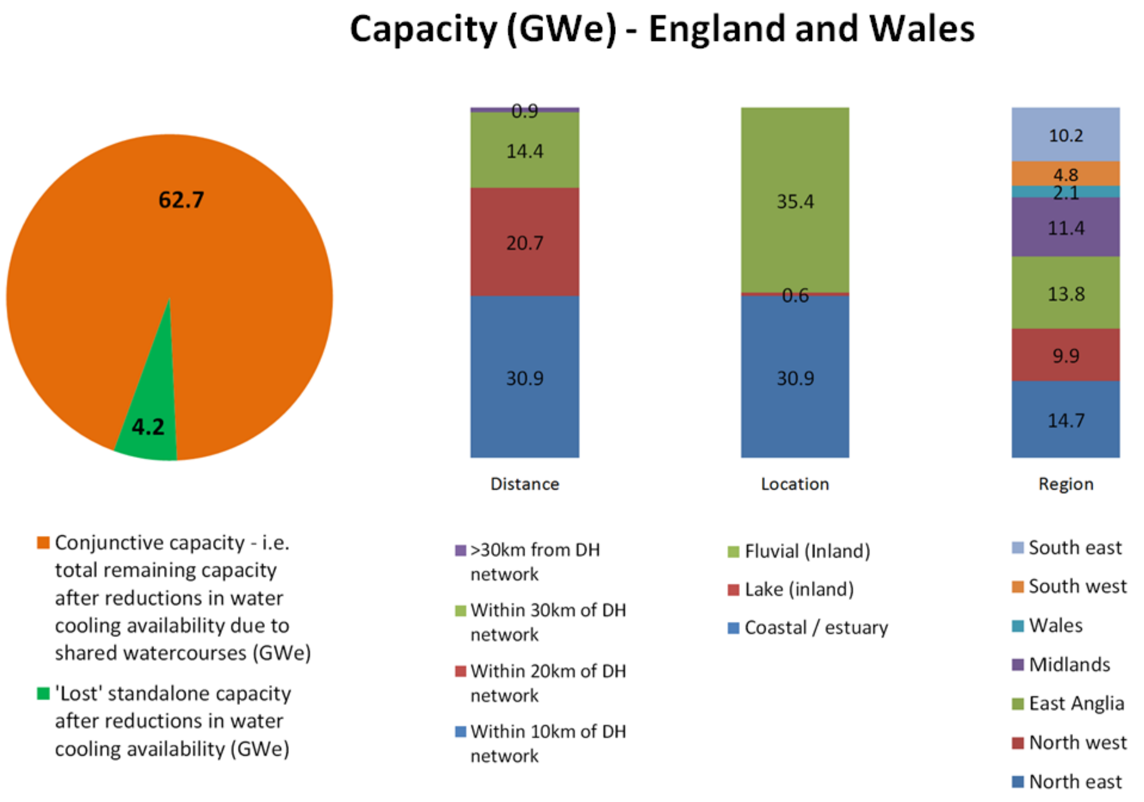
- The PPSS analysis was not exhaustive. It did not assess every part of GB; instead it focussed on regions and locations considered to be most relevant (such as locations within the vicinity of potential DH networks). Further analysis in the future could identify more potential sites.
- The small plant site capacity is less proven than the large plant site capacity. This is because of the constraints of time and budget on the PPSS project when looking at a large number of individual sites.
- The PPSS represents the first stage of a multi stage assessment process for new nuclear power plants leading up to the award of a Nuclear Site Licence for each site. The site capacities determined in the PPSS should be understood as a starting point. Actual plant capacity deployed on identified sites will be lower once the full assessment process has run its course, and will depend on many factors including procedural and regulatory requirements and site specific characteristics.

3.6.1 Small plant site capacity breakdown

Figure 3.9 shows the breakdown of this small site capacity by distance from the nearest DH network, type of cooling water source, and region of GB. The key conclusions are:

- Less than 10% of small site stand-alone capacity is 'lost' when water cooling availability due to shared watercourses is taken into account;
- Around 75% of the 66.9GWe is within 20km of the nearest potential DH network;
- The standalone capacity is broadly split 50:50 between coastal and inland areas;
- The standalone capacity is distributed across the England and Wales, with the highest amounts in the North-east, North-west, East Anglia, Midlands and South-east of England.

Figure 3.9: Breakdown of standalone small plant site capacity in England and Wales



Source: Mott MacDonald

3.6.2 DH network energisation

Two scenarios were explored to show how sites identified in the PPSS could be ‘matched’ to the DH network locations identified in the ANT project. It was a starting assumption of the ANT project that DH networks could be viable with a distance between heat source and DH network of 30km (based on installations demonstrated elsewhere). However for the two scenarios this was relaxed where necessary.

The first scenario showed that there is enough site capacity identified through the PPSS work to energise all of the identified DH networks ‘once-over’. This means that within a reasonable distance from each DH network there is sufficient site capacity for CHP SMR plants to meet ~80-90% of network heat demand (with plants operating at a 40% heat ACF). Most of this ‘once-over’ capacity is <30km from the network it energises and located on sites suitable only for small power plants.

The second scenario showed that there is enough PPSS site capacity to energise most DH networks ‘twice-over’. Twice-over means that within a reasonable distance of a DH network there is twice as much capacity than is required to energise it. Compared to the once-over scenario, more capacity is >30km from the relevant DH network and located on sites also suitable for large reactors (this excludes existing large nuclear sites). A small but significant number of DH networks could not be energised twice-over.

These findings suggest there could be a potential market for SMR heat in England and Wales.

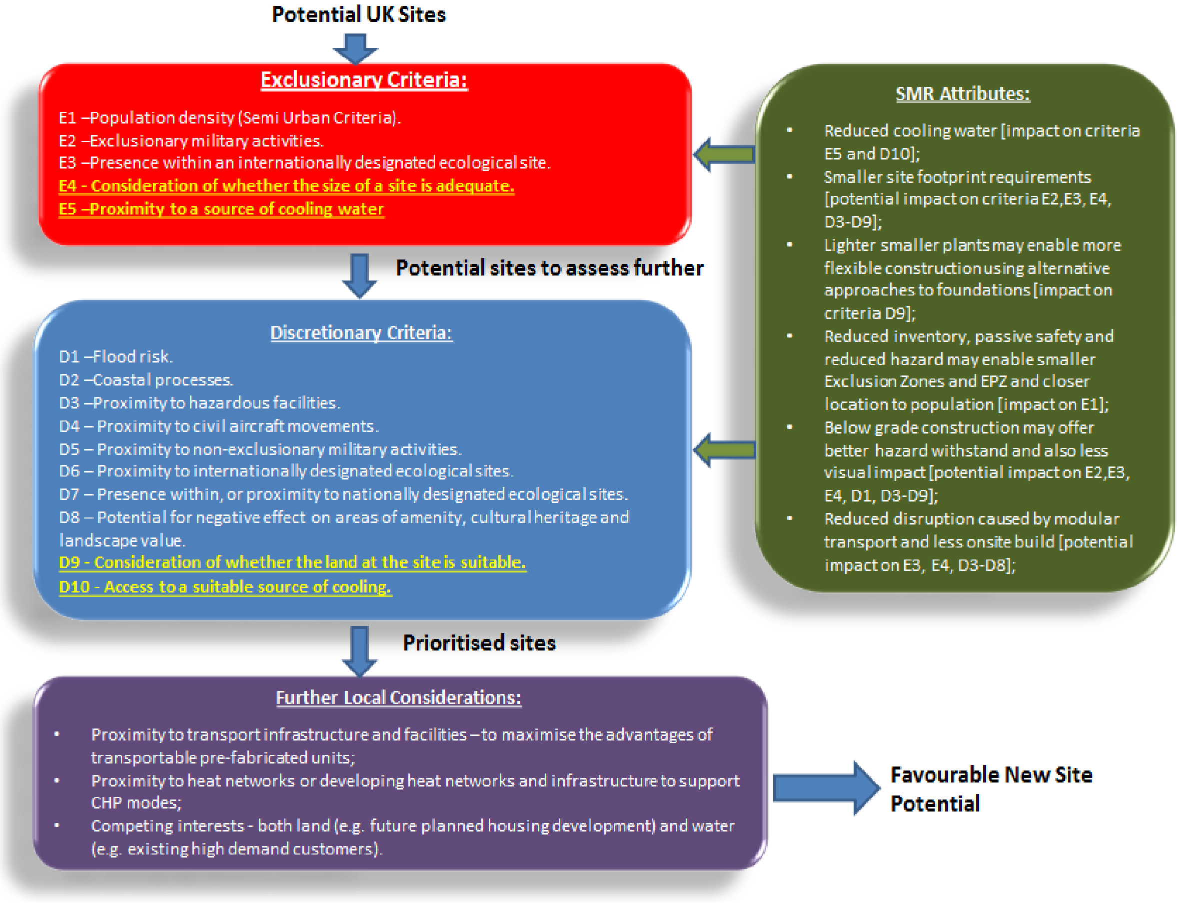
3.7 Siting criteria

Independent from the PPSS, the ANT project included a high-level review of the UK's current siting criteria for large nuclear plants. The purpose was to assess whether these criteria are applicable to SMRs and to identify if they may need to be implemented differently to unlock the full-range of potential SMR sites.

The siting criteria are set out in the UK's NPS for Nuclear Power Generation (2011) and are categorised as either 'exclusionary' (which, if breached, automatically exclude a site) or 'discretionary' (which, if breached do not necessarily mean a site is excluded). In our review of these criteria, we considered characteristics that differentiate SMRs from conventional large reactor technologies. This process was informed by input from stakeholders.

Figure 3.10 summarises our review. We conclude that all existing siting criteria are relevant to SMRs, but that those relating to the size and suitability of land at a site (E4, D9) and to the proximity and suitability of water cooling source (E4, D10) should be applied flexibly, as they were in the PPSS. These criteria are highlighted in yellow. In addition, there may be potential in the long term for criterion E1 (relating to population density) to be relaxed; a decision that would ultimately be made by the Office of Nuclear Regulation.

Figure 3.10: UK Nuclear Siting Criteria – applicability to SMR power plants



Potential UK Sites

Exclusionary Criteria:

E1 –Population density (Semi Urban Criteria).
E2 –Exclusionary military activities.
E3 –Presence within an internationally designated ecological site.
E4 - Consideration of whether the size of a site is adequate.
E5 –Proximity to a source of cooling water

Potential sites to assess further

Discretionary Criteria:

D1 –Flood risk.
D2 –Coastal processes.
D3 –Proximity to hazardous facilities.
D4 – Proximity to civil aircraft movements.
D5 – Proximity to non-exclusionary military activities.
D6 – Proximity to internationally designated ecological sites.
D7 – Presence within, or proximity to nationally designated ecological sites.
D8 – Potential for negative effect on areas of amenity, cultural heritage and landscape value.
D9 - Consideration of whether the land at the site is suitable.
D10 - Access to a suitable source of cooling.

SMR Attributes:

- Reduced cooling water [impact on criteria E5 and D10];
- Smaller site footprint requirements [potential impact on criteria E2,E3, E4, D3-D9];
- Lighter smaller plants may enable more flexible construction using alternative approaches to foundations [impact on criteria D9];
- Reduced inventory, passive safety and reduced hazard may enable smaller Exclusion Zones and EPZ and closer location to population [impact on E1];
- Below grade construction may offer better hazard withstand and also less visual impact [potential impact on E2,E3, E4, D1, D3-D9];
- Reduced disruption caused by modular transport and less onsite build [potential impact on E3, E4, D3-D8];

Prioritised sites

Further Local Considerations:

- Proximity to transport infrastructure and facilities – to maximise the advantages of transportable pre-fabricated units;
- Proximity to heat networks or developing heat networks and infrastructure to support CHP modes;
- Competing interests - both land (e.g. future planned housing development) and water (e.g. existing high demand customers).

Favourable New Site Potential

Source: Rolls Royce

3.8 Plant operating modes

The above analysis suggests that if successfully developed and deployed, SMR power plants would occupy a diverse range of sites around the UK. Whilst we would expect all of these plants to provide electricity to the national grid, it is possible only some would provide heat for city-scale DH networks or flexible load-following power. To understand this energy system requirement in more detail, we considered the technical and operational implications that could result from SMRs being deployed at a range of sites to meet different local and national needs.

3.8.1 Technical Implications

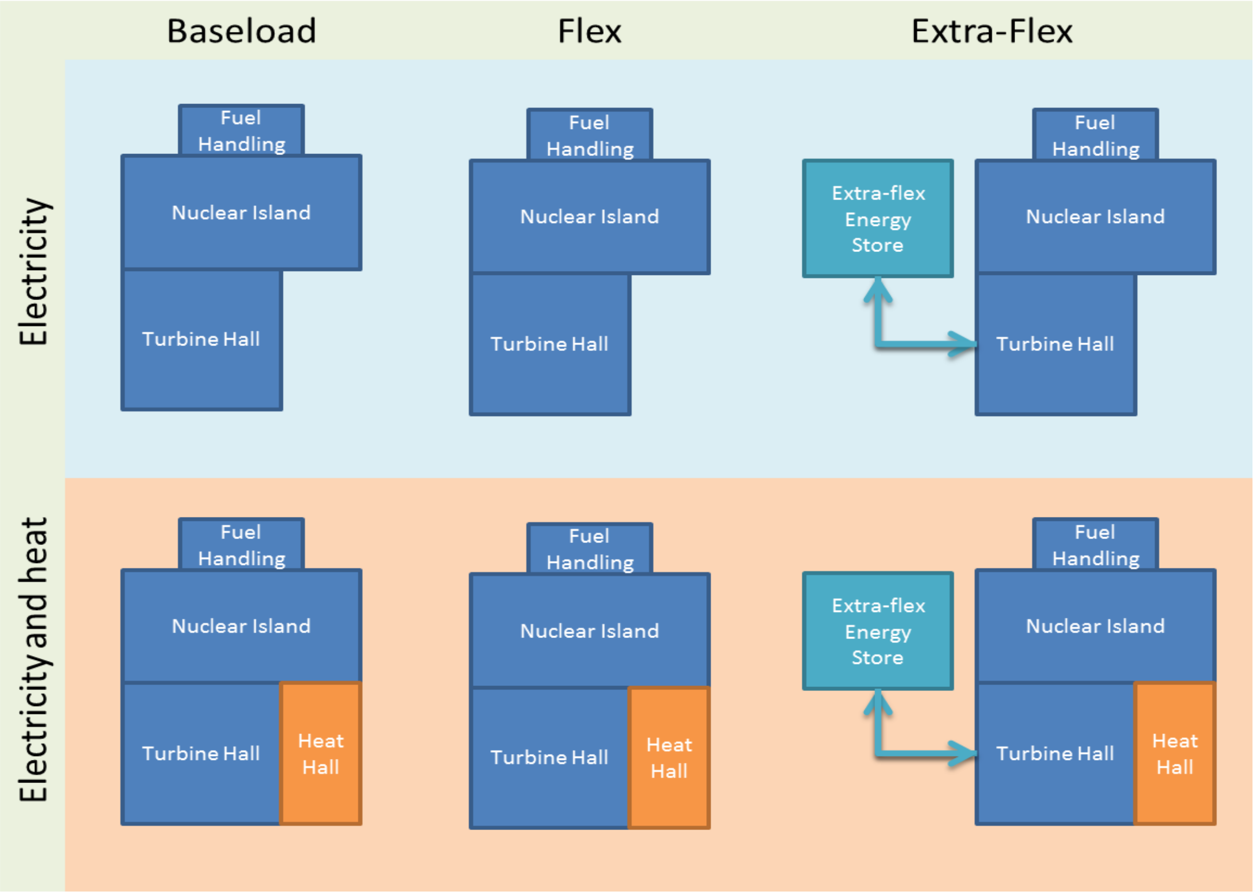
For SMR plants to produce heat as well as electricity the reactor will need to run at a near constant rate (maintaining a relatively stable core power) whilst throttling heat production up and down to meet demand. There are a variety of technical solutions that can be applied to steam system and turbine design in order to achieve this. However it appears that vendors have given little consideration to this requirement to date. In technical terms, throttling heat and electricity output independently of each other may involve designing the back-end of the secondary loop such that it can ‘swap’ between utilising a conventional ultimate heat-sink (UHS) and a DH network for steam condensation/cooling. A stable core-power also lends itself to the application of ‘Extra-flex’ storage devices that in turn drive a flexible secondary turbine. The interaction between two such systems (flexible heat and flexible power) will need to be investigated in more detail during early stage engineering concept design.

Balancing heat removal provided by the DH network and heat removal provided by the conventional heat sink will be a key operational challenge, and this challenge will be made more difficult if new sites with a relatively low abundance of cooling water are chosen for SMRs. In these circumstances, meeting cooling demand during hot, dry summers could result in additional operational constraints. This is common for nuclear plants situated on rivers in the rest of the world, but would be a novel constraint for commercial nuclear generation in the UK. This would be a significant challenge to the current UK regulatory regime that desires the availability of a UHS of a certain level at all times (based on an ‘As Low As Reasonably Practicable’ position). As a result, an engineered heat sink is likely to be required, for example a forced draft cooling tower. The ability to ‘switch-off’ individual (or multiple) SMR modules is potentially an additional solution in such a scenario. This is potentially compatible with the current scope of nuclear plant operational licenses but would result in a different dynamic to that seen in today’s (UK) nuclear industry.

3.8.2 Plant Layout

Assuming an SMR plant is able to provide a near continuous electrical output whilst throttling heat, modifying plant layout for different site contexts becomes relatively simple. Figure 3.11 shows the different SMR service offerings in schematic form, applying a module approach. The basic electricity only plant shown in the top-left of remains the same for each of the other plant configurations. Various capabilities can then be added in the form of modular ‘plug-in’ systems to provide heat or electricity. The ‘Heat-hall’ is an addition to the turbine hall that contains the various systems and pipes required to connect the intermediate heat exchange systems into the existing balance of plant and DH main. The Extra-flex facility is a standalone addition that allows energy to be charged and discharged as required. Note that the ‘flexible’ service offering refers to operating a standard SMR plant (one without Extra-flex facilities) in load-following mode.

Figure 3.11: Potential plant layout schematics for different SMR service offerings



Source: Rolls Royce

In terms of licensing, one possible approach would be for the design configuration in the bottom right of Figure 3.11 to be progressed through the Generic Design Assessment (GDA) process in the UK. The plant design would be such that the removal of the Extra-flex system and/or the removal of the Heat-hall system would not impact upon the integrity or design of the remaining basic nuclear plant configuration. The GDA process would need to involve a review of all configurations, such that the regulator could be satisfied that any plant configuration was operable in a justifiably safe way. There are challenges associated with such an approach and further work is required to determine the optimal way forward.

In summary, it is likely to be possible for a small number of standardised SMR modules and other plug-in systems to combine to produce different offerings depending on local site and national requirements.

3.8.3 Operations & Maintenance (O&M)

Current nuclear operations are optimised around large power plants with generally between one and three large reactors. Regulation is tailored to this situation, for example in the US there are specific quantitative limits for on-site staffing and security levels. Such an approach may prove inadequate and uneconomic for SMR technology, particularly for small reactor sizes with many reactor modules per plant, but also more generally for a ‘national fleet’ of SMRs. In the UK, appropriate safety management approaches must be demonstrated to the regulatory authorities to ensure that risks are reduced in accordance with the ‘ALARP’ principle.

SMRs are designed to exploit standardisation and economies of multiples. Even with the above variety of configurations and operating modes for SMR power plants, there will be new opportunities for more standardised approaches to O&M. For example, training, procedures and equipment that are required to service an SMR fleet could be standardised and applied by a small centralised team that visits each plant as required. This would be a step-change from current practice in the nuclear industry, where most plants have significant on-site stand-alone maintenance capability.

3.9 UK national nuclear infrastructure

The UK currently has a network of national nuclear infrastructure to support its existing fleet of large nuclear reactors, covering all major stages of the fuel cycle including fuel manufacture and logistics, spent fuel storage, waste disposal and decommissioning. Whilst work is already underway to assess the implications of a new fleet of large reactors on this infrastructure, the deployment of a fleet of SMR power plants would further add to these national nuclear infrastructure requirements.

We are aware of no existing work that has specifically considered the infrastructure implications of wide scale fleet deployment of SMRs in the UK (or any other country). However infrastructure costs associated with the wider nuclear lifecycle are potentially substantial; this is particularly the case with ‘back-end’ activities relating to waste management and disposal. These implications will be relevant to any decisions related to SMR technology choice.

To better understand the potential range and extent of additional infrastructure requirements, we considered the aggregate impact of SMR fleet deployment on the UK’s national nuclear infrastructure at each stage of a generic SMR lifecycle, from design to decommissioning. Our focus was infrastructure relating to critical back-end activities such as spent fuel management and waste disposal: despite the costs of these activities, they are often not fully considered when new reactor concepts are being proposed.

A conclusion from this review was that the overall cost of infrastructure upgrades is likely to be lower if SMR deployment is based on more conventional LWR technologies that are compatible with existing infrastructure, rather than more novel SMR technologies. In addition, existing UK policy and industrial strategy do not account for technologies that are not legacy UK fleet or new build of LWR systems; moving away from such systems would be challenging from a ‘back-end’ perspective in the immediate 15-20 year timeframe. In addition, SMRs that require changes to Government policy on waste management to accommodate alternative fuel cycles and waste-forms may face additional delays to deployment whilst such policy matters are concluded. The capability and skills to service novel fuel cycles also need to be considered.

Regardless of type of SMR technology, additional capacity for all levels of nuclear waste handling and disposal is likely to be required in the event of widespread SMR deployment in the UK. In particular:

- Fuel enrichment and fuel handling – increased demand for fuel would require an increase in capacity in these areas. Providing the increased demand is for standardised LWR type fuel we would expect the market to meet this need incrementally, reducing investment risk.
- New centralised dry-storage facilities for spent nuclear fuel may be required if SMR sites do not have this facility in situ. Overall, we do not anticipate the cost associated with this to be significant in the context of overall nuclear infrastructure requirements.
- More space may be required in waste handling and disposal facilities than is currently being planned for. However we note that plans set out by the UK Nuclear Decommissioning Authority (NDA) already anticipate additional large plant nuclear new build, and plans for a UK Geological Disposal Facility (GDF) include significant additional capacity above that required for large new build nuclear plants.

Ultimately, the implications for the UK’s national nuclear infrastructure of SMR fleet deployment will depend on both the type of SMR technology and the capacity deployed. Understanding the compatibility between existing infrastructure and proposed SMR technologies will be a key part of understanding the feasibility of SMR power plant fleet deployment in the UK. We recommend further work into this area in the future.

3.10 Technical requirements specification

Based on the above analyses - supplemented by an expert stakeholder workshop - we developed a list of 98 technical requirements that SMR power plants will need to meet in order to be of value to the UK's future energy system. These technical requirements are intended to draw out, at a high level, fundamental areas where SMR power plant technology is likely to differ from existing large nuclear plant offerings.

The requirements are divided into the following sub-sets:

- Constructability – requirements influencing the construction and build lifecycle phase;
- Operation and Maintenance – requirements influencing ongoing operations at the plant;
- Performance – overarching performance requirements that the plant must achieve;
- Safety – requirements concerned with the safe operation of the whole plant facility;
- Siting – requirements related to the location and geography of the plant site.

The requirements were then further categorised by applying the 'shall/should/may' methodology used in the European Utility Requirements document for LWR nuclear power plants – defined in Table 3.3.

Table 3.3: 'Shall, Should, May' definitions

Requirement type	Explanation
Shall	Any design that does not fulfil these requirements will be non-compliant.
Should	Other solutions can be accepted, but the Plant Designer will have to demonstrate that they are equivalent or better.
May	Acceptable solutions without preference from the customer.

Source: European Utility Requirements document

The full requirements list is provided in the Full Report. A shortened and simplified list is provided in Table 3.4.

Table 3.4: Selected SMR technical requirements

Req. Type	Req. Category	Req. No.	Requirement	Metric
Shall	Constructability	CO02	The SMR power plant shall be designed on a modular basis with the maximum possible amount of factory based construction and assembly.	% of construction modularised.
Shall	Constructability	CO05	The SMR power plant modules shall be designed to be transportable from a construction facility to site.	640 ton UK road limit (5.5m height, 6.1m wide, 45m long), UK train dimensional limits (large ISO container).
Shall	Constructability	CO26	The SMR project shall be planned and constructed in 'whole' plant quanta in line with UK planning legislation that requires an entire project to be completed in a discrete scope of work.[5]	Each SMR plant constructed as a single discrete project with individual SMR plants achieving individual planning permission.
Shall	O&M	OM01	The SMR power plant shall be designed to require the minimum number of on-site staff at any given operational time.	Number of on-site staff to maintain safe operation.

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[5] A single programme of works would not preclude an incremental approach to building capacity.

Req. Type	Req. Category	Req. No.	Requirement	Metric
Shall	O&M	OM02	The SMR power plant shall be designed to ensure safe installation of additional power modules whilst existing power modules are under operation.	SMR power plant on-line during additional module installation capability.
Shall	O&M	OM03	The SMR power plant shall be designed to ensure safe refuelling of power modules whilst other power modules are under operation.	Full operation of other power modules whilst one is being refuelled.
Shall	O&M	OM04	Where required, the SMR power plant shall be designed with a control room capable of safely managing the operation of multiple SMR power modules.	SMR power modules per control room successfully licensed.
Should	Performance	PE01	The SMR power plant should be designed to achieve flexible electricity and/or heat output to match diurnal load requirements.	0.5% per minute power ramp rate as minimum (30-100% power output).
Shall	Performance	PE02	The SMR power plant shall be designed to produce electricity, district heat or industrial process heat as the client requires.	Modularised secondary circuit design to allow for multiple operating design modes.
Should	Performance	PE03	The SMR power plant should be designed to provide electricity whilst achieving operability in one of the following areas (district heating, desalination, industrial process heat).	Modularised secondary circuit design to allow for multiple operating design modes.
May	Performance	PE06	The designer may choose to use natural environmental features to enhance the aesthetic appeal of the SMR power plant.	Maximum aesthetic design using natural features is desirable.
Should	Performance	PE07	The SMR power plant should have a total electricity output of between 100MWe and 1000MWe (a core thermal output of~300-3000MWth).*	Total SMR power plant electricity output.
Shall	Performance	PE08	The plant shall consist of a number of SMR power modules, (e.g. between 1 and 30).	E.g. 1 -30 SMR power modules to provide ~100-1000MWe of power.
May	Performance	PE09	The SMR power plant may consist of multiple power modules to fulfil requirements PE07, PE08 and CO26.	Balance between power module size and SMR power plant size should be struck based on whole lifetime SMR plant cost projection.
Shall	Safety	SA06	The SMR power plant shall be designed to be safe in the event of normal or abnormal operation irrespective of operator presence or intervention.	No operator intervention required during design basis accident.

Source: Rolls Royce

* The thermal power ratings shown in PE07 relate to core power and not saleable heat output – this is the reason for the difference with the thermal heat output used in other parts of the ANT project for CHP power plants.

4 SMR business case workstream

The business case workstream focussed primarily on what SMRs will need to achieve from an economic perspective to be of value to the UK's future energy system. The main component was the economic appraisal, which served two functions. First, and most important for the ANT project, it estimated broad 'target costs' for SMRs – i.e. the *maximum* amount an SMR power plant could cost whilst still delivering commercial rates of return to investors under future market conditions. Thus, 'target costs' should be understood as the upper cost limit for viable SMR projects in the UK. Second, the appraisal developed an indicative scenario for actual SMR costs by making high-level estimates of future CAPEX and OPEX for LWR type SMRs and how these might reduce over time. This scenario was compared with target costs to provide an initial view on the relative viability of different SMR service offerings.

We stress here that there is a great deal of uncertainty about the future costs of SMRs and this element of our economic appraisal should be treated as indicative only. Given the pre-commercial status of the technology, the lack of current real-world cost data, and the fact it was not part of the ANT project to undertake any kind of detailed engineering cost assessment of SMR designs, we caution against any over-interpretation of our results. We recognise that other cost scenarios are possible.

The business case workstream also included tasks to identify some of the main risks and opportunities for SMR deployment in the UK, and explore the high-level issues and options Government and Industry would need to consider in deploying and financing a fleet of UK SMRs.

Each of the main business case workstream tasks is outlined in this section, with a focus on presenting the principle outputs and conclusions. A summary of the key findings is also presented upfront.

4.1 Summary of key findings

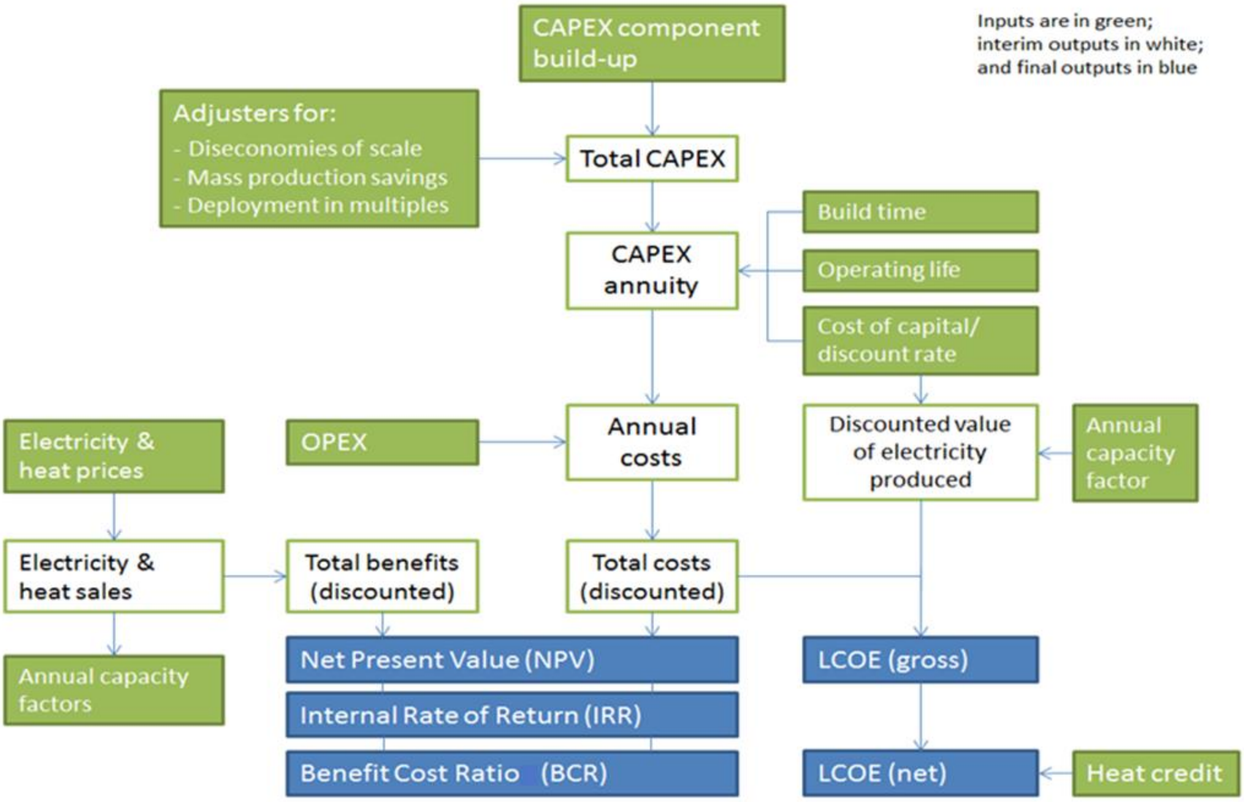
- We estimate the future unit prices available to SMR plants for low-carbon electricity to be ~£80/MWhe for baseload power and ~£163/MWhe for peaking power.
- There is significant uncertainty about the future price of low-carbon heat. Our base case estimate of the price available to CHP SMR plants is ~£65/MWhth. Note that these prices reflect what we think could be available to generators. They are not retail prices and they do not include network costs (transmission and distribution in the case of electricity or DH network infrastructure in the case of heat).
- The target CAPEX for electricity-only SMR plants providing baseload power is <£3,600/kWe. This broadly equates to a target LCOE of <£80/MWhe.
- Our own indicative cost scenario (which is speculative at this stage) suggests electricity-only SMRs could have a higher first factory CAPEX than the target cost. This is reflected in an indicative project IRR of just under 8%, which is lower than our assumed 10% hurdle rate. By second factory stage, if costs fall further, our scenario would broadly reach parity with target costs.
- The target CAPEX for CHP SMR plants providing baseload power and operating at a 40% heat ACF is <£6,500/kWe. This reduces to <£5,000/kWe in downside scenarios with more pessimistic assumptions. This target includes the cost of the heat mains from the plant to the DH network, but excludes all other DH network infrastructure costs.
- Our indicative costs scenario suggests CHP SMR plant CAPEX could be significantly lower than the target cost. This is reflected in an indicative project IRR of ~13% under our base case assumptions, suggesting CHP SMRs would be attractive to investors. Whilst this conclusion should be treated with caution, our analysis suggests CHP plants could be viable even in moderate downside scenarios.

- The target incremental CAPEX for Extra-flex SMR plants is estimated at £350-£750/kWe, depending on the size of the capacity boost. This target reflects the maximum *additional* CAPEX that could be justified for providing the storage system and extra generation equipment, based on the additional revenues available. Target costs would vary further with different peaking price and storage capacity assumptions.
- Our indicative cost scenario (based broadly on molten salt storage costs) suggests that the incremental CAPEX for Extra-flex facilities would exceed the target costs. This suggests that in order to be viable new storage technologies capable of fulfilling the Extra-flex function will need to have lower costs than are achieved by currently available commercial storage solutions. However both the target costs and cost scenario for Extra-flex have high levels of uncertainty and further work is recommended here.
- Deploying a fleet of UK SMRs in time to help meet 2050 decarbonisation targets is likely to require Government leadership and active intervention over a period of decades. Whilst there will be options over the extent of this intervention, Government will need to provide funding, take risks, create markets and ensure supportive regulatory and planning frameworks are in place.
- To ensure enough certainty is in place for investors in SMR plants, Government will need to ensure reliable long-term offtake arrangements are in place. For electricity this could be in the form of CfD contracts awarded for multi-gigawatt tranches of SMR capacity. For heat this could come via a contractually guaranteed minimum heat price and/or capacity payment for plants energising DH networks.

4.2 Economic model

To achieve the objectives of the Economic appraisal, we developed a discounted cash-flow (DCF) model that provides the Levelised Cost of Energy (LCOE), Internal Rate of Return (IRR) and Net Present Value (NPV) for the different SMR offerings based on a range of input assumptions. The model focusses on the economics of future SMR power plants from a developer / investor perspective, in line with ANT project objectives. It does not provide an energy system wide economic appraisal of SMR technology, nor does it consider pre-FOAK technology development and design licensing activities.

Figure 4.1: Flow diagram showing the key inputs and outputs of the SRM power plant economic model



Source: Mott MacDonald

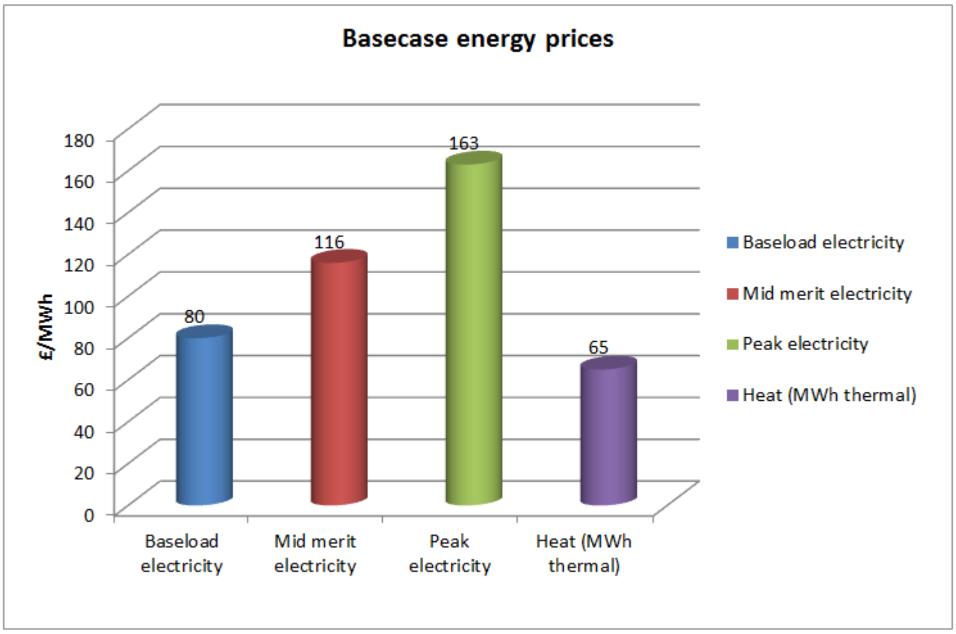
The model covers all the major costs we would expect to be met by an SMR project company (excluding land, since these costs can vary considerably depending on site location and type, and taxes). It is assumed to include infrastructure costs specific to SMRs such as supply chain development (via components of the EPC price), and the costs of fuel-cycle related infrastructure (via a charge included in the OPEX costs). However it excludes wider infrastructure costs that would be needed even without SMRs, such as the roll-out of city-scale DH network infrastructure. It was an explicit assumption of the ANT project that DH networks will be needed regardless of the technologies that feed them.

4.3 Prices and revenues

The future revenues available to SMRs for the services they provide will be a key driver of their economic viability. In our DCF model, revenues are a calculated by multiplying the amount of energy generated each year (itself a function of rated capacity and ACF) by our projected unit prices for each MWh of heat and electricity. In estimating these unit prices we focussed on the medium to long term when SMR power plants are more likely to be deployed, rather than the near future. Our analysis considered what the likely benchmarks will be by drawing on competing zero or low carbon options, or where appropriate conventional technologies with an uplift to reflect the future carbon price.

Figure 4.2 shows our base case unit prices for low-carbon baseload, mid-merit and peaking electricity, and low-carbon heat in the 2030s. These prices reflect what we think could be available to generators. They are not retail prices and do not include network costs.

Figure 4.2: Projected future unit prices for SMR electricity and heat (base case)



Source: Mott MacDonald

For electricity, the £80/MWhe price was based on expected future strike prices for other low carbon technologies awarded via auction under the UK Government's Contracts for Difference (CfD) regime. Strike prices were assumed to be equivalent to the LCOE of the most competitive comparator technology. For baseload electricity these were wind, large nuclear and gas CCS. For peaking electricity they were gas CCS, biomass, and gas turbines or engines (or fuel cells) running on clean fuel.

For heat the price of £65/MWhth was assumed to be set by the levelised cost of heat from a gas fired boiler paying a carbon price of £75/tonne. Gas CCS and biomass yielded higher heat price comparators, although we also consider it possible that in the future CHP plants competing for low-carbon heat offtake contracts could push the price of heat below our base case. So whilst £65/MWhth represents a significant increase on today's price of heat, we stress there is therefore uncertainty in this regard. In our economic appraisal we tested sensitivities of £45/MWhth and £85/MWhth.

4.4 Target costs

We used the economic model to explore the target CAPEX for an electricity-only SMR plant, a CHP SMR plant, and an electricity-only Extra-flex plant, all at NOAK stage. This involved applying our base case assumptions on revenue, OPEX, ACF and plant build/operation and then ‘forcing’ the model to determine the CAPEX threshold that would deliver commercial rates of returns for investors (defined as a 10% IRR).

It is important to stress again that ‘target costs’ refer to the *upper* threshold project developers should be looking to achieve. The ‘target’ is really to be *at or below* these levels. It should also be noted that if OPEX costs were lower than we have assumed, or plant performance better, then target CAPEX would reduce below levels stated here. Table 4.1 summarises the target costs under our base case assumptions.

Table 4.1: Summary of target costs under base case assumptions

SMR offering	Target costs for NOAK plants	Key assumptions
Electricity-only SMR	Specific overnight CAPEX: <£3,600/kWe LCOE: ≤£80/MWhe (note: target CAPEX increases to ~£3,900/kWe if more optimistic ACF assumptions are used)	85% electricity ACF £80/MWhe CfD price ~£165/kWe per year OPEX
CHP SMR (providing baseload electricity and load-following heat)	Specific overnight CAPEX: <£6,500/kWe (note: this reduces to <£5,000/kWe if more pessimistic assumptions are used) Excludes cost of DH network infrastructure (except heat mains between plant and network)	75% electricity ACF (de-rated) 40% heat ACF 1.8 heat:power ratio £80/MWhe CfD price £65/MWhth heat price ~£170/kWe per year OPEX
Extra-flex SMR	Incremental specific CAPEX: <£415/kWe (~11% uplift on base plant target CAPEX) (note: this changes significantly with different capacity boosts)	20% boost capacity 85% electricity ACF £80/MWhe price for baseload power £163/MWhe price for peaking power ~£170/kWe per year OPEX

Source: Mott MacDonald

For CHP SMRs, the target CAPEX is significantly higher than for electricity-only SMRs. This is because the additional heat revenues allow more room for increased costs whilst still remaining attractive to investors. We also tested the impact of different heat prices and ACFs on CHP target costs. The results of this are shown in Figure 4.6, but as expected, when heat ACFs and prices reduce the target CAPEX also reduces. This is because less revenue is available, so costs also need to come down in order to deliver a 10% IRR.

Extra-flex SMR plants will be able to access additional revenue due to providing extra surge power. The extent of this additional revenue will depend on the boost capacity, duration of the surge, the average price levels achieved at peak and impact on out-of-peak sales price. These additional revenues will need to be offset against the additional costs of providing the storage system and extra power generation equipment. Thus our target costs reflect the maximum additional CAPEX that could be justified for these extra facilities. It does not necessarily mean the underlying power plant will achieve an IRR of 10% - that will depend on the economics of the underlying power plant. Here we explored how the target incremental CAPEX varies with the size of capacity boost, assuming the capacity of the energy storage device is held constant. The results are shown in Figure 4.7. The target CAPEX range for Extra-flex is estimated to be between £350-£750/kWe, with a 50% boost enabling the greatest additional spend.

4.5 Indicative cost scenario

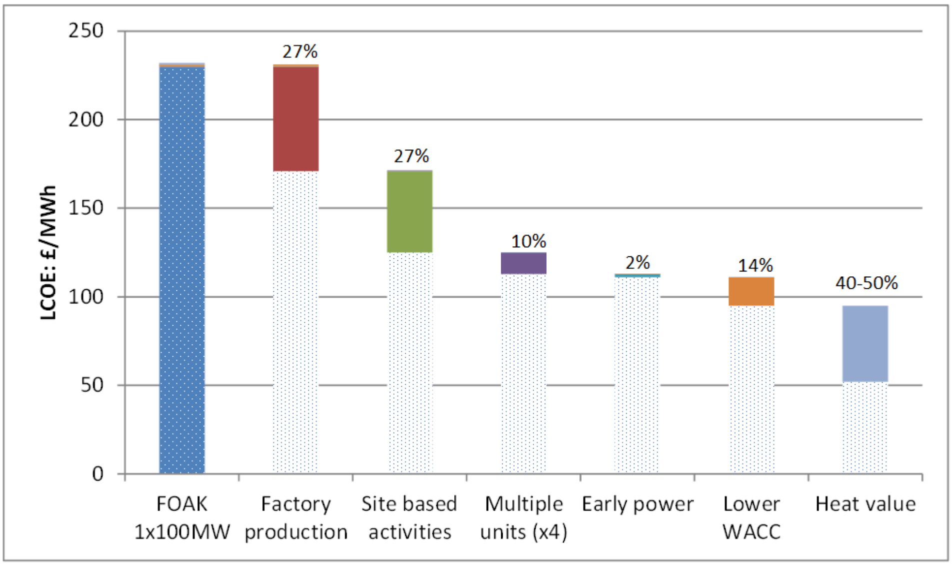
Separate from the task of projecting target costs, we also developed an indicative scenario for actual SMR costs. The main focus here was CAPEX for Light Water Reactor (LWR) type SMRs, and to estimate this we developed a methodology that started with large reactor FOAK costs, made adjustments for economies of scale to arrive at SMR FOAK costs, then applied a series of cost reduction drivers based on factory production and economies of multiples to arrive at NOAK costs. This approach allowed us to illustrate the potential drivers of cost reductions as SMR technology matures, and to explore the relative viability of different service offerings.

In this context, we define an SMR FOAK plant as the first custom-built commercial demonstration plant that would need to operate for a full fuel cycle before an investment decision to proceed with more widespread deployment. Once the factory facilities are built and a regular production drumbeat established the majority of the cost savings might be expected to come. We consider SMRs built at this stage to be NOAK, and our cost scenario is intended to represent the middle cost of the 1st factory, after about 5GWe deployment. A second factory or major upgrade would lower costs further, so conceptually there would be a NOAK 2nd factory cost level – we speculate that this could be 10-20% lower than 1st factory level.

4.5.1 Cost reduction drivers

For our cost scenario, Figure 4.3 shows the drivers of reductions in LCOE from FOAK to NOAK, and as heat sales are realised. The values above the columns show the % reduction versus the preceding total.

Figure 4.3: Impact of main cost reduction drivers in our SMR cost scenario



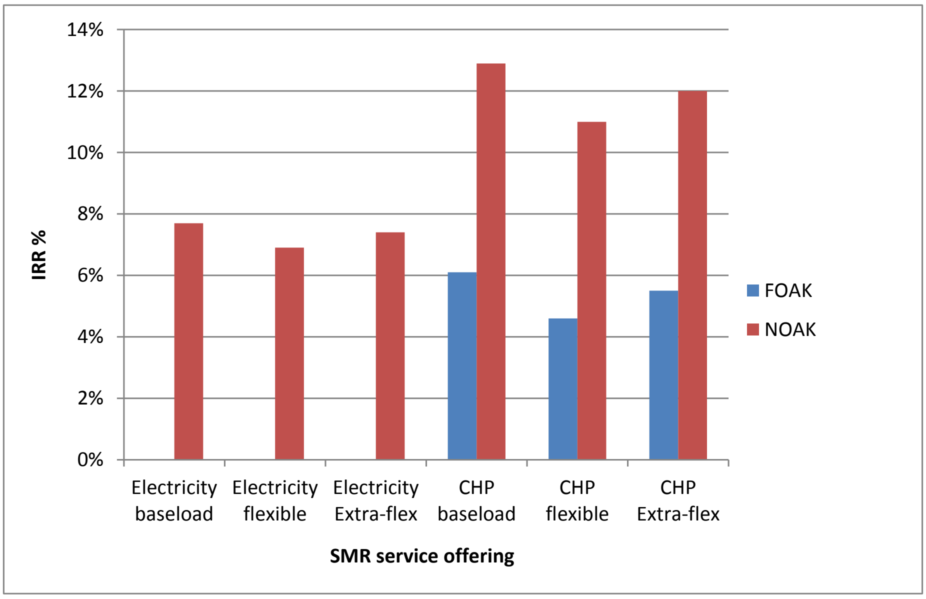
Source: Mott MacDonald

The main drivers of cost reduction for an electricity-only SMR are factory based production techniques (arising from modular production in a highly controlled environment) and site based activities (including both onsite modular activities and traditional activities subject to learning-by-doing). The next most significant driver is a reduced cost of capital. In addition, it is clear that for CHP SMR plants heat sales would provide a huge value driver that would offset a substantial element of costs. Under our CHP plant base case, heat sales account for 45% of the benefits stream versus 55% for electricity sales.

4.5.2 Relative viabilities of different SMR offerings

To compare the relative viabilities of different SMR service offerings we used IRR as our metric rather than LCOE, because the offerings produce outputs of different value. The results for our cost scenario are shown in Figure 4.4.[6]

Figure 4.4: Projected IRRs for SMR power plants under different service offerings



Source: Mott MacDonald

The major difference is between CHP plants and electricity-only plants. CHP plants are in a strong economic position with IRRs above 10% (with a £65/MWhth heat price), whilst electricity-only plants have IRRs under the 10% hurdle rate at 1st factory NOAK stage (based on a £80/MWhe CfD price and 85% ACF). It is important to note here that changes to our base case assumptions would change these IRRs. For example if SMR plant performance resulted in a 90% electricity ACF then the IRR for the baseload electricity SMR would increase from 7.7% to 8.4%, closer to the hurdle rate.

The ‘flexible’ offerings (i.e. standard configuration SMR plants that don’t have Extra-flex facilities but operate in load-following mode) are projected to have a lower IRR than baseload offerings. This is because the additional revenue benefits from focussing on higher price periods are more than offset by reduced operation and lower fixed cost dilution.

The Extra-flex offerings do not suffer from the same fixed cost dilution because they continue to generate virtually the same total energy as the baseload SMRs. However the CAPEX premium we have assumed in this scenario (14% versus the baseload offerings) more than offsets the additional value from selling more profiled power, pushing down IRRs.

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[6] Electricity-only FOAK IRRs are all below zero and are not shown here.

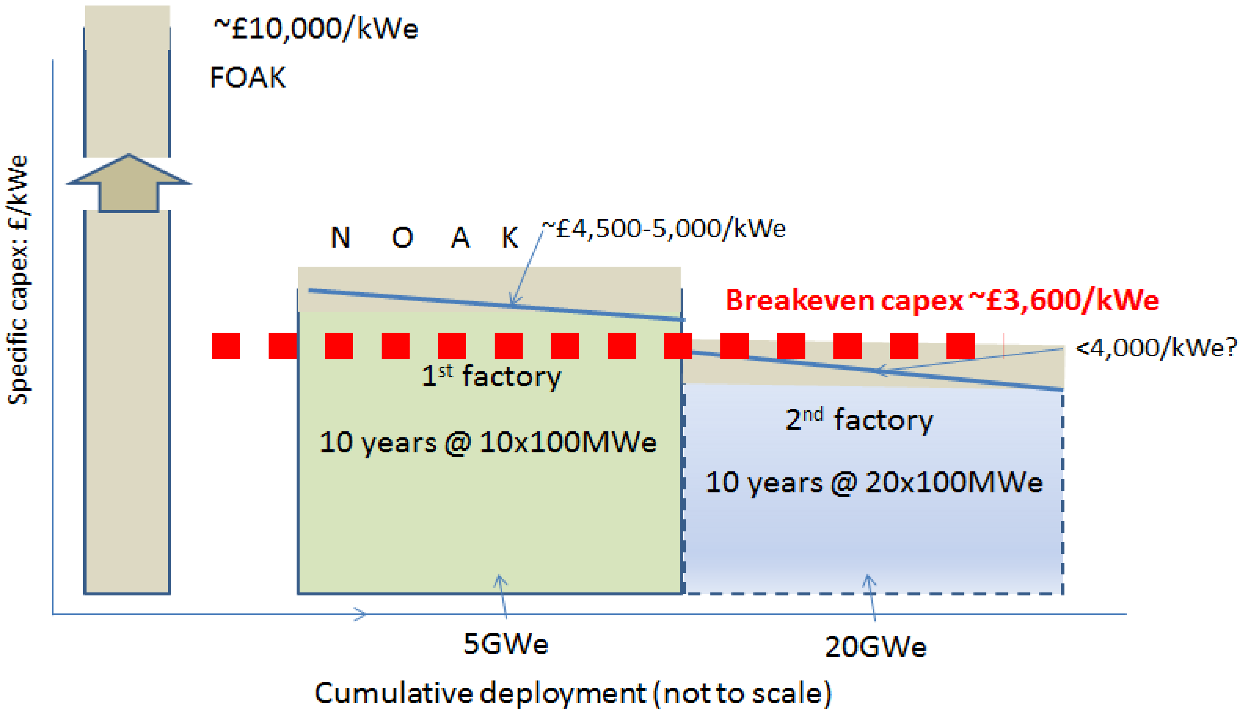
4.6 Cost scenario vs target costs

The final strand of the economic appraisal was to compare the target costs with the indicative cost scenario to provide further insight into the relative viability of different SMR service offerings.

4.6.1 Electricity-only SMRs

Figure 4.5 shows that the projected CAPEX for electricity-only SMRs under our cost scenario is ~20% higher (at first factory NOAK stage) than the target CAPEX. This suggests electricity-only SMR plants will need to deliver greater cost reductions than we have assumed in order to be of commercial interest to investors. The gap could also be narrowed if plant performance is better than our base case assumption (for example, a 90% rather than 85% electricity ACF). By second factory stage, if costs fall a further 20%, our cost scenario could reach parity with the target cost.

Figure 4.5: Target CAPEX vs indicative cost scenario for a baseload electricity-only SMR plant



Source: Mott MacDonald

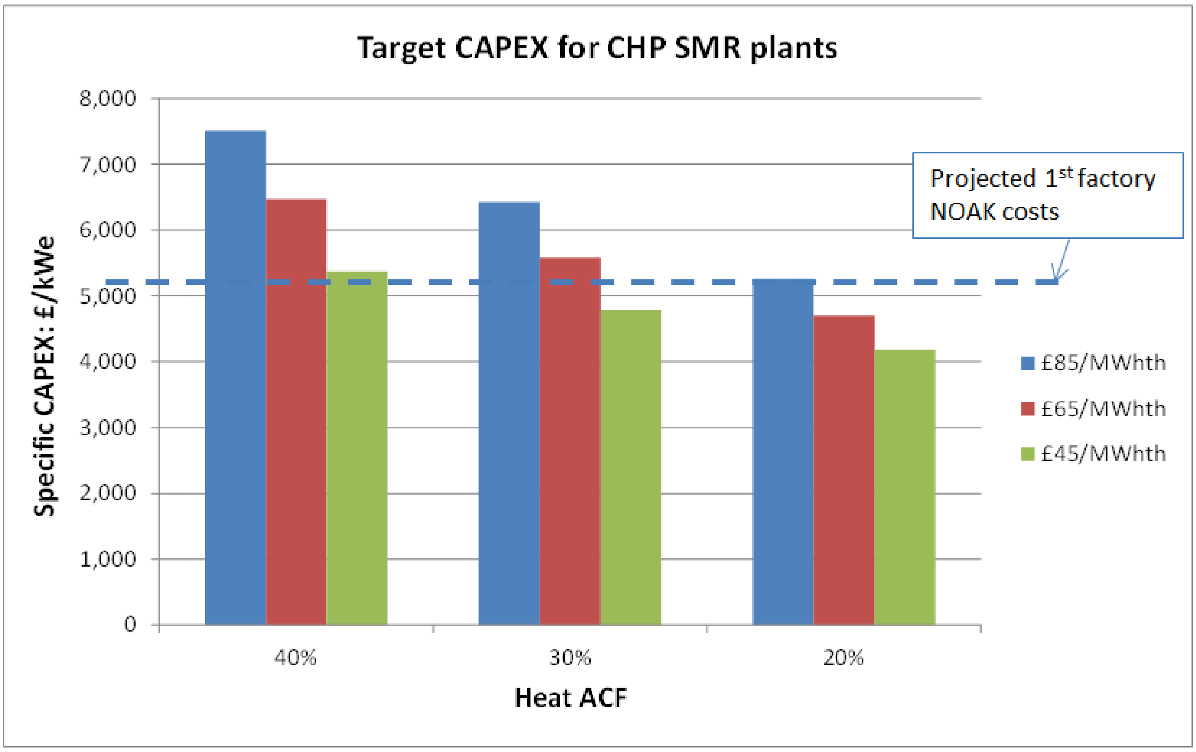
4.6.2 CHP SMRs

Figure 4.6 shows that the projected CAPEX for CHP SMRs under our cost scenario is significantly lower than the target CAPEX (under base case assumptions of a 40% heat ACF and £65/MWhth heat price). This suggests that CHP SMRs will be viable and attractive to investors as long as DH network infrastructure and heat offtake arrangements are in place.

It is important to treat this conclusion with caution however. It is possible that only lower heat ACFs will be achieved and/or the heat price will be substantially lower than we assume in our base case, perhaps because competition between CHP generators pushes heat prices down. We have not undertaken any comparative analysis between SMR CHP plants and other potential low carbon CHP providers such as gas CCS and biomass, both of which could also benefit from the economics of co-generation.

Nonetheless, even moderate our downside cost scenarios still have our projected CAPEX either below or only just above the amended target costs, suggesting that CHP SMR plants could be economically viable even in these more unfavourable circumstances.

Figure 4.6: Target CAPEX vs indicative cost scenario for a baseload CHP SMR plant



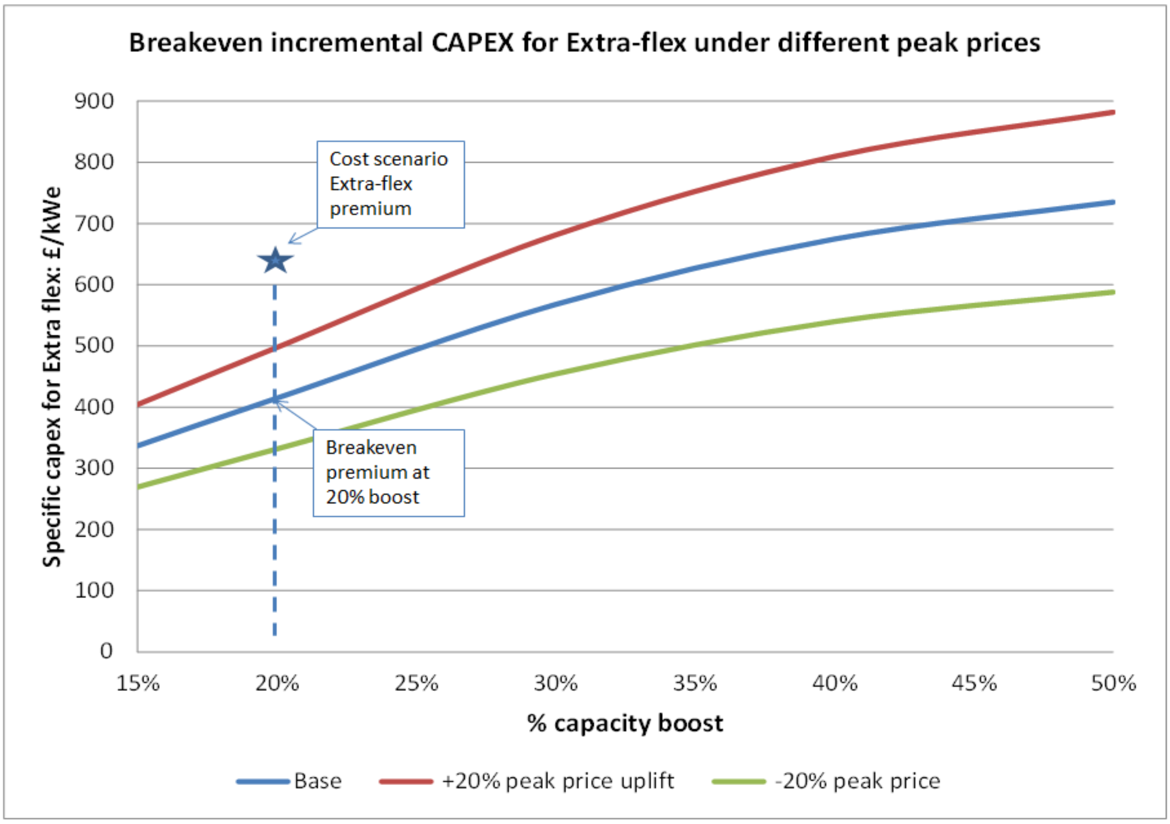
Source: Mott MacDonald

4.6.3 Extra-flex SMRs

Figure 4.7 shows the incremental target CAPEX for an Extra-flex SMR at a range of different boost capacities (assuming the capacity of the storage facility is kept constant). The target CAPEX is between £350-£750/kWe, with the 50% boost enabling the greatest additional CAPEX spend. These target cost figures must cover the additional cost of the power generation equipment plus the energy storage system. They have been calculated based on a 10% return and a 20 year life for the Extra-flex facility. Adjusting peak prices upwards and downwards by 20% shifts the target CAPEX up/down by about £80-180/kWe.

For our base case 20% boost scenario, the target CAPEX is ~£415/kWe – a premium of ~11% on the base plant. This compares to a projected premium of ~14% (~£650/kWe) in our cost scenario, broadly based on the cost of molten salt storage. This suggests that in order to be viable new storage technologies capable of fulfilling the Extra-flex function will need to have lower costs than are achieved by currently available commercial storage solutions.

Figure 4.7: Target incremental CAPEX vs indicative cost scenario for Extra-flex facilities



Source: Mott MacDonald

4.7 Risks and opportunities

We have identified a number of risks and opportunities relating to the deployment of SMRs in the UK, based on the ANT project analyses. The most important of these are summarised in Tables 4.2 and 4.3. The probability and impact categories are indicative terms only, and represent a pre-mitigation view.

Table 4.2: Summary risk register

Title	Description	Consequence	Prob.	Impact	Mitigations
Technology					
Transport-ability	Modules and associated parts too large to transport to site without major alterations to the UK's transport network.	▪ Infrastructure upgrades at significant additional cost. ▪ Otherwise suitable sites excluded. ▪ Less off-site manufacture, impacting on cost.	Medium-High	Medium-High	▪ Specified in Technical Requirements as a 'should'. ▪ SMR designs could be further modularised (sectioned). ▪ Special designed vehicles to provide more clearance under bridges
Technology Development					
Delays bringing technology to market	Delays in technology development or in creating a market framework push back SMR deployment.	▪ Other technologies could already have met energy system requirements. ▪ Lower deployment could threaten factory production techniques and cost reductions.	Medium	High	▪ A co-ordinated funded public-private SMR development and commercialisation programme – at both the UK level and internationally.
Stakeholder engagement					
Public perception	Stakeholders perceive little difference to large reactors. Local communities less in favour due to fewer construction jobs.	▪ Objection to deployment at specific sites leads to delayed and/or reduced overall deployment, with knock-on effects for cost reductions.	Medium-High	High	▪ Engagement between national and local levels. ▪ Awareness campaign. ▪ Early deployment could show beneficial attributes of SMRs. ▪ Local benefit schemes. ▪ Communities nominate sites as per Geological Disposal Facility.
Political					
Insufficient Government backing	Lack of consistent support (e.g. with regulation) would undermine development of SMR supply chain or projects.	▪ Lack of private sector confidence to make critical upfront CAPEX investments. ▪ Higher imports and less domestic economic benefits.	Medium	High	▪ Government to provide financial and other resources to develop a national SMR deployment programme. ▪ Cross party support for SMR deployment and regulatory framework.
Cost/Economic					
Factory production fails to reduce costs.	Factory production facilities unable to deliver projected efficiencies and cost reductions.	▪ Higher SMR capital costs.	Medium	High	▪ Factory designed to allow refitting/retooling with relative ease and at low cost.
Market					
Insufficient or uncertain demand	'Drumbeat' too low to support factory mass production techniques, due to (for example): ▪ Slow roll-out of heat networks; ▪ Competition from other technologies	▪ Without commercially viable factory production and the associated learning and cost reductions, a key underpinning of the economic case for SMRs would be removed.	Medium	High	▪ Implement measures to support the roll-out of DH networks. ▪ Consider setting national SMR deployment targets. ▪ Long-term offtake contracts (heat and electricity). ▪ Access international markets.

Source: Mott MacDonald

Table 4.3: Summary Opportunities Register

Title	Description	Consequence	Prob.	Impact	Facilitation measures
Technology					
Production in controlled (factory) environment	Offsite production using advanced methods, with the potential for factory build, testing and commissioning.	▪ Mass production techniques have delivered cost reductions in a number of industries. ▪ Reduction in on-site construction and delays. ▪ May depend on the size of SMR module.	High	High	▪ Will require strong demand for SMRs (in UK and/or globally). ▪ Advanced manufacturing methods tailored to SMRs. ▪ Prioritise SMR module sizes compatible with factory handling, processing and transportation.
Technology Development					
International collaboration	UK could proactively engage with overseas partners to co-invest in SMR technology.	▪ Reduced risk and cost compared to 'going it alone'. ▪ More productive context for innovation & cost reduction.	Medium	Medium-High	Initiate/engage in international collaborative programme.
Site					
Increase in suitable UK nuclear sites	Small plant with lower water requirements than large reactors means more potential sites, including those next to inland water sources.	▪ Potential for greater overall UK nuclear capacity beyond large reactor sites. ▪ Sites closer to demand are more suited to provision of low-carbon heat as well as power.	Medium	Medium-High	Non exhaustive work undertaken by the PPSS has identified locations that could host 60GWe+ SMR capacity, although the plant capacity delivered on these identified sites would ultimately be lower due to attrition as further phases of assessment are undertaken.
Economic					
Low carbon heat	Future value of low carbon heat is likely to be high (£65/MWhe is our central estimate)	SMRs providing heat and power will be in a strong economic position, and able to cope with increased costs.	High	High	▪ Heat provision capability is covered in the Technical Requirements. ▪ Widespread roll out of city-scale DH networks.
Market					
Create robust SMR market	Government backed ambition to roll out SMRs would deliver confidence in a forward market.	Provide the certainty required for technology developers and investors to invest in the technology, reduce costs and bring SMRs to market.	Medium	High	▪ Long term SMR target. ▪ Long-term offtake contracts for electricity and heat.

Source: Mott MacDonald

4.8 Fleet deployment, operations and financing

Work carried out for the ANT project suggests that if SMRs can meet the functional and economic requirements outlined here then they have the potential to play a significant role in the UK's future energy system. On the basis of this conclusion, our work culminated in an exploration of the options Government and Industry will have in relation to SMR development and deployment in the UK. This was informed by a series of workshops and interviews with relevant stakeholders and resulted in a high-level 'think-piece' that is intended to inform discussion and aid a better understanding of the potential range of activity required.

In summary, deploying a fleet of UK SMRs in time to help meet 2050 decarbonisation targets is likely require Government leadership and active intervention over a period of decades. Taking one or more SMR designs through to commercial readiness and widespread deployment will not happen without relatively large capital investments and a high-degree of confidence in a long-term market for SMRs. The Government will need to provide funding, take risks, create markets and ensure supportive regulatory and planning frameworks are in place.

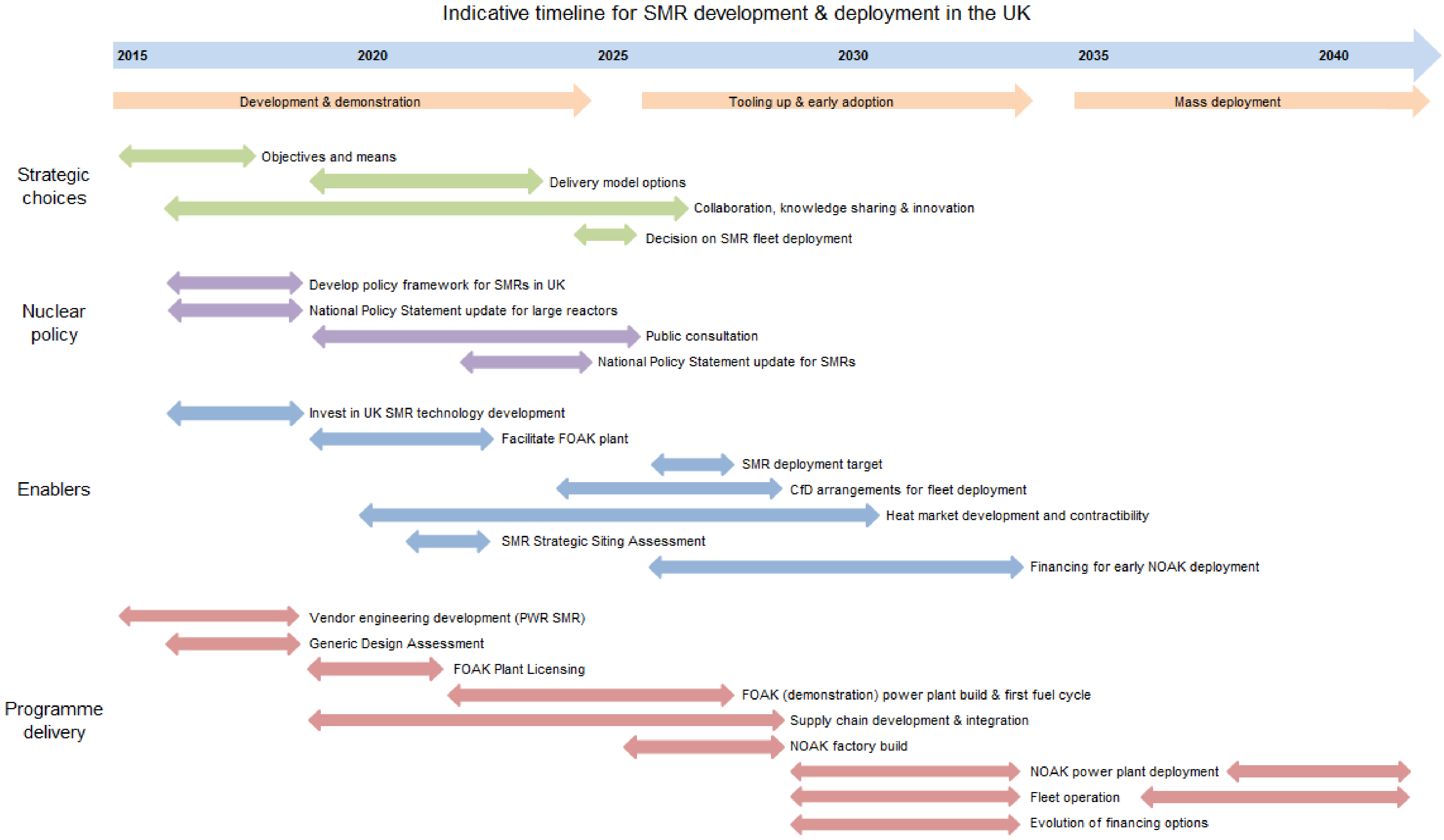
A central issue will be the model of Government intervention and the willingness to 'pick winners'. A hands-on approach could see Government initially taking an equity stake in one or more SMR technologies and later joining with other partners to create a single state-backed utility. This would give Government more control to drive deployment and secure UK economic benefits, but could risk locking-in an ultimately unsuccessful SMR design. A more arms-length approach could see the creation of a framework for private sector entities with different SMR designs competing for support at key stages of the development process. This could see benefits from competition but would also leave Government with little control or ability to drive the deployment of a UK SMR whist still requiring it to underwrite technology and project risks.

Moving from demonstration to commercial deployment will be a particular challenge for SMRs. Building a factory, scaling up the supply chain and delivering the first projects will all be viewed as high risk. To attract the investment at this stage, Government will need to take steps to build confidence in a future market, for example through national deployment targets and an appropriate regulatory regime. It will also need to ensure reliable long-term offtake arrangements are in place. For electricity this could be in the form of CfD contracts awarded for multi-gigawatt tranches of SMR capacity. For heat this could come via a contractually guaranteed minimum heat price and/or capacity payment for plants energising DH networks.

The O&M strategy for SMRs has the potential to be fundamentally different from large reactors. A large number of SMRs around the country could employ a centralised O&M model with training, operating procedures and equipment standardised across the fleet and applied by a small centralised team that visits each plant as required. This would be a step-change from current practice and could lend itself to a single utility model.

Key activities in the deployment of a fleet of UK SMRs are shown on the timeline in Figure 4.8.

Figure 4.8: Indicative timeline for SMR Fleet Deployment in the UK



Source: Mott MacDonald

5 Conclusion

The analysis undertaken for the ANT project supports the proposition that SMRs have the potential to make a valuable contribution to the UK’s future energy system. Our work suggests that in addition to baseload electricity they could provide low-carbon heat to energise city-scale DH networks; open up a diverse range of sites to deliver more capacity than would be available from large plants alone; and, potentially, integrate with new storage technologies to provide flexible ‘load-following’ electricity for the grid.

To turn this potential into reality SMR technologies will need to meet a number of functional and economic energy system requirements. On the functional requirements side, these cover a wide range of issues including construction based on high levels of off-site manufacture and modularity, heat provision, transportability, safety, and compatibility with the UK’s national nuclear infrastructure. On the economic requirements side, ambitious cost reductions will need to be realised in order for SMR plants to be attractive to investors and developers. A comparison between our estimated target costs and our indicative cost scenario suggests CHP SMRs will be in the most economically favourable position, whilst electricity-only and Extra-flex SMRs (those with new storage and surge technologies) may need to achieve lower NOAK costs than we have assumed in order to exceed investor hurdle rates.

The ANT project sets out an initial view of these energy system requirements. The project outputs are intended to provide guidance to SMR developers interested in the UK market and to be a useful framework for assessing the potential suitability of different SMR designs for the UK context. They also set out a number of high-level strategic issues and options for overcoming the challenges associated with SMR fleet deployment. As such they have relevance for Government and Industry bodies interested in taking up this task.

Appendices

Appendix A. Further reading

We would suggest the following documents for the interested reader:

Carelli et al (2010), Economic features of integral modular small to medium size reactors. *Progress in Nuclear Energy 52 (2010) 403-414*.

Carlsson et al (2012). Economic Viability of small nuclear reactors in future European cogeneration markets. *Energy policy 43 (2012) 396-406.*

Cooper (2014), Small Modular Reactors and the future of nuclear power in the United States. *Energy Research & Social Science 3 (2014) 161-177*.

DECC (2013). The future of Heating: Meeting the challenge.

ETI (2012). Macro Distributed Energy Project.

IAEA (2012). Status of Small and Medium Sized Reactor Designs.

IAEA (2013). Approaches for Assessing the Economic Competitiveness of Small and Medium Reactors. IAEA Nuclear Series. No. NP-T-3.7.

IAEA (2014). Advances in Small Modular Reactor Technology Developments.

Kuznetsov (2008). Options for small and medium sized reactors to overcome loss of economies of scale and incorporate increased proliferation resistance and security. *Progress in Nuclear Energy 50, pp242-250.*

Locatelli et al (2014). Small modular reactors: a comprehensive overview of their economics and strategic aspects. *Progress in Nuclear Energy, 73. Pp75-85 ISSN 0149-1970*.

National Nuclear Laboratory (2012). Small Modular Reactors – Their Potential Role in the UK.

National Nuclear Laboratory (2014). SMR Feasibility Study. December 2014.

OECD-NEA (2011), Current Status, Technical Feasibility and Economics and Small Nuclear Reactors.

Rosner & Goldberg (Nov 2011), Small Modular Reactors – Key to Future Nuclear Power Generation in the U.S, University of Chicago / Energy policy Institute at Chicago

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Glossary

CAPEX	Capital Expenditure. In the context of the ANT project, the upfront costs associated with building a power plant.
CCGT	Combined Cycle Gas Turbine.
CCS	Carbon Capture and Storage.
CfD	Contract for Difference. The UK Government’s main financial support scheme for large-scale low-carbon electricity generators.
CHP	Combined Heat and Power. An approach that involves the recovery of ‘waste’ heat from electricity generation for useful purposes.
DCF	Discounted Cash Flow. A type of financial analysis that estimates discounted future outflows and inflows.
DECC	UK Government Department for Energy and Climate Change.
ESME	An Energy System Modelling tool used by the ETI.
ETI	Energy Technologies Institute.
FOAK	‘First-of-a-kind’. Refers in this context to the first full-scale power plants based on new technology.
GDA	Generic Design Assessment. The established process in the UK for the assessment of new nuclear reactors ahead of site-specific proposals.
GIS	Geographical Information System.
GWe	Gigawatt electrical. A measure of electrical output capacity, equal to a thousand megawatts electrical.
GWth	Gigawatt thermal. A measure of thermal output capacity, equal to a thousand megawatts thermal.
GWh	Gigawatt hour. A measure of energy equal to 1000 megawatt hours.
IRR	Internal Rate of Return. A measure used to compare the profitability of investments. The higher the IRR, the more financially attractive a project is considered to be, all other things being equal.
kWe	Kilowatt electrical. A measure of electrical output capacity.
kWth	Kilowatt thermal. A measure of thermal output capacity.
kWh	Kilowatt hour. A measure of energy.
LCOE	Levelised Cost of Electricity. A measure of the unit cost (per kWhe or MWhe) of generating electricity, taking into account the lifetime costs of a power plant, and the lifetime electricity generated, at a given discount rate.
LWR	Light Water Reactor. A common and widely deployed type of nuclear reactor that uses normal (as opposed to heavy) water.

MWe	Megawatt electrical. A measure of electrical output capacity, equal to a thousand kilowatts electrical.
MWth	Megawatt thermal. A measure of thermal output capacity, equal to a thousand kilowatts thermal.
MWh	Megawatt hour. A measure of energy equal to 1000 kilowatt hours.
MSOA	Mid-Level Super Output Area. An Office of National Statistics designation most recently defined for the 2011 census. There are 6,791 MSOAs in England, 410 in Wales, and 1,235 equivalent areas in Scotland.
NOAK	‘Nth-of-a-kind’. Refers in this context to power plants based on established, proven technology and construction methods.
NPV	Net Present Value. The difference between the discounted project outflows and discounted project inflows.
O&M	Operations and Maintenance activities.
OPEX	Operational Expenditure. In the context of the ANT project, the annual ongoing expenditure relating to O&M, insurance, fuel, grid charges etc.
PPSS	Power Plant Siting Study. An ETI commissioned study that was undertaken alongside the ANT project.
PWR	Pressurised Water Reactor. A type of Light Water Reactor commonly found in many nuclear countries.
SMR	Small Modular Reactor. Generally defined as nuclear power reactors that deliver an electrical output below 300MWe. They are generally considered to incorporate distinct characteristics that make them fundamentally different from conventional large reactors.
TRL	Technology Readiness Level. A framework originally utilised by NASA in the 1980s to assess the maturity of evolving technologies. It is now used across many industries and organisations.
UHS	Ultimate Heat Sink. The systems used to remove heat from the reactor coolant system.