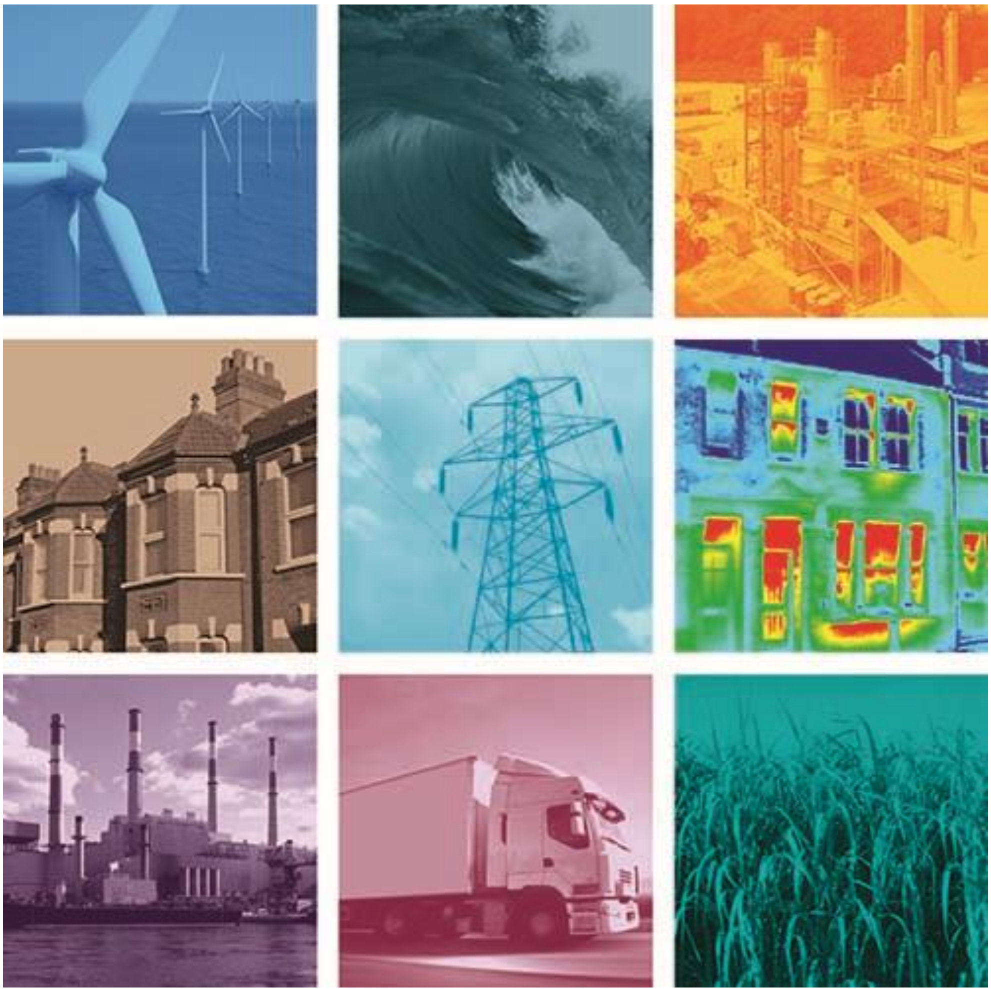
DECC Small Modular Reactor Techno-Economic Assessment – Project 2 Report

Strategic tools and assessment for SMR technologies in a UK low carbon energy system

Project Report – 20th May 2016



Contract 1001/03/2015 dated 3rd August 2015

Document Version

Document Title	DECC Small Modular Reactor – Techno-Economic Assessment – Project 2
Client	DECC
Version	Final Project Report
Issue Date	20/05/2016

Approval

Name	Jonathan Wills
Title	Programme Director ETI
Date	18/05/2016

Revision Record

Version	Date	Originator	Checker	Reviewer	Approver
A	19/02/2016	Scott Milne Mike Middleton	Richard Knight	Andrew Haslett	Jonathan Wills
B	10/03/2016	Scott Milne	Richard Knight		Jonathan Wills
C	20/05/2016	Scott Milne	Richard Knight		Jonathan Wills

Revision Description

Version	Description
A	The report was structured as for the technical report. Comment and feedback were sought on the structure, layout and content to support subsequent preparation of the final version.
B	Revised following feedback from DECC on version A.
C	Minor revisions following further feedback from DECC on version B.

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Executive Summary

Key Findings:

The role and value of SMRs is critically dependent on the wider energy system configuration.

In an energy landscape where large nuclear, carbon capture and storage (CCS) and a basket of renewables can be developed and rolled out successfully to offer a balanced generation portfolio, SMRs for baseload electricity constitute a low value, easily substitutable technology option. However, the availability of other technologies in a cost effective and timely manner cannot be taken for granted.

The risks associated with other low carbon technologies suggest a role for SMR development as a 'hedge' option.

If the deployment of a new fleet of large nuclear reactors is not fully realised, an opportunity would open up for SMRs to provide baseload energy. Similarly, if a CCS programme fails to materialise or is deemed unattractive due to the risk of sustained high gas prices – SMRs can play a role in providing additional, affordable energy and power sector flexibility.

SMRs with combined heat and power capability would provide wider system value while tapping into other revenue streams emerging as part of a whole system low carbon transition.

CHP capability would raise the value of SMRs through the delivery of low carbon heat to new district heating networks in major cities. Under high deployment scenarios, as much as half of all energy for heat networks could be provided by SMRs.

While baseload generation offers a conventional revenue stream for SMRs, load following and wider system services can form a critical part of the technology and commercial offering.

The ability for SMRs to operate on a load following basis as part of a daily cycle would increase their value further by offering a wider set of system services beyond baseload energy. This need is driven in part by variation in demand, but may increasingly be driven by intermittent supply in high renewables scenarios.

In addition to these wider system needs, the role of SMRs out to 2050 will be impacted by technology-specific factors including: capital cost, date of first deployment and build rates.

As a capital intensive technology, a more optimistic capital cost profile clearly improves the prospects for SMRs to contribute as part of a least-cost low carbon energy system.

As more optimistic SMR assumptions are explored (alongside system assumptions favourable to their deployment), 2050 SMR capacity comes up against two limiting factors: annual build rates and date of first commercial operation. Even under favourable conditions, it must be assumed that build rates will initially be constrained by the need to develop supply chains and production facilities. Earlier ETI analysis suggested an maximum build rate of 400MW/yr for the first ten years, followed by a step up to 1200MW/yr thereafter. Clearly, to make a substantial impact by 2050, the date of first operation must happen early enough to allow a meaningful period of deployment at the higher rate.

Project 2 Overview

Within the DECC Small Modular Reactor (SMR) Techno-Economic Appraisal, Project 2 delivers tools and assessment of the use and deployment of SMRs in a UK low carbon energy system. The analysis is undertaken using the ETI's established and peer reviewed ESME modelling system, which enables a cost optimised analysis of scenarios for the transition to a low carbon energy system. The extensive results from the ESME analysis are collated in the SMR Energy System Opportunity (SESO) Model which accompanies this report.

The scope of the project and this report is in six parts:

1. A description of the ETI, the ESME model and ETI's current analysis on SMRs
2. A description of this project and the interface with TEA Project 1
3. The definition of DECC's preferred deterministic baseline scenario for this project
    - This is based on ETI's "Clockwork" scenario but with modifications agreed with DECC at the start of the project.
4. Results of a range of deterministic sensitivity scenarios specified by DECC
    - These scenarios made use of generic SMR cost and performance characteristics provided by the ETI.
5. Results of a number of deterministic scenarios testing individual SMR technologies
    - For these scenarios, ETI used anonymised data (provided by Project 1) from prospective SMR vendors, for "near term" technologies with potential for first UK operations around 2030. There was useful learning from this analysis with indications of the probable differing levels of design maturity between reactor vendors as well as general vendor optimism bias.
6. Results of three probabilistic 'Monte Carlo' runs selected by DECC
    - For these probabilistic runs, ETI again used an anonymised dataset from Project 1, this time representing a single consolidated SMR technology (corrected for vendor bias[1] by Project 1). A series of three Monte Carlo runs were conducted, each involving many simulations where different cost outcomes occur across the full set of technologies. This dataset also included ranges for SMR cost parameters which enabled a probabilistic assessment of the impact of key uncertainties on SMR deployment.

The key contribution of Project 2 is to test a range of SMR assumptions within the context of a low carbon transition across ***the whole energy system***. A rapid decarbonisation of the power sector is now a robust feature of most UK low carbon scenarios, including those explored in this report. Decarbonising electricity can help achieve near-term emissions reductions in the most cost-effective way, and is an important precondition for further reductions through electrification of heat, transport and industry.

Although an extensive range of electricity generating technologies are available, each of these has its limitations, risks and uncertainties, meaning there is always the potential for a new technology

[1] Where data used in ESME has been corrected for vendor optimism, this correction was derived and applied by Project 1 prior to sharing with Project 2. No further adjustment has been made in Project 2.

such as SMRs - with the right costs and characteristics - to find a place in a least cost energy system design.

While decarbonising the electricity grid may be a 'no regrets' option, a whole system analysis reveals the need for a range of low carbon energy vectors, rather than a blanket 'all electric' approach across the board. Although the electrification of heat is likely to play an important role in decarbonising energy use in our buildings, ETI assesses district heat networks as offering a more cost-effective approach for many homes, particularly in dense urban areas. As such, there is a significant opportunity for any technology, such as CHP-capable SMRs, that can energise heat networks in a cost effective way.

The role and value of SMRs is critically dependent on the wider energy system configuration.

Across the many scenarios explored within this project, SMRs have been tested alongside over 250 other technologies. In some cases, the assumptions adopted for those other technologies create favourable conditions for the deployment of SMRs, in other cases not. It is therefore critically important to consider the wider system context before concluding the role that SMRs might play.

As part of its energy system analysis activities, ETI examines the opportunity cost associated with different technologies. This is the difference in cost between a system with all technology options available, and one with the given technology removed from the dataset. The high opportunity costs of CCS and bioenergy have been a consistent feature of this analysis for a number of years, indeed these are an order of magnitude above that of other technologies. Still, a number of other technologies have significant opportunity costs, including district heating, large nuclear, offshore wind etc.

In a policy-neutral pathway, assuming perfect foresight, and with all the technology options available, the opportunity space for electricity-only SMRs tends to be crowded out by large nuclear reactors, carbon capture and storage (CCS) and a basket of renewables (dominated by offshore wind). Even where some capacity of SMRs is deployed in this context, comparison against a baseline scenario reveals that the reduction in total system cost through deployment of SMRs is modest. That is, SMRs are substitutable for other technologies at relatively low cost. This is especially true of electricity-only SMRs, but even CHP SMRs have been shown to be substitutable by other electricity and heat generating technologies in a manageable way.

Where there are barriers to the successful rollout of the various higher value technologies though, we have seen that SMRs can play a role in a reconfigured least cost solution.

The risks associated with other low carbon technologies suggest a role for SMR development as a 'hedge' option.

While a techno-economic optimisation model will always deploy the most cost effective combination of technologies to satisfy demand (and other constraints), in reality technology deployment is not policy neutral, perfect foresight of technology and resource costs does not exist, and there are a variety of other risks associated with the key technologies that typically form part of a cost-optimal low carbon pathway.

This points towards the need to develop and prove a variety of technology options to ensure there is some combination capable of delivering an energy system that meets our needs in the event of technology failure, or as other factors emerge.

Across the scenarios explored here, there are sufficient grounds to consider SMRs as one of a number of important 'hedge' technologies that can make a valuable contribution under certain conditions. For example, if further cost reductions in offshore wind fail to materialise, the deployment of a new fleet of large nuclear reactors is stalled, or a CCS programme fails to materialise (or is deemed unattractive due to the risk of sustained high gas prices), SMRs could play a significant role in making up the shortfall in low carbon electricity.

From the many scenarios examined throughout this project, some of the key sensitivities around the role of SMRs are listed below.

SMR sensitivity to large nuclear deployment

In the context of the electricity sector, SMRs offer similar benefits to large nuclear but at higher costs. If more sites are available for large reactors, these could be deployed on a sufficient scale as to undermine the case for SMRs. On the other hand when tighter limits are placed on large reactors, SMRs could be one of the key technologies to provide replacement capacity.

Importantly, there are limits to how much combined nuclear capacity can be deployed before the average capacity factors of some reactors begin to decline due to periods of low demand. For a combined total nuclear capacity in the region of 40GW, both large reactors and SMRs would be able to deliver electricity unconstrained at their design capacity factor. In most of the runs in this project with a higher level of combined nuclear capacity, it is the SMRs which operate on a daily cycle.

It is important to note that high levels of deployment of large nuclear reactors remains dependent on site availability and eventual cost competitiveness. ETI have assumed (2010 GBP) capex levels of £3800/kWe in the near term falling to £3000/kWe by 2050 due to learning, consistent with government publications. This compares with the approximately £5000/kWe associated with the CfD arrangement for a 'first of a kind' plant at Hinkley Point C.

SMR sensitivity to gas price and CCS deployment

When constraints are placed on deployment of Gas CCGT with CCS, we see increased SMR capacity as one part of a reconfigured cost optimal solution (other notable changes include a role for Coal CCS). The optimal capacity of CCGT with CCS is itself highly sensitive to the price of gas. The optimal capacity of SMRs is therefore highly sensitive to the cost of gas via the impact on CCGT with CCS.

SMR sensitivity to biomass availability

ESME places a high value on biomass, typically developing the UK resource supply to the maximum available, as well as importing considerable quantities from overseas in later years. This is in large part due to the potential for negative emissions when combined with CCS. However, the biomass resource availability is uncertain, and is therefore modelled probabilistically in ESME. In those cases where we see less biomass in the system, and therefore less negative emissions, more comprehensive efforts must be made to fully decarbonise the energy system, including reducing residual emissions from Gas CCGT with CCS. In the 'low biomass' runs then, the lower capacity of CCGT with CCS presents an opportunity for deployment of SMRs.

SMRs with combined heat and power capability would provide wider system value while tapping into other revenue streams emerging as part of a whole system low carbon transition.

CHP capability would raise the value of SMRs through the delivery of low carbon heat to new district heating networks in major cities. Under high deployment scenarios, as much as half of all energy for heat networks could be provided by SMRs.

Without district heating, (electricity-only) SMRs can support higher electrification

Although district heating has been identified as an important component of a low-cost, low carbon transition for heat, there may be barriers to deployment that limit its role in the UK. It is therefore important to consider the least-cost energy system configuration where district heating has been prohibited.

In cases where district heating is unavailable in ESME, space heating across the entire building stock is comprehensively electrified, resulting in: more household retrofits to reduce space heat demand, more heat pump installations supported by electric resistive heaters and within-building heat storage, higher electricity capacity and generation and local distribution grid reinforcement.

In such 'high electricity demand' scenarios, large scale nuclear reactors remain the most cost effective option for baseload electricity in ESME (given cost and performance assumptions), but the upper capacity limit of 35GWe of new large scale reactors by 2050 (due to siting constraints), means that additional capacity must be provided by other technologies. This presents an opportunity for any cost-effective SMR design.

With district heating, CHP-capable SMRs are a robust feature of the cost-optimal pathway

Where ESME has been configured to allow the deployment of large scale district heat networks, there is considerable value to be gained from deploying SMRs with combined heat and power capability. These SMRs can provide a significant volume of baseload electricity generation whilst simultaneously helping to energise heat networks with low carbon heat.

Other options for energising these networks include: heat recovery from large scale thermal power stations (excluding large nuclear plants), large scale marine-sourced heat pumps (e.g. from rivers, lakes, seawater); geothermal energy (where available). In the absence of CHP SMRs, these alternative technologies are sufficiently cost effective to ensure that ESME still chooses to deploy heat networks extensively. When CHP SMRs are available though, they tend to take a sizeable share of network hot water provision across the country.

With district heating, electricity-only SMRs play a more limited role

There is a clear narrative around the role of electricity-only SMRs in a high electrification scenario. Similarly, the narrative is clear for CHP SMRs in a district heating scenario. A third case to consider is where electricity-only SMRs are the only variant available, but in a district heating scenario. Other things being equal, electricity-only SMRs would be deployed to a lesser extent in a district heating scenario, as the substantial increase in demand that accompanied the high electrification scenario does not materialise. However, the results of the runs in this project suggest that if the cost and performance assumptions are sufficiently favourable, electricity-only SMRs can still play a limited role in a scenario with district heating.

While baseload generation offers a conventional revenue stream for SMRs, load following and wider system services can form a critical part of the SMR technology and commercial offering.

The ability for SMRs to operate on a load following basis as part of a daily cycle would increase their value further by offering a wider set of system services beyond baseload energy. This need is driven in part by variation in demand, but may increasingly be driven by intermittent supply in high renewables scenarios.

There are many examples throughout this report of runs in which SMRs are required to operate below maximum capacity at certain times of the year, suggesting that in practice the flexible operation of SMRs is an important consideration in assessing their competitiveness versus large nuclear and renewables. This is especially apparent in those runs where favourable cost assumptions result in higher deployment of SMRs, on top of the 30GW+ capacity of large nuclear plants. Since there are periods of the year where electricity demand drops below this combined nuclear capacity, it is necessary to ramp down some of that capacity as part of a daily cycle.

In this context, the value of SMRs depends critically on system service provision, where the ability to load follow contributes to their competitiveness vs large nuclear and renewables.

High temperature process heat

The claim from some proponents that emerging SMR technologies could play a role in hydrogen production is discussed in section 1. It is the view of the ETI that a range of alternatives are available for hydrogen production (including electrolysis, methane reforming, coal and/or biomass gasification) that are better understood, available in the nearer term and therefore capable of being scaled up to the levels required as part of a cost-effective low carbon pathway to 2050. By comparison, insufficient evidence is available to judge whether and when nuclear hydrogen production might compete with more established technologies. As new evidence emerges though, ETI can test this in the context of a whole systems analysis.

In addition to these wider system needs, the role of SMRs out to 2050 will be impacted by technology-specific factors including: capital cost, date of first deployment and build rates.

As a capital intensive technology, a more optimistic capital cost profile clearly improves the prospects for SMRs to contribute as part of a least-cost low carbon energy system. As more optimistic SMR assumptions are explored (alongside system assumptions favourable to their deployment), 2050 SMR capacity comes up against two limiting factors: date of first commercial operation and annual build rates.

SMR date of first operations and build rate limits

From the runs conducted using ETI's generic SMR cost data, the date of first (possible) operations does not appear to be a major sensitivity. This is because most of these runs show SMRs being initially deployed much later than they could be. Similarly, the maximum build rate tends not to constrain the majority of those runs. By contrast (and unsurprisingly), the more favourable cost assumptions adopted in some of the vendor runs and in the Monte Carlo runs result in a much higher level of SMR deployment, often at the bounds of the build rate limit.

Even under favourable conditions, it must be assumed that build rates will initially be constrained by the need to develop supply chains and production facilities. Earlier ETI analysis suggested a maximum build rate of 400MW/yr for the first ten years, followed by a step up to 1200MW/yr thereafter. Clearly, to make the greatest impact by 2050, the date of first operations must happen early enough to allow a meaningful period of deployment at the higher rate. In those cases, modelling a higher build rate or earlier deployment date would enable higher total capacity to be achieved by 2050.

Capital Cost

SMRs, like large nuclear reactors, have a through-life cost profile that is dominated by front-end capital cost. Across the range of model runs conducted for this study, a large variation in SMR capex has been explored, and unsurprisingly this has been shown to greatly impact on the cost-optimal deployment[2]. Although capital costs dominate, operating & maintenance costs cannot be ignored, as shown by SMR deployment levels in the two vendor runs (D2.5.2 & D2.5.6) sharing the same level of capex but with very different operating cost assumptions.

Probabilistic assessment of SMR Deployment (using TEA derived generic SMR data)

The various batches of scenarios conducted in this project culminated in a series of three probabilistic ESME runs (described in section 10), using a generic SMR dataset collated and synthesised by Project 1 from the provisional findings of the different projects in the wider TEA. This 'TEA generic SMR' data included: input from Project 3 on emerging technologies; first UK operations dates adjusted for vendor bias by Project 1; capex and opex costs adjusted for vendor bias by Project 1; and a learner rate derived by projects 5, 6 & 7.

For near term electricity-only SMRs, Project 1 provided a (central) capex of £3505/kWe (in 2010 GBP) for the first deployment from 2031, falling to £3329/kWe by 2050 (this represented a substantial reduction from the comparable 'ETI generic SMR' assumptions used in the earlier batch of scenarios i.e. £4750/kWe with no learner effect). In the probabilistic run where these electricity-only SMRs were available from 2031 (and where heat networks could be deployed), an average deployment of 10GWe of SMRs was observed in 2050 across the 150 simulations.

In a second probabilistic run, SMRs were made available from 2031 on a combined heat and power (CHP) basis, with cost and performance adjusted accordingly. In this case, where SMRs could support district heat networks, average deployment by 2050 was 14GWe (with most of the runs reaching the capacity limit of 15GWe).

In the third probabilistic run, the electricity-only SMR design represented an emerging technology, with a later first deployment date of 2035 and a capex markup applied. As a result, an average of only 3GWe was observed across the 150 simulations.

Recommendation to update the DECC TEA agreed baseline scenario and test SMR deployment

Section 4 outlines the approach taken to agree a baseline scenario for these runs. This built upon previous discussions between DECC and ETI in August 2015. Since that time, the Comprehensive Spending Review and related announcements have amounted to an energy policy 'reset', with profound implications for the least-cost pathway previously set out. The most significant change is the withdrawal of capital support for a CCS demonstration competition in the UK, meaning the demonstration projects assumed to occur in the baseline run are highly unlikely to go ahead. As a result, the commercial-scale deployment of CCS technologies from 2020 as represented in the baseline seems highly unlikely.

In addition to these policy changes, DECC has been working on a revised set of cost assumptions for electricity generation technologies, which are yet to be published. Since SMRs have been shown to be highly sensitive to the deployment of other technologies, it is important to check the findings of this report against these new costs. There is therefore a need to bring the baseline up to date with latest DECC assumptions and in the context of a delay to CCS deployment, to assess the impact on the potential role of SMRs. Given the attractiveness of CHP SMRs in the ETI baseline for example, these

[2] While more or less optimistic assumptions have been tested for SMR technologies in these runs, ETI has not validated these alternative assumptions.

would be expected to become more attractive if other technologies are delayed or face higher costs. Electricity-only SMRs are less attractive than CHP SMRs but might become significantly more attractive with less competition from other generating technologies.

Contents

1. Introduction

Energy Technologies Institute (ETI)

The Energy Technologies Institute (ETI) is a public-private partnership between the UK government and several global companies: BP, Caterpillar, EDF, Rolls-Royce and Shell. ETI makes targeted investments in R&D projects to accelerate the development of affordable, clean, secure technologies needed to help the UK meet its emissions targets.

Energy Systems Modelling Environment (ESME)

The ETI's Energy Systems Modelling Environment (ESME) is a whole-energy system model for the UK, which sits at the heart of ETI's modelling and analysis capability. ESME is a least-cost optimisation model designed to explore technology options out to 2050 for a carbon constrained UK energy system, subject to additional constraints around energy security, peak energy demand and more. The model covers the power, transport, buildings and industry sectors, and the infrastructure that supports and connects them.

ESME informs and is informed by strategic activities across a range of ETI programme areas, including Bioenergy, Carbon Capture & Storage, Energy Storage & Distribution, Offshore Renewables, Smart Systems & Heat and Transport. The model is also used by member organisations to support strategic thinking and decision making. Notable citations include: The Renewable Energy Review[3], The Carbon Plan[4], UK Bioenergy Strategy[5], The Future of Heating[6,7]. In addition, ESME has been licensed to support a number of academic research projects, for example: exploring the role of demand reduction[8] and energy strategy under uncertainty[9],[10].

In ESME, energy supply and demand across the year is sub-divided into ten timeslices (morning, mid-day, early evening, late evening, overnight in each of two seasons, summer and winter). A further five timeslices are used to represent an exceptional peak day and ensure that ESME designs a system capable of responding to extreme conditions, an important consideration for the delivery of electricity and particularly heat.

Spatially, the UK is divided into 12 onshore regions. Energy demand in each region can be met by exploiting energy resources within that region, through transmission of energy from an adjacent region or in some cases by importing energy resources. There are also 12 offshore regions containing energy

[3] CCC (2011) "The Renewable Energy Review", http://www.theccc.org.uk/publication/the-renewable-energy-review/
[4] HMG (2011) "The Carbon Plan: Delivering our low carbon future", https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/47613/3702-the-carbon-plan-delivering-our-low-carbon-future.pdf
[5] DfT, DECC, DEFRA (2012) "UK Bioenergy Strategy", https://www.gov.uk/government/publications/uk-bioenergy-strategy
[6] DECC (2012) "The Future of Heating: A strategic framework for low carbon heat in the UK", https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/48574/4805-future-heating-strategic-framework.pdf
[7] DECC (2013) "The Future of Heating: Meeting the challenge", https://www.gov.uk/government/publications/the-future-of-heating-meeting-the-challenge
[8] Pye, S., Usher, W., & Strachan, N. (2014a). The uncertain but critical role of demand reduction in meeting long-term energy decarbonisation targets. Energy Policy, 73, 575-586.
[9] Pye, S., Sabio, N., & Strachan, N. (2014b). An integrated systematic analysis of uncertainties in UK energy transition pathways [forthcoming].
[10] Pye S., Sabio, N., Strachan, N. (2014c). Energy Strategies Under Uncertainty: An Integrated Systematic Analysis of Uncertainties in UK Energy Transition Pathways. UKERC Report UKERC/WP/FG/2014/002.

resources (wind, wave, tidal energy) that can be harvested and transmitted to an adjacent onshore region, as well as storage sites for captured CO_2.

Since there is a great deal of uncertainty around the long term costs and availability of technologies and resources, ESME incorporates a 'Monte Carlo' mode. In this mode, rather than a single deterministic outcome, ESME will perform many simulation runs, using different values each time for selected parameters within an uncertainty range. Analysis of these Monte Carlo results can then reveal trends within the interactions of the many uncertainties.

ESME Assumptions

The assumptions used in ESME come in three main baskets: demands, technologies, and constraints. Energy demand is specified as a series of end-use energy services, such as 'passenger km' for private vehicles, 'freight km' for haulage, 'lumens' of light in the home etc. In the model runs conducted for this report, these demands were built upon HM Government central assumptions where possible.

Different technologies are available for ESME to use to deliver these energy services, e.g. electric / liquid fuel / hydrogen fuel cell cars for 'passenger km'; heat pumps / heat networks / gas boilers for 'space heat' etc. Since competing technologies have different input fuels and efficiencies, the actual volume of energy required is not established until ESME identifies the cost-optimal supply side solution to satisfy these demands. In doing so, ESME must balance energy supply and demand in each region, during each timeslice.

In the latest release of ESME, over 250 technologies are represented. Primarily, these are derived from ETI's own portfolio of technology research, development and demonstration projects. However, where the ETI has no projects in a technology area, such as for solar, ETI has conducted a critical appraisal of the available evidence in the published literature. For each technology, capital, fixed and variable costs are defined out to 2050 on an 'n^{th} of a kind' basis, similarly for performance characteristics such as efficiency, load factors etc.

In addition to the overarching constraint of a decreasing carbon budget over time, ESME is populated with a series of other constraints intended to improve the realism of the energy system transition. These include limits on the availability of certain resources, maximum build rates and quantities for different technologies, as well as constraints governing their operation.

ESME Treatment of Industrial and Process Heat

There is no representation in ESME of the ability for nuclear power to provide process heat to industries. Although it is a possible future development, provision of nuclear heat was not included in the UKERC industry review, nor has it been included in other comparable datasets or energy models. The development and licensing of nuclear technologies for industrial heat is at an early stage.

In contrast there are many proven abatement options in the form of switching to low-carbon fuels, and a body of literature on the potential for industry CCS. SMRs for industrial process heat are currently unproven, with little time to develop, prove and deploy them in sufficient quantities to make a significant contribution to process heat by 2050. The ETI currently judges that there are likely to be lower risk and more cost effective solutions based on more proven technologies for the supply of industrial process heat.

2. ETI internal SMR analysis

Prior to and separate from the analysis conducted for this report, ETI carried out its own internal assessment of the potential role of SMRs in the UK, in early 2015. This included a series of ESME model runs to identify the preferred SMR technology parameters under different conditions, in order to arrive at a generic set of assumptions for an SMR technology to be used in other ESME modelling. These runs were built upon the ESME dataset at the time (v3.5), which has since been superseded. It is worth emphasising that any discrepancies in the model results between ETI's internal analysis and the work described in this report are due to inevitable variations in the selection of sensitivities and input assumptions between the two. To support its earlier analysis, ETI carried out the two projects summarised below.

Power Plant Siting Study (PPSS)

The Power Plant Siting Study investigated the theoretical UK site capacity for the deployment of large nuclear power stations at locations that meet the established UK criteria. A range of sensitivity studies then explored:

- The theoretical site capacity for the deployment of small reactors at locations not suitable for large reactors
- The potential for competition for development sites between developers of nuclear power stations and developers of thermal power stations with CCS

The PPSS summary report is available from the ETI website[11]. ETI's conclusions and data carried forward into ESME are reported in ETI's Nuclear Insights[12].

System Requirements for Alternative Nuclear Technologies (ANT)

The Alternative Nuclear Technologies (ANT) project examined what SMRs would be required to do in terms of outputs, performance, availability and cost envelope to be of interest for potential deployment in the UK energy system. The project involved the derivation of a set of credible technical performance characteristics for use in ESME, and also derived an indicative cost model independent of cost assumptions created by current SMR reactor vendors. The ANT summary report is available from the ETI website[13]. ETI's conclusions and data carried forward into ESME are reported in ETI's Nuclear Insights[14].

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[11] http://www.eti.co.uk/wp-content/uploads/2015/10/PPSS-Summary-Report-with-Peer-Review.pdf
[12] http://www.eti.co.uk/the-role-for-nuclear-within-a-low-carbon-energy-system/
[13] http://www.eti.co.uk/wp-content/uploads/2015/10/ANT-Summary-Report-with-Peer-Review.pdf
[14] http://www.eti.co.uk/the-role-for-nuclear-within-a-low-carbon-energy-system/

3. Methodology

Interfaces With Other TEA Projects

As part of Project 2, a series of ESME runs were conducted to test representative SMR technologies from prospective vendors (see results of these runs in section 9). Participating vendors provided data to the Project 1 contractor, where the datasets were anonymised before being passed on to ETI.

The results of these runs were then provided back to Project 1, where they were consolidated with early findings from all projects in the TEA. This consolidated dataset represented a generic SMR design (with uncertainty ranges where appropriate). This arising generic SMR design was then used in the Monte Carlo runs described in section 10.

Overview of Project 2 Methodology

The headline activities carried out for Project 2 are summarised below and expanded on in subsequent sections of this report. For a detailed description of the project methodology, see the full technical report.

Agreement on a Baseline Scenario: Before conducting any runs, it was necessary to establish and 'lock-down' a set of baseline assumptions to be used for the runs. An agreement was reached to use the latest ESME dataset, adjusted to incorporate the DECC view in place of the ETI view in a number of areas.

Development of SMR Energy System Opportunity (SESO) model framework: To enable the reporting of ESME data in an intelligible and navigable way, it was necessary to define a subset of all the possible data that could be reported, and a consistent platform for sharing this. The SESO model framework was proposed by ETI and agreed with DECC for this purpose. The SESO model framework includes, for each run conducted, a set of core results charts and tables showing the energy system transition over time, along with more detailed charts for 2050.

Energy System Transition Scenarios: This set of runs explored various sensitivities including: a range of delays on SMR deployment, a range of SMR capex costs, scenarios with and without district heating networks (where SMR recoverable heat might be used). Additional scenarios looked at impacts from delays on other technologies, including bioenergy, Large (Gen III) nuclear reactors and CCGT with Carbon Capture and Storage (CCS).

SMR Technology (and Technology Genre) Comparisons: A series of runs were conducted with vendor SMR technology data, to see if and how these varied from the generic SMR data. Five of the vendor datasets were sufficiently complete to enable these specific technology runs. Five others were identified as representing less developed and less well-defined technologies, and were therefore treated as representative of a 'technology genre'.

Monte Carlo Runs: Having consolidated early findings from Projects 2-7, Project 1 then provided ETI with a revised set of generic SMR technology assumptions, including uncertainty ranges, to be tested using ESME's Monte Carlo feature.

4. Design of Baseline assumptions

The runs conducted for this project were built upon the August 2015 ESME v4.0 release. Some of the technology assumptions and constraints were adjusted to bring the dataset into line with a baseline scenario agreed previously between ETI and DECC as part of a separate project. Those modifications are detailed in the technical report.

The full ESME dataset includes assumptions on the cost, performance, operational and deployment constraints of more than 250 technologies across the power, conversion, heat, transport and industry sectors. In addition to technology data, there are assumptions covering resource availability and prices. Assumptions for some of the key technologies are summarised here, namely those power sector technologies observed to play a significant role across the model runs conducted in this Project.

Notably, this initial dataset does not feature Nuclear SMRs. The purpose of this was to provide a 'no SMR' baseline against which to compare later runs featuring Nuclear SMRs.

Technology Cost Assumptions

Table 1 summarises capital, fixed, variable and fuel costs for a selection of power sector technologies (in real 2010 £GBP). Across all technologies, an 8% cost of capital is assumed (see technical report for more information).

Cost category	Capital	Fixed O&M	Variable O&M	Fuel	Capital	Fixed O&M	Variable O&M	Fuel
Year	**2010**	**2010**	**2010**	**2010**	**2050**	**2050**	**2050**	**2050**
Unit	£/kW(e)	£/kW(e)/yr	£/MWh(e)	£/MWh(e)	£/kW(e)	£/kW(e)/yr	£/MWh(e)	£/MWh(e)
CCGT	589	27.2	0	28.1	496	27.2	0	45.1
CCGT with CCS	997	52.3	0.4	30.5	745	52.3	0.4	46.2
H2 Turbine	590	30	0	0	500	30	0	0
Large Scale Solar PV	1400*	50	0	0	400	15	0	0
Nuclear (Gen III)	3800	67.8	5.0	4.1	3040	67.8	5.0	8.4
Offshore Wind (fixed)	3000	86	0	0	1500	50	0	0
Offshore Wind (floating)	3000	86	0	0	1261	48.5	0	0
Onshore Wind	1490	17.6	0	0	1251	17.6	0	0

*Table 1: Baseline cost assumptions for selected technologies (in real 2010 £GBP) *Solar PV capital cost declines non-linearly (925 by 2015, 800 by 2020 then linearly to 400 in 2050)*

Other Technology Assumptions

For the same set of technologies, Table 2 provides some of the key build/performance characteristics. The indicative scale is provided as this has informed the cost assessment for each type of technology. For availability factor, flexible technologies have a maximum value (though utilisation may be lower in ESME depending on wider system needs), while non-flexible technologies have a fixed average utilisation (subject to seasonal and diurnal variation), so the annual average is shown (in some cases this is also subject to variation by region, so these figures shown the maximum of any region).

	Indicative Scale	Technical Life	Construction Period	Availability Factor	Max Annual Build Rate:			
Year				2050	2020	2030	2040	2050
Unit	MW	years	years	% max (avg)	MW/yr			
CCGT	1000	30	2.5	90	2000	2000	2000	2000
CCGT with CCS	1000	30	3.5	85	1000	2000	2000	2000
H2 Turbine	500	20	2	90	2000	2000	2000	2000
Large Scale Solar PV	50	30	1	(10)**	1000	1000	1000	1000
Nuclear (Gen III)	1600	50	5	90	-	1500	1500	1500*
Offshore Wind (fixed)	500	20	2	(40)	2000	3000	3000	3000
Offshore Wind (floating)	500	20	2	(45)	-	1000	3000	3000
Onshore Wind	500	20	2	(31)**	1000	1000	1000	1000

*Table 2: SESO Baseline additional assumptions for selected technologies. *Available sites limited to 35GW, build limit up to 2025 allows for Hinkley Point C only. **varies by region.*

Addition of Generic Nuclear SMRs

Using the generic Nuclear SMR technology assumptions derived from ETI internal analysis, four SMR variants were then added to the dataset before performing a second baseline run, this time *with* SMRs. This enabled an assessment of the impact on the cost and configuration of the energy system using these generic technology assumptions. The four SMR variants were:

- a baseload electricity only variant (**SMR Elec**)
- a baseload CHP-capable variant (**SMR CHP**)
- a highly flexible electricity only variant (**SMR Elec Extraflex**), and
- a highly flexible CHP-capable variant (**SMR CHP Extraflex**)

In the ESME runs conducted for this Project, the SMR 'Extraflex' variants were not selected and are not examined further in this report. For more details see the full technical report.

SMR Cost Assumptions

Each variant represents a 'several hundred MW' scale reactor with a technical life of 50 years. The construction period is defined as 3 years (used in calculating financing costs, i.e. including interest during construction). The costs for each variant are summarised below, alongside Nuclear (Gen III) for comparison.

Cost category	Capital	Fixed O&M	Variable O&M	Fuel	Capital	Fixed O&M	Variable O&M	Fuel
Year	2010	2010	2010	2010	2050	2050	2050	2050
Unit	£/kW(e)	£/kW(e)/yr	£/MWh(e)	£/MWh(e)	£/kW(e)	£/kW(e)/yr	£/MWh(e)	£/MWh(e)
Nuclear (Gen III)	3800	67.8	5.0	4.1	3040	67.8	5.0	8.4
Nuclear (SMR CHP)	4950	135	5.0	5.8	4950	105	5.0	12.6
Nuclear (SMR Elec)	4750	130	5.0	4.6	4750	100	5.0	10.1

Table 3: The cost assumptions used for the SMR technologies, and for comparison Nuclear (Gen III). Although SMRs cannot be deployed from 2010, placeholder costs are necessary for all years in ESME. Fuel costs reflect conversion efficiencies (unit costs of fuel are consistent across nuclear technology variants)

Performance characteristics

Like the large scale 'Gen III' reactors, SMRs are assumed to have a 95% availability factor during periods of peak demand, making them extremely reliable contributors during these times. The average availability factor over the whole year though is lower at 85% to account for maintenance and forced outage (this compares to 90% for Gen III and 70% for legacy reactors, see technical report for more detail on assumptions).

The SMR CHP variant can operate in either of two modes: electricity only mode or CHP mode. In electricity only mode, the thermal efficiency of electricity generation is assumed to be 34% as for the electricity only variant. In CHP mode, where a significant volume of hot water is being diverted to heat networks, the thermal efficiency of electricity generation falls to 27%. However, since useful heat is being recovered during this operation mode, the total energy conversion efficiency is assumed to be 88%.

Deployment Constraints

The deployment of SMRs in ESME is constrained by a *total capacity* limit as well as an *annual build rate* limit. The capacity limit applied was 21GW for SMRs, while the build rate limit was 400MW/yr for ten years, 1200MW/yr thereafter.

However, since the central runs assume no deployment before 2030, the annual build rate limits are such that no more than 16GWe can actually be deployed by 2050. This 'date of first deployment' is a key sensitivity though, and there are runs in sections 7&8 in which this is brought forward to 2025 (hence the need for a total capacity limit). Furthermore, the total capacity and build rate limits were themselves tested as sensitivities in certain cases.

5. Design of model reporting (SESO)

The SMR Energy System Opportunity (SESO) model framework was developed to act as a repository of results from a series of discrete ESME runs. The volume of possible outputs from an ESME run can be overwhelming to a non-user, so ETI agreed with DECC a selection of the key results charts and datasets to support DECC analysis. This included:

Pathway Charts: This is a collection of 20 charts for each run detailing the change in the UK energy system in 5 year time steps from 2010 to 2050, covering each of the main sectors and energy vectors represented in ESME. The full list of charts includes: net CO_2 emissions, primary resource consumption; capacity and generation charts for electricity, space heat and hot water; road transport fleet and energy consumption; energy storage capacity and power rating; retrofit of power plants and of dwellings; electricity consumption; hydrogen production and consumption; gas consumption; biomass consumption; network hot water production.

Cashflow Charts: This collection of charts shows expenditure across the energy system out to 2050, including capital expenditure, fixed and variable operating costs, and resource costs. Capex costs are shown at various levels of aggregation. Also see abatement costs below.

2050 Electricity Supply: This chart focuses on the energy system solution in 2050, and shows how electricity is being supplied during each of the timeslices in a typical summer and winter day, and during the extreme peak day.

2050 Space Heat Supply: This chart again focuses on the 2050 solution, this time showing how our buildings - including homes, public and commercial buildings - are heated across the day and year, including for the peak day (which represents an extreme cold weather event).

2050 Electricity Capacity by Region: This dataset shows the breakdown of technologies contributing to the 2050 electricity capacity within each region (both onshore and offshore) in ESME.

LCOE calculations: These calculations show the levelised cost of energy (LCOE) for the range of electricity (and hydrogen) generating technologies seen in the scenario. Note that these values are derived from the full system cost of each technology. Since ESME takes the wider system needs into account, including e.g. the need for operational flexibility, the model may choose to deploy more expensive technologies than would be necessary if the only requirement was for (time-independent) units of energy output. Furthermore, these LCOE values are levelised over the actual units of generation observed for a given technology, which may be below the potential output. Again running a technology below its design potential load factor can have wider system value, e.g. in cases where a certain amount of capacity must be kept in reserve, but will necessarily show up as a higher LCOE.

Abatement costs: Finally, a single worksheet is included with each version of SESO summarising the abatement cost of all runs in that set.

6. Baseline Runs

Baseline (No SMRs)

In this baseline run overall electricity capacity remains at around 80-90GW for most of the transition, with significant deployment of additional capacity towards the end, reaching over 140GW by 2050. This is made up of a balanced generation mix, including: 32GW of Gas CCS, 35GW of new large Nuclear, 40GW of Wind plus a range of supplementary renewable and interconnector capacity.

Due to the higher load factor of large nuclear (Gen III), the total annual generation from each source shows a quite different balance, with large nuclear as the dominant source of electricity (>50%) by 2050. The various renewables technologies make a smaller contribution relative to their share of capacity, while the average annual load factor of Gas CCS declines over time as this technology increasingly operates seasonally (running as baseload through the winter to support electrification of heat).

For day-to-day provision of space heat, our buildings gradually shift away from reliance on gas boilers. In the long term the system relies on two key solutions: district heat networks and electric heating (primarily heat pumps but supplemented by electric resistive heating). Gas boilers do continue to play a role in this 2050 energy system as a backup solution in the event of an extreme cold weather event.

Other sectors of the energy system merit discussion here. This baseline run is able to take advantage of the significant potential for *negative emissions* through the combination of biomass and CCS. This negative emissions route is critical in keeping down the cost of transition in other sectors.

Because of the comprehensive decarbonisation of the power and heat sectors by 2050 and the significant role for negative emissions, the transport sector is able to transition in a more modest fashion. Light vehicles rely on continued improvements in the efficiency of internal combustion engines (ICEs) and gradually the hybridisation of ICEs with batteries. For heavy duty vehicles, the preferred lower carbon option is the integration of natural gas as a fuel. The combination of these measures means demand for liquid fuel falls to below half of today's levels by 2050.

Baseline (with SMRs)

In a second baseline run, the same assumptions were used for the ESME technology dataset, but this time Nuclear Small Modular Reactors (SMRs) were added to the set of options.

The purpose of the Techno-Economic Assessment (TEA) overall was to improve the understanding of the cost and performance characteristics of SMRs and their potential role in a low carbon UK energy system. In later runs (described below) assumptions were derived through consultation with potential SMR vendors, and through consolidation of learning within the TEA. In this first instance though, generic assumptions were made for SMRs on the basis of earlier work conducted by the ETI.

In this baseline, 2030 was assumed as the earliest date of deployment, with annual deployment limited to 400MW for the first ten years and 1200MW thereafter. A maximum of 16GWe is therefore possible by 2050.

The electricity capacity results chart (Figure 1) shows a material role for SMRs in the energy system, with deployment beginning in the 2030s and reaching 9GWe of installed capacity by 2050. As a result of the higher load factor associated with SMRs (compared with renewables), the total power sector capacity is significantly reduced, with the 9GW of SMRs displacing 25GW of capacity elsewhere, primarily solar PV and offshore wind.

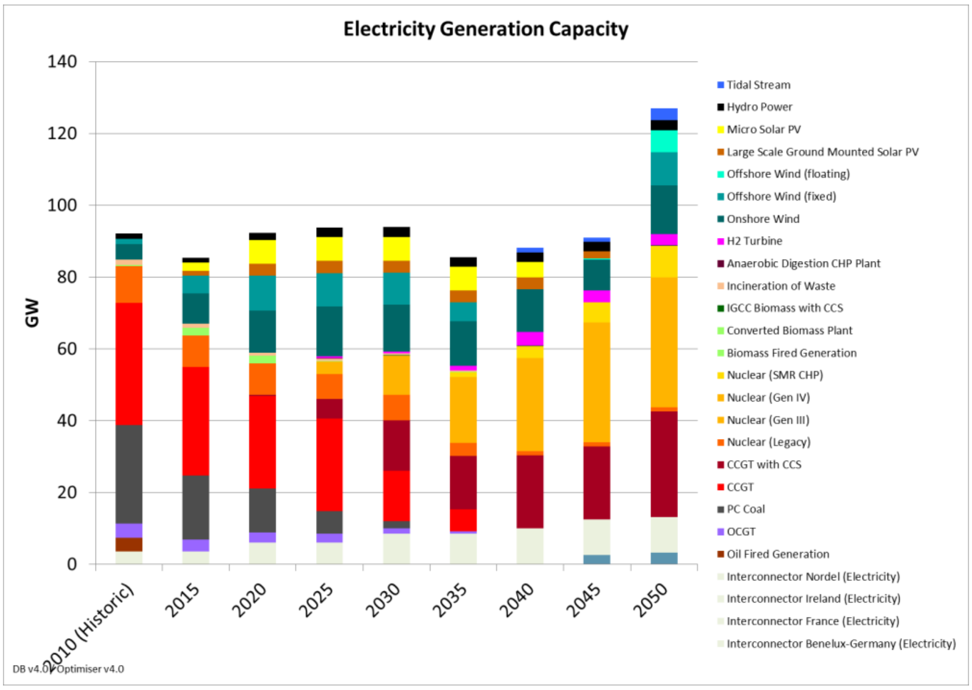

Figure 1 – Electricity capacity in the Baseline run (with SMRs)

The only SMR technology selected in this run was the less flexible CHP variant, i.e. the model deems the extra cost of CHP relative to 'electricity only' SMRs to be good value for money, but higher flexibility was not valued in the same way, with ESME preferring a baseload role for SMRs while securing flexibility through other technologies.

Over half of all heat supply to district heat networks comes from SMRs by 2050 in this run. The availability of CHP SMRs evidently improves the cost-effectiveness of district heating, leading to an increase in its share of total space heat supply, with correspondingly less input from heat pumps (and consequently less electricity demand).

The 9GWe of CHP SMR capacity deployed in this transition implies £44bn undiscounted capital investment, or equivalently £15bn when discounted back to the present value in 2010. In terms of the overall system though, this scenario sees an overall net *saving* of £1.3bn in the discounted cumulative energy system costs compared with the run without SMRs.

7&8. Sensitivity runs

Having established a baseline scenario and a baseline with generic Nuclear SMRs, the next set of runs set out to examine the impact of adjustments to key variables for SMRs and throughout the wider energy system landscape. The purpose of these runs was to understand in more detail the conditions that support a role for SMRs in a least-cost, low carbon energy system. By testing a variety of scenarios it is possible to discover what alternative assumptions might enhance, or reduce, the value of SMRs in the energy pathway.

During this stage of the TEA project the principle reason for studying exploratory scenarios was to perform a sensitivity analysis: many of the assumptions taken on the costs and build rates of SMRs are uncertain, so it is important to understand the sensitivity of the results and conclusions to variations in these assumptions. Likewise there are very many uncertainties in the wider energy system which might affect the role for nuclear SMRs, and these too need to be explored.

The variables examined for these runs included:

- Adjustments to the SMR technology - higher/lower capital costs, the introduction of a learner rate, earlier/later first deployment, higher build rate limits;
- Adjustments elsewhere in the energy system - district heat networks ruled out, lower bioenergy resource, lower gas CCS deployment, higher/lower large nuclear deployment, higher/lower gas price, slower heat decarbonisation.

These sensitivities were chosen based on ETI's years of experience in running ESME and understanding which variables tend to have the most significant impact on energy system design, or would be expected to impact upon SMR deployment specifically. A high level summary of the impact of each variable is provided below.

Wider energy system adjustments

District heating

In a cost effective low carbon energy system, there is an inescapable need to transition away from natural gas for heating our buildings. One approach is to shift to electrification of heat via heat pumps, and this will be the preferred option for many millions of UK homes. However, an 'all electric' heating future would place substantial stress on the electricity grid at times of peak demand, and necessitate reinforcement of the transmission grid and local distribution networks throughout the country. A more cost-effective option for many homes, particularly in dense urban areas, will be the adoption of district heat networks. This helps to dampen peak electricity demand and such networks can be energised from a variety of sources, making them a robust solution against the failure or high cost of any particular heat supply technology.

In many of the runs explored in this project, district heating was available to the model, while in other runs these were ruled out, enforcing a substantial electrification of heat. The intention was to test the attractiveness of SMRs in both contexts and identify the optimal technology offering.

Irrespective of the role that SMRs can play in either of these pathways, the decision to rule out district heat has a substantial impact on the cost effectiveness of the low carbon transition more generally. Any lessons about the role of SMRs must be understood in this context.

Where heat networks are available, CHP-capable SMRs make an attractive option for the provision of network heat. In many of the runs conducted in this project SMRs provided the majority of all network heat by 2050. By contrast, when electricity-only SMRs were tested in the context of a future with district heating, these have a more marginal role in the energy system.

Where heat networks are not available though, the additional demand for electricity to support heat pumps presents an opportunity for electricity-only SMRs (albeit as part of a more expensive system overall).

Gas price and CCGT with CCS deployment levels

In the baseline run, gas CCGT with CCS is one of the dominant technologies in the power sector. However, the deployment schedule of this technology is uncertain. A 'slow CCS' scenario was therefore conducted, with SMRs playing a role as one of the preferred substitute technologies. CCGT with CCS is also highly sensitive to the price of gas. In the baseline, gas prices rise from 1.5p/kWh in 2010 to 2.73p/kWh in 2050. When a high and a low gas price trajectory were tested as part of the sensitivity runs (high reaching 4.44p/kWh, low reaching 1.36p/kWh in 2050), this had a profound impact on the optimal level of CCGT with CCS deployment. In those runs where cheaper gas leads to more CCGT with CCS, this effectively prices SMRs out of the market. In contrast, a high gas price leads ESME to drop CCGT with CSS altogether in favour of a range of substitute technologies, including Nuclear SMRs.

Large nuclear deployment levels

Large nuclear reactors are typically seen as an attractive technology in ESME, given the 'nth of a kind' cost profile assumed for these. A site capacity limit of 35GW applies for large nuclear in ESME, and this limit tends to be hit (or somewhere close). Since electricity only SMRs effectively do the same job as large nuclear but at greater expense, their selection tends to be as a 'top up' to the 35GW of large nuclear. When a higher capacity limit was tested for large nuclear, this had the expected impact of taking SMRs out of the market. Conversely, when a lower limit was place on large nuclear, SMRs were able to step in and deploy closer to their own capacity limit.

SMR specific adjustments

When the SMR technology itself was made the subject of sensitivity adjustments, a number of observations were made.

Capital cost and learner rate

As a capital intensive technology, SMR deployment is clearly sensitive to variation in capital cost. Where the deployment is already marginal, such as for electricity only SMRs, a capex increase of 20% can be sufficient to remove this technology from the mix. In the case of CHP SMRs, the system value is more robust, and therefore the same capex increase, although resulting in lower deployment, is not sufficient to remove SMRs from the system altogether. In later runs, summarised below, new capex assumptions were tested.

Where a learner rate is applied, meaning capex levels are reduced over time, this can clearly have an impact on the cost effectiveness of SMRs[15]. However, this benefit only accrues over time, whereas

[15] Note that in ESME these cost reductions occur irrespective of the level of deployment in previous periods, as a restriction of the modelling approach.

the 'low capex' scenarios assume a lower cost from the date of first deployment. As a consequence, achieving a learner rate inevitably has less impact than achieving a lower capex level from the outset.

Date of earliest deployment and build rate limits

Since Nuclear SMRs are not ready for deployment today, a date has to be assumed for the earliest possible deployment in ESME. Across the sensitivity runs a range of 'earliest deployment' dates were tested, from 2025-2035, with 2030 taken as the standard central case. In those runs where SMRs are only of marginal value to the system, it is often the case that the model chooses to forego deployment of SMRs at the earliest possible date, opting instead to introduce these much later.

In some of the later runs, including the vendor runs discussed below, the capital cost assumptions of SMRs were improved to such an extent that they were deployed from the earliest deployment date, and the maximum annual build rate limits were reached throughout the remainder of the pathway. In a future where those SMR economics apply, an even earlier deployment would facilitate a higher level of deployment by 2050, and therefore a greater contribution to low carbon energy. Similarly, even with highly attractive economics, if the earliest deployment is pushed back by several years, this can put a severe limitation on the ability of SMRs to contribute to the system.

9. Specific SMR technologies/genres

As part of the TEA, potential vendors of SMRs were invited to submit cost and engineering assessments of their own SMR designs. To test these in a whole system context, ETI took receipt of anonymised vendor datasets from the Project 1 contractor. In many cases the vendors had omitted key characteristics (e.g. build rates, fixed and variable operating costs), in which case the relevant data was taken from the ETI generic SMR technology.

Model runs were conducted for five vendors corresponding to relatively near-term SMR technologies. Table 4 gives a summary of the key data for these vendors, and for comparison the generic ETI electricity-only SMR technology used in previous scenarios. Note that the survey completed by all the vendors specified that costs be given in 2015 USD. ETI then converted these into 2010 GBP for use in the ESME model, as shown in the table below.

Vendor	CAPEX (£/kW)		Fixed O&M (£/kW/yr)		Variable O&M (£/kWh/yr)	
	2010	2050	2010	2050	2010	2050
2	3037	3037	130*	100*	0.0050*	0.0050*
6	3037	3037	76	76	0.0043	0.0043
7	5640	5640	196	196	0.0066	0.0066
15	1530	1530	130*	100*	0.0050*	0.0050*
17	2804	2804	86	86	0.0050*	0.0050*
Generic	4750	4750	130	100	0.0050	0.0050

Table 4. Summary of the cost data (2010 GBP) used for the scenarios of near-term SMR technology vendor data and, for comparison, the cost data of the generic electricity-only SMR used in D2.4. Asterisks denote costs where the generic data was used because of lacking data in a vendor's response to the survey.

Where a considerably more optimistic assessment of capital cost was made by the vendors (2, 6, 15, 17) it is unsurprising that a higher level of deployment was observed than in the previous generic SMR runs. In three of these runs (6, 15, 17) the level of SMR deployment was constrained only by the build out constraints. As a speculative exercise, these limits were doubled in order to test the attractiveness of further additional capacity, and this time around 32GW of SMR capacity was observed for these three runs. For vendor 2, although the capex was the same as vendor 6, the higher fixed operating costs prevented the same high level of deployment.

Five other vendor datasets were identified as representing less developed/defined technologies, but were nevertheless treated as representative of a 'technology genre'. Project 3 assisted in defining appropriate parameters for these. Only two of these technology genres were assessed as being available for deployment before 2050 (the remaining three could not therefore be tested in ESME). With an earliest deployment date of 2035 and 2040, these two vendor technologies were deployed to a 2050 capacity of 8GW and 4GW respectively.

10. Monte Carlo runs

The various scenarios in the preceding sections were all conducted as single deterministic runs. In addition to those, ETI conducted a series of three 'Monte Carlo' runs. When ESME is operated in Monte Carlo mode, it conducts a given number of simulations (150 in each of these runs) where key variables are assigned a randomly selected value from a 2050 range (in contrast to a single deterministic run using only mean values). Once the 2050 value is assigned, the intermediate values are interpolated linearly from 2010.

Deterministic runs are valuable in ensuring a common baseline can be compared against a series of targeted interventions, based on expert judgement about the likely key factors. The Monte Carlo mode is a useful complement to this, enabling the generation of many simulations that may unearth unexpected effects, or provide confirmation of impacts observed in the deterministic runs.

In the baseline runs and sensitivity scenarios (Sections 6,7&8), a generic SMR dataset developed by ETI was adjusted according to the particular issue being analysed (capex/first deployment etc). In the specific SMR technology/genre runs (Section 9), a bespoke SMR dataset was built up for each run using data provided by vendors (with any gaps filled using generic ETI data).

In preparation for the Monte Carlo runs, the Project 1 contractor consolidated provisional learnings from across the TEA, and developed an updated generic technology dataset for an *electricity only* SMR. This 'TEA generic SMR' data included: input from Project 3 on emerging technologies; first UK operations dates adjusted for vendor bias by Project 1; capex and opex costs adjusted for vendor bias by Project 1; and a learner rate derived by projects 5, 6 & 7.

This constituted the basis for the first Monte Carlo run. For the second run, ETI made adjustments to represent a CHP-capable SMR, by applying a capex markup, and providing data on how the SMR performs in CHP mode. For the third run, electricity only SMRs were represented as an 'emerging technology genre' as per section 9, with adjustments made to capex and earliest deployment date accordingly. The capex adjustment reflects the expectation from project 3 that emerging technologies are unlikely to be as cost competitive as near term light water reactor technologies.

Cost category	Capital	Fixed O&M	Variable O&M	Capital (Mean)	Capital (Range)	Fixed O&M (Range)	Variable O&M (Range)
Year	**2010**	**2010**	**2010**	**2050**	**2050**	**2050**	**2050**
Unit	£/kW(e)	£/kW(e)/yr	£/MWh(e)	£/kW(e)	+/- %	+/- %	+/- %
Near term SMR (Elec only)	3505	84	5	3329	+35/-31	+20/-23	+4/-4
Near term SMR (CHP)	3705	89	5	3529	+35/-31	+20/-23	+4/-4
Emerging SMR (Elec only)	4381	84	5	4381	+35/-31	+20/-23	+4/-4

Table 5: Revised SMR costs for use in Monte Carlo runs. For mean values, the cost curve is flat from 2010 to first deployment, then sloping according to any learner rate out to 2050 (no learner rate assumed for emerging tech). For probabilistic values, a 2050 cost is selected from the range and the cost curve over the pathway interpolated accordingly. Ranges for Variable O&M costs provided to Project 2 were limited, but were carried through into the modelling for completeness.

Other things being equal, the probabilistic values assigned to SMR costs would clearly influence their attractiveness. However, the various sensitivity runs explored earlier also highlighted the impact of wider system uncertainties on the deployment of SMRs. In the Monte Carlo process these impacts are captured by the fact that around 100 other variables are subject to probabilistic value assignments, not just SMR costs. Table 6 shows the uncertainty ranges for a selection of these.

Year	2010	2050 (mean)	2050 (range)
Unit	£/kW(e)	£/kW(e)	+/- %
CAPEX CCGT with CCS	997	745	+60 / -40
CAPEX H2 Turbine	590	500	+30 / -30
CAPEX Large Scale Solar PV	1400	400	+39 / -44
CAPEX Nuclear (Gen III)	3800	3040	+40 / -30
CAPEX Offshore Wind (fixed)	3000	1500	+50 / -30
CAPEX Offshore Wind (floating)	3000	1261	+50 / -30
CAPEX Onshore Wind	1490	1251	+30 / -30
Gas Price (p/kWh)	1.5 p/kWh	2.73 p/kWh	+63 / -50
UK Biomass Availability (TWh)	28 TWh	140 TWh	+50 / -50

Table 6 - Mean values (in 2010£) and uncertainty ranges for selected probabilistic variables.

In the first Monte Carlo run, representing an electricity only SMR available from 2031, average deployment by 2050 was 10GW. Clearly there is variation across simulations, but the lower average SMR capex in these runs has led to a significantly higher deployment compared to a central case using the generic ETI SMR assumptions.

In the second Monte Carlo run, with CHP-capable SMRs available from 2031, deployment is consistently higher again, at 14GW on average. While most simulations reach the maximum possible deployment of 15GW, the slightly lower average occurs due to a smaller number of outlier simulations with lower CHP SMR deployment.

In the third run, the emerging technology is unable to scale to the same level by 2050, given the delayed deployment from 2035. Even when it is available, the higher capex makes this a less attractive option than in the other runs. As such, average deployment by 2050 is only 3GW.

Regression analysis

Across all three of these Monte Carlo runs, a multiple linear regression analysis was carried out to identify those variable inputs associated with the greatest impact on SMR deployment. The capex of SMRs comes out as an obvious high impact uncertainty in all three cases. Many of these simulations showed SMRs being deployed at the upper build rate limit, a model constraint. Note that where capex assumptions are already low enough to encourage deployment at this build rate limit, those limits cannot be overcome by lowering capex further.

At the other end of the capex uncertainty range, the reduced deployment in many of those simulations with a higher SMR capex showed the downward pressure this can have on the optimal level of deployment. The value of CHP-capability in the second run means SMRs prove more resilient to this effect, with fully two thirds of simulations reaching the max build rate (i.e. including many sims with above average SMR capex).

After SMR capex, the next most important variable was the gas price. The sensitivity of SMRs to gas prices (via the cost effectiveness of CCGT with CCS) was illustrated above in the context of the gas price sensitivity runs. These Monte Carlo runs reaffirm this effect. Biomass availability also emerged as an important variable. Biomass is typically regarded as a high value resource in a low carbon energy system, given the potential for negative emissions (through combination with CCS). Where more of this resource is available to the model, less 'heavy lifting' has to be done by other technologies including SMRs (and vice versa).

The capex associated with large nuclear reactors is a further driver of SMR deployment, with a higher capex making large nuclear less attractive and potentially creating an opportunity for SMRs.

11. Conclusions

The various runs described in this report help to build an overall picture of the potential role for SMRs as part of a low carbon energy system in the UK. Some of the key messages have been drawn out within the individual summaries, and these are collected together here:

- The role and value of SMRs is critically dependent on the wider energy system configuration.
- The risks associated with other low carbon technologies suggest a role for SMR development as a 'hedge' option.
- SMRs with combined heat and power capability would provide wider system value while tapping into other revenue streams emerging as part of a whole system low carbon transition.
- While baseload generation offers a conventional revenue stream for SMRs, load following and wider system services can form a critical part of the SMR technology and commercial offering.
- In addition to these wider system needs, the role of SMRs out to 2050 will be impacted by technology-specific factors including: capital cost, date of first deployment and build rates.

The role and value of SMRs is critically dependent on the wider energy system configuration.

Across the many scenarios explored within this project, SMRs have been tested alongside over 250 other technologies. In some cases, the assumptions adopted for those other technologies create favourable conditions for the deployment of SMRs, in other cases not. It is therefore critically important to consider the wider system context before concluding the role that SMRs might play.

In a policy-neutral pathway, assuming perfect foresight, and with all the technology options available, the opportunity space for electricity-only SMRs tends to be crowded out by large nuclear reactors, carbon capture and storage (CCS) and a basket of renewables (dominated by offshore wind). Even where some capacity of SMRs is deployed in this context, comparison against a baseline scenario reveals that the reduction in total system cost through deployment of SMRs is modest. That is, SMRs are substitutable for other technologies at relatively low cost. This is especially true of electricity-only SMRs, but even CHP SMRs have been shown to be substitutable by other electricity and heat generating technologies in a manageable way.

Where there are barriers to the successful rollout of the various higher value technologies though, we have seen that SMRs can play a role in a reconfigured least cost solution.

The risks associated with other low carbon technologies suggest a role for SMR development as a 'hedge' option.

While a techno-economic optimisation model will always deploy the most cost effective combination of technologies to satisfy demand (and other constraints), in reality technology deployment is not policy neutral, perfect foresight of technology and resource costs does not exist, and there are a variety of other risks associated with the key technologies that typically form part of a cost-optimal low carbon pathway.

This points towards the need to develop and prove a variety of technology options to ensure there is some combination capable of delivering an energy system that meets our needs in the event of technology failure, or as other factors emerge.

Across the scenarios explored here, there are sufficient grounds to consider SMRs as one of a number of important 'hedge' technologies that can make a valuable contribution under certain conditions. From the many scenarios examined throughout this project, some of the key sensitivities around the role of SMRs are listed below.

SMR sensitivity to large nuclear deployment

In the context of the electricity sector, SMRs offer similar benefits to large nuclear but at higher costs. If more sites are available for large reactors, these can be deployed on a sufficient scale as to undermine the case for SMRs. On the other hand when tighter limits are placed on large reactors, SMRs are one of the key technologies to provide replacement capacity. Importantly, there are limits to how much combined nuclear capacity can be deployed before the capacity factors of these technologies begin to decline. This is because electricity demand drops away at certain times of the year.

It is important to note that high levels of deployment of large nuclear reactors remains dependent on site availability and cost competitiveness. ETI have assumed capex levels of £3800/kWe in the near term falling to £3000/kWe by 2050 due to learning, consistent with government publications. This compares with the approximately £5000/kWe implied by the CfD arrangement for a 'first of a kind' plant at Hinkley Point C.

SMR sensitivity to gas price

When constraints are placed on deployment of Gas CCGT with CCS, we see increased SMR capacity as part of a reconfigured cost optimal solution. The optimal capacity of CCGT with CCS is itself highly sensitive to the price of gas. The optimal capacity of SMRs is therefore highly sensitive to the cost of gas through the impact on the attractiveness of CCGT with CCS.

SMR sensitivity to biomass availability

ESME places a high value on biomass, typically developing the UK resource supply to the maximum available, as well as importing considerable quantities from overseas in later years. This is in large part due to the potential for negative emissions when combined with CCS. However, the biomass resource availability is uncertain, and is therefore modelled probabilistically in ESME. In those cases where we see less biomass in the system, and therefore less negative emissions, more comprehensive efforts must be made to fully decarbonise the energy system, including reducing residual emissions from Gas CCGT with CCS. In the 'low biomass' runs then, the lower capacity of CCGT with CCS presents an opportunity for deployment of SMRs.

SMRs with combined heat and power capability would provide wider system value while tapping into other revenue streams emerging as part of a whole system low carbon transition.

The whole system perspective followed by ESME identifies the clear opportunity for minimising cost through the interaction of a number of energy vectors, rather than a blanket 'all electric' approach across the energy system. As part of this, although the electrification of heat is likely to play an important role in decarbonising energy use in our buildings, ESME assesses district heat networks as offering a more cost-effective approach for many homes, particularly in dense urban areas. As such, there is a potentially significant opportunity for any technology that can energise heat networks in a cost effective way. The CHP-capable SMRs tested in this project are potentially a very cost effective low carbon heat source, whose investment case is strengthened by the revenues from the electricity co-product.

However, it cannot be taken for granted that all SMR technologies will be designed for CHP, thus we tested cases where district heating is available but SMRs are deployed on an electricity-only basis. Finally, in the case where district heat networks are not deployed (perhaps due to lack of investor confidence or consumer acceptance), a more comprehensive electrification of heat would be required. While this may be a suboptimal solution from a whole systems perspective, if those are the conditions into which SMRs are able to be introduced, then it is important to understand how this changes the economic case for this technology. Our summary of these three cases starts with the latter case.

Without district heating, (electricity-only) SMRs can support higher electrification

Although district heating has been identified as an important component of a low-cost, low carbon transition for heat, there may be barriers to deployment that limit its role in the UK. It is therefore important to consider the least-cost energy system configuration where district heating has been prohibited.

In cases where district heating is unavailable in ESME, space heating across the entire building stock is comprehensively electrified, resulting in: more household retrofits to reduce space heat demand, more heat pump installations supported by electric resistive heaters and within-building heat storage, higher electricity capacity and generation and local distribution grid reinforcement.

In such 'high electricity demand' scenarios, large scale nuclear reactors remain the most cost effective option for baseload electricity in ESME (given cost and performance assumptions), but the upper capacity limit of 35GWe of new large scale reactors by 2050 (due to siting constraints), means that additional capacity must be provided by other technologies. This presents an opportunity for any cost-effective SMR design.

With district heating, CHP-capable SMRs are a robust feature of the cost-optimal pathway

Where ESME has been configured to allow the deployment of large scale district heat networks, there is considerable value to be gained from deploying SMRs with combined heat and power capability. These SMRs can provide a significant volume of baseload electricity generation whilst simultaneously helping to energise heat networks with low carbon heat.

Other options for energising these networks include: heat recovery from large scale thermal power stations (excluding large nuclear plants), large scale marine-sourced heat pumps (e.g. from rivers, lakes, seawater); geothermal energy (where available). In the absence of CHP SMRs, these alternative technologies are sufficiently cost effective to ensure that ESME still chooses to deploy heat networks extensively. When CHP SMRs are available though, they tend to take a sizeable share of network hot water provision across the country.

With district heating, electricity-only SMRs play a more limited role

There is a clear narrative around the role of electricity-only SMRs in a high electrification scenario. Similarly, the narrative is clear for CHP SMRs in a district heating scenario. A third case to consider is where electricity-only SMRs are the only variant available, but in a district heating scenario. Other things being equal, electricity-only SMRs would be deployed to a lesser extent in a district heating scenario, as the substantial increase in demand that accompanied the high electrification scenario does not materialise. However, the results of the runs in this project suggest that if the cost and performance assumptions are sufficiently favourable, electricity-only SMRs can still play a limited role in a scenario with district heating.

While baseload generation offers a conventional revenue stream for SMRs, load following and wider system services can form a critical part of the technology and commercial offering.

The ability for SMRs to operate on a load following basis as part of a daily cycle would increase their value further by offering a wider set of system services beyond baseload energy. This need is driven in part by variation in demand, but may increasingly be driven by intermittent supply in high renewables scenarios.

There are many examples throughout this report of runs in which SMRs are required to operate below maximum capacity at certain times of the year, suggesting that in practice the flexible operation of SMRs is an important consideration in assessing their competitiveness versus large nuclear and renewables. This is especially apparent in those runs where favourable cost assumptions result in higher deployment of SMRs, on top of the 30GW+ capacity of large nuclear plants. Since there are periods of the year where electricity demand drops below this combined nuclear capacity, it is necessary to ramp down some of that capacity as part of a daily cycle.

When deployed alongside significant capacity of large nuclear baseload, the value of SMRs would depend critically on system service provision, with the abilities to deliver a daily shaped power profile and operate within a band contributing to their competitiveness.

High temperature process heat

The proposition from some proponents that emerging SMR technologies could play a role in hydrogen production was raised in section 1. It is the view of the ETI that a range of alternatives are available for hydrogen production that are better understood, available in the nearer term and therefore capable of being scaled up to the levels required as part of a cost-effective low carbon pathway to 2050.

In addition to these wider system needs, the role of SMRs out to 2050 will be impacted by technology-specific factors including: capital cost, date of first deployment and build rates.

As a capital intensive technology, a more optimistic capital cost profile clearly improves the prospects for SMRs to contribute as part of a least-cost low carbon energy system. As more optimistic SMR assumptions are explored (alongside system assumptions favourable to their deployment), 2050 SMR capacity comes up against two limiting factors: date of first commercial operation and annual build rates.

SMR Date of First Deployment and Build out rate

From the range of scenarios in this Project using ETI's generic SMR cost data, the date of first (possible) operations does not appear to be a major sensitivity. This is because most of these runs show SMRs being deployed much later than they could be anyway. Similarly, the build rate tends not to constrain the majority of those runs.

By contrast, the more favourable cost assumptions adopted in some of the vendor runs and in the Monte Carlo runs result in a much higher level of SMR deployment, often at the bounds of the build rate limit. Clearly, in those cases, applying a higher build rate or earlier deployment date would enable higher total capacity to be achieved by 2050. In the vendor runs where this occurred, we chose to model a higher build rate out of curiosity, and higher capacity is indeed what we observe. It is important to note that the vendors themselves did not provide a view on possible build rates, hence ETI used the approach described in the ANT report of a first tranche of deployment at a lower build rate (to represent getting to NOAK costs), followed by faster deployment.

CAPEX

SMRs, like large nuclear reactors, have a through-life cost profile that is dominated by front-end capital cost. Across the range of model runs conducted for this study, a large variation in SMR capex has been explored, and this has been shown to greatly impact on the cost-optimal deployment. Operating costs cannot be ignored however, as shown by the two vendor runs (D2.5.2 & D2.5.6) sharing the same level of capex but with very different operating cost assumptions.

Probabilistic assessment of SMR Deployment (using TEA derived generic SMR data)

The various batches of scenarios conducted in this project culminated in a series of three probabilistic ESME runs (described in section 10), using a generic SMR dataset collated and synthesised by Project 1 from the provisional findings of the different projects in the wider TEA.

For near term electricity-only SMRs, Project 1 provided a (central) capex of £3505/kWe (in 2010 GBP) for the first deployment from 2031, falling to £3329/kWe by 2050 (this represented a substantial reduction from the comparable 'ETI generic SMR' assumptions used in the earlier batch of scenarios i.e. £4750/kWe with no learner effect). In the probabilistic run where these electricity-only SMRs were available from 2031 (and where heat networks could be deployed), an average deployment of 10GWe of SMRs was observed in 2050 across the 150 simulations.

In a second probabilistic run, SMRs were made available from 2031 on a combined heat and power (CHP) basis, with cost and performance adjusted accordingly. In this case, where SMRs could support district heat networks, average deployment by 2050 was 14GWe (with most of the runs reaching the capacity limit of 15GWe).

In the third probabilistic run, the electricity-only SMR design represented an emerging technology, with a later first deployment date of 2035 and a capex markup applied. As a result, an average of only 3GWe was observed across the 150 simulations.

Further analysis recommended to update baseline scenario and test SMR deployment

Section 4 outlined the approach taken to agree a baseline scenario for these runs. This built upon previous discussions between DECC and ETI in August 2015. Since that time, the Comprehensive Spending Review and related announcements have amounted to an energy policy ‘reset’, with profound implications for the least-cost pathway previously set out. The most significant change is the withdrawal of capital support for a CCS demonstration competition in the UK, meaning the demonstration projects assumed to occur in the baseline run are highly unlikely to go ahead. As a result, the commercial-scale deployment of CCS technologies from 2020 as represented in the baseline seems highly unlikely.

In addition to these policy changes, DECC has been working on a revised set of cost assumptions for electricity generation technologies, which are yet to be published. Since SMRs have been shown to be highly sensitive to the deployment of other technologies, it is important to check the findings of this report against these new costs. There is therefore a need to bring the baseline up to date with latest DECC assumptions and in the context of a delay to CCS deployment, to assess the impact on the potential role of SMRs. Given the attractiveness of CHP SMRs in the ETI baseline for example, these would be expected to become more attractive if other technologies are delayed or face higher costs. Electricity-only SMRs are less attractive than CHP SMRs but might become significantly more attractive in the face of less competition from other generating technologies.

Glossary

ANT	System Requirements for Alternative Nuclear Technologies (ANT) was an project funded by ETI to examine what SMRs would be required to do in terms of outputs, performance, availability and cost envelope to be of interest for potential deployment in the UK energy system.
Availability Factor	For dispatchable technologies, the *maximum* percentage of the year that a technology is capable of operating at. For non-dispatchable technologies, the *average* percentage of the year that a technology is assumed to operate at.
Capacity Factor	The percentage of the year that a technology is observed to operate at in a given ESME run. For dispatchable technologies this must be less than or equal to the availability factor. For non-dispatchable technologies this must be equal to the availability factor.
CCGT	Combined Cycle Gas Turbine
CCS	Carbon Capture and Storage
CHP	Combined Heat and Power
ESME	Energy Systems Modelling Environment, ETI's internationally peer-reviewed whole energy systems model.
FOAK/ NOAK	First of a kind / Nth of a kind. FOAK costs represent the real-world expense of deploying a new technology for the first time. NOAK cost represents the cost that can be achieved after a period of learning through deployment. In ESME only NOAK costs are used. The additional 'wedge' of costs incurred in moving from FOAK to NOAK remain an important consideration for off-model analysis and reflection.
LCOE	Levelised Cost of Energy. See Section 5 for further details of how LCOE has been calculated in this report.
PPSS	Power Plant Siting Study was an ETI funded project to explore the potential for deployment of Nuclear Small Modular Reactors at sites across the UK.
SESO	SMR Energy System Opportunity (SESO) model. Used to refer to the collection of discrete ESME runs conducted in this project.
SMR	Nuclear Small Modular Reactor.