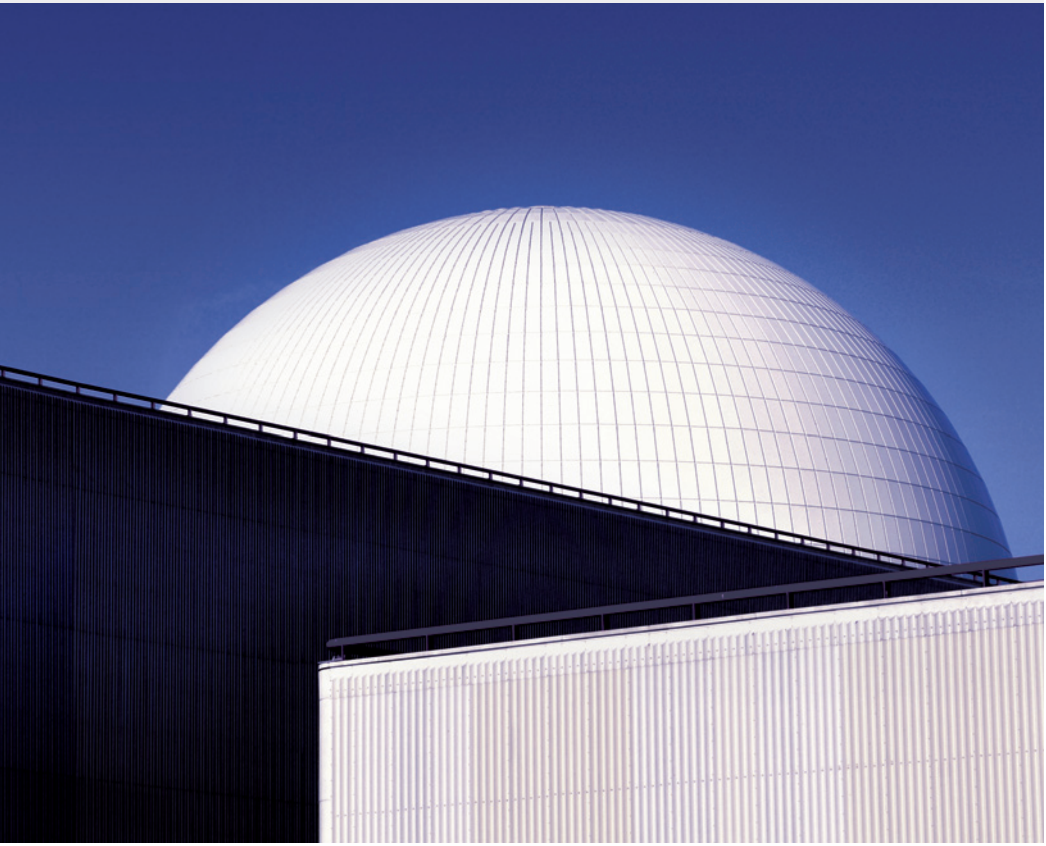
energy technologies institute

An insights report by the
Energy Technologies Institute

Nuclear
The role for nuclear within a low carbon energy system



Contents

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Key headlines

» New nuclear plants can form a major part of an affordable low carbon transition, with potential roles for both large nuclear and Small Modular Reactors (SMRs)

» Large reactors are best suited for baseload electricity production – analysis indicates an upper capacity limit in England and Wales to 2050 from site availability of around 35 GWe – actual deployment will be influenced by a number of factors and could be lower. Alongside large nuclear, SMRs may be less cost effective for baseload electricity production

» SMRs could fulfil an additional role in a UK low carbon energy system by delivering combined heat and power (CHP) – a major contribution to the decarbonisation of energy use in buildings – but deployment depends on availability of district heating infrastructure

» SMRs offer more flexibility with deployment locations that could deliver heat into cities via hot water pipelines up to 30km in length – assessed potential capacity of at least 21GWe – but the limit may be higher

» Total nuclear contribution in the 2050 energy mix could be around 50 GWe; SMRs contributing nuclear capacity above 40 GWe will require flexibility in power delivery to aid balancing of the grid

» Future nuclear technologies will only be deployed if there is a market need and these technologies provide the most cost effective solution

» A decision is required now whether to begin 10 years of enabling activities leading to a final investment decision for a first commercially operated UK SMR – earliest operational date around 2030

» A strategic approach to reactor siting together with public consultation will be important in determining the extent of deployment of both large nuclear and SMRs

Context

In March 2015 the Energy Technologies Institute (ETI) published "Options Choices Action" featuring two contrasting scenarios – "Patchwork" and "Clockwork" – for a UK low carbon energy system transition to 2050[1]. New nuclear power stations featured as a prominent component of both scenarios.

In this context the ETI has commissioned new analysis of how large and Small Modular Reactor (SMR) nuclear technologies can contribute to decarbonising the UK energy system. For this purpose SMRs are defined as modular for the purpose of incremental addition to power station capacity, and with an electrical generation capacity in units of 300 MWe or less. The emergence of multiple developing SMR designs opens up the potential to deploy a wider range of nuclear technologies within an integrated energy system.

This document summarises the insights from three ETI activities undertaken in 2014 and 2015:

- Power Plant Siting Study (PPSS) –delivered for the ETI by Atkins
- System Requirements For Alternative Nuclear Technologies (ANT) – delivered for the ETI by Mott MacDonald with technical support from Rolls-Royce
- In-house ETI energy system modelling and analysis incorporating the learning from the PPSS and ANT projects

This analysis has created new understanding of the potentially different contributions from large baseload reactors and SMRs in the UK energy system. These two nuclear technologies can offer potentially complementary roles in baseload and flexible CHP generation, and also in terms of the location of development sites.

Generation IV nuclear technologies are not considered in detail in any of the projects above, but are recognised as a new type of reactor technology potentially available for deployment from 2040 onwards. The PPSS recognises the need to allocate site capacity for such reactors; without suitable sites such future designs could not be built.

[1] http://www.eti.co.uk/options-choices-actions-uk-scenarios-for-a-low-carbon-energy-system/

"ETI has commissioned new analysis of how large and SMR nuclear technologies can contribute to decarbonising the UK energy system"

ATKINS

Mott MacDonald

Introduction

The Energy Technologies Institute (ETI) is a partnership between global energy and engineering companies and the UK Government. Its role is to act as a conduit between academia, industry and government to accelerate the development of low carbon energy technologies.

The ETI works across a portfolio of technology areas and undertakes system wide energy system modelling and analysis to build a better understanding of the UK's energy challenges. Each area has its own strategic insights to offer. By consolidating these insights, the ETI has developed a system wide strategic view regarding a low carbon energy system transition for the UK. Further detail can be found in Appendix A and on the ETI website.[2]

The role of nuclear in electricity generation

In March 2015 the ETI published two contrasting scenarios (Clockwork and Patchwork) for the UK's energy system transition to 2050.[3] The electrical generating capacity in 2050 within the ETI's Clockwork scenario is shown in Figure 1, which shows a balance in 2050 between the 3 largest groups of capacity of wind, gas with Carbon Capture and Storage (CCS), and nuclear. Nuclear is deployed up to 40 GWe in this scenario, but there is no differentiation of the types of nuclear technology deployed or distinction between constraints or opportunities associated with individual technologies. In this scenario nuclear was constrained by an overall build rate and maximum deployment level.

ETI projects to explore nuclear constraints and opportunities

The ETI has developed understanding of the potential role of nuclear power technologies through three interrelated initiatives:

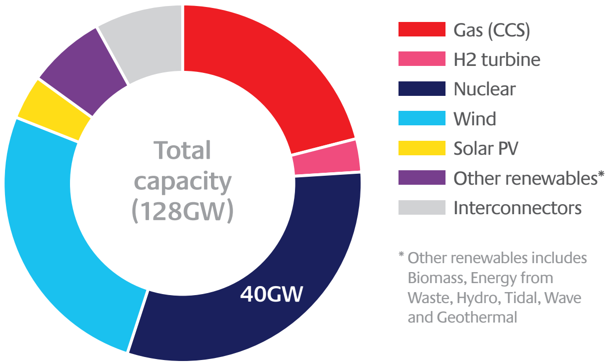
(1) Power Plant Siting Study (PPSS)
This project applied existing nuclear power station siting criteria to clarify the potential for expanded nuclear deployment. The project delivered a baseline assessment of siting capacity for large nuclear power stations in England and Wales, and then examined a wide range of sensitivity studies including indicative site capacity for SMRs, and the potential competition for sites between nuclear and CCS power plants.

(2) System requirements for Alternative Nuclear Technologies (ANT)
This project assessed the operational performance and cost characteristics required of SMRs to enable them to deliver value as part of a 2050 low carbon energy system.

(3) Energy system analysis & sensitivity studies for nuclear
This work incorporates the results from the PPSS and ANT projects to explore the potential roles for large and small nuclear within the ETI's energy system scenarios.

FIGURE 1

2050 Electrical Generating Capacity In The ETI's Clockwork Scenario



[2] http://www.eti.co.uk/project/esme/

[3] http://www.eti.co.uk/options-choices-actions-uk-scenarios-for-a-low-carbon-energy-system/

UK timeline for nuclear

In 2013 the Government published its Nuclear Industrial Strategy[4] which included lifetime extension of the existing reactor fleet, new large reactors, SMRs, collaborative design projects for more advanced new reactors and the development of new fuel cycle technologies for deployment domestically and globally.

The Nuclear Industrial Strategy includes the following elements which are summarised in a nuclear policy decision timeline prepared by the ETI and shown at Figure 2:

» Plant Life Extension of existing UK reactor technologies

» Deployment and operation of Large Generation III+ reactors and SMRs

» Deployment and operation of Generation IV reactor technologies with appropriate fuel cycles. Generation IV reactors are intended to provide a further improvement in safety, with a more sustainable use of fuel, increased proliferation resistance, with some technologies offering the potential to "burn" long lived nuclear wastes containing actinides

Large Reactor types in a UK context

» Generation I – Magnox

» Generation II – Advanced Gas Cooled Reactors

» Generation III – Sizewell B Pressurized Water Reactor

» Generation III+ Light-Water Reactors (LWRs)* with enhanced safety

EPR PWR design for deployment by EDF

AP1000 PWR design from Toshiba Westinghouse for deployment by NuGen

ABWR design of boiling water reactor from Hitachi GE for deployment by Horizon

» Generation IV – Future reactor designs for deployment from 2040

*Light Water Reactors – Pressurised Water Reactors (PWRs) and Boiling Water Reactors (BWRs) using water with naturally occurring levels of deuterium

[4] https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/168048/bis-13-627-nuclear-industrial-strategy-the-uks-nuclear-future.pdf

The same timeline at Figure 2 also recognises that renewal and replacement of the UK energy system through to 2050 will eventually mature so that individual energy plants or groups of technologies would only next be replaced when they have reached the end of their economic lives. This is relevant because future nuclear technologies will only be deployed if there is a market need and such nuclear technologies provide the most cost effective solution. The policy questions and decisions for the period from 2020 to 2030 shown in Figure 2 include:

» What is the optimum LWR capacity (i.e. Gen III and Gen III+)?

» What is the optimum UK SMR capacity?

» How can SMR deployment be integrated with UK IP development/acquisition and deployment for the benefit of long term jobs and economic growth?

» When to stop deploying SMRs in the UK?

» Should the UK invest in Generation IV development and when should such plants be deployed?

» If Generation IV reactor technology is deployed, what should be the optimum capacity within the energy system and when should deployment cease?

The programme for the design, construction and operation of large Generation III+ reactors is now well established; by 2017 three separate designs anticipated for development in the UK are forecast to have been demonstrated through construction and operation elsewhere in the world. Final Investment Decisions are currently scheduled by EDF, Horizon and NuGen within the next few years for three separate UK new nuclear power station projects.

However, there is currently no programme for UK SMR deployment and no specific policies which would encourage the development of such a programme. In April 2015, the Department of Energy and Climate Change (DECC) launched a Government inter-Departmental Techno-Economic appraisal to run from June 2015 to March 2016 to gather information to support Government policy development with respect to SMRs.

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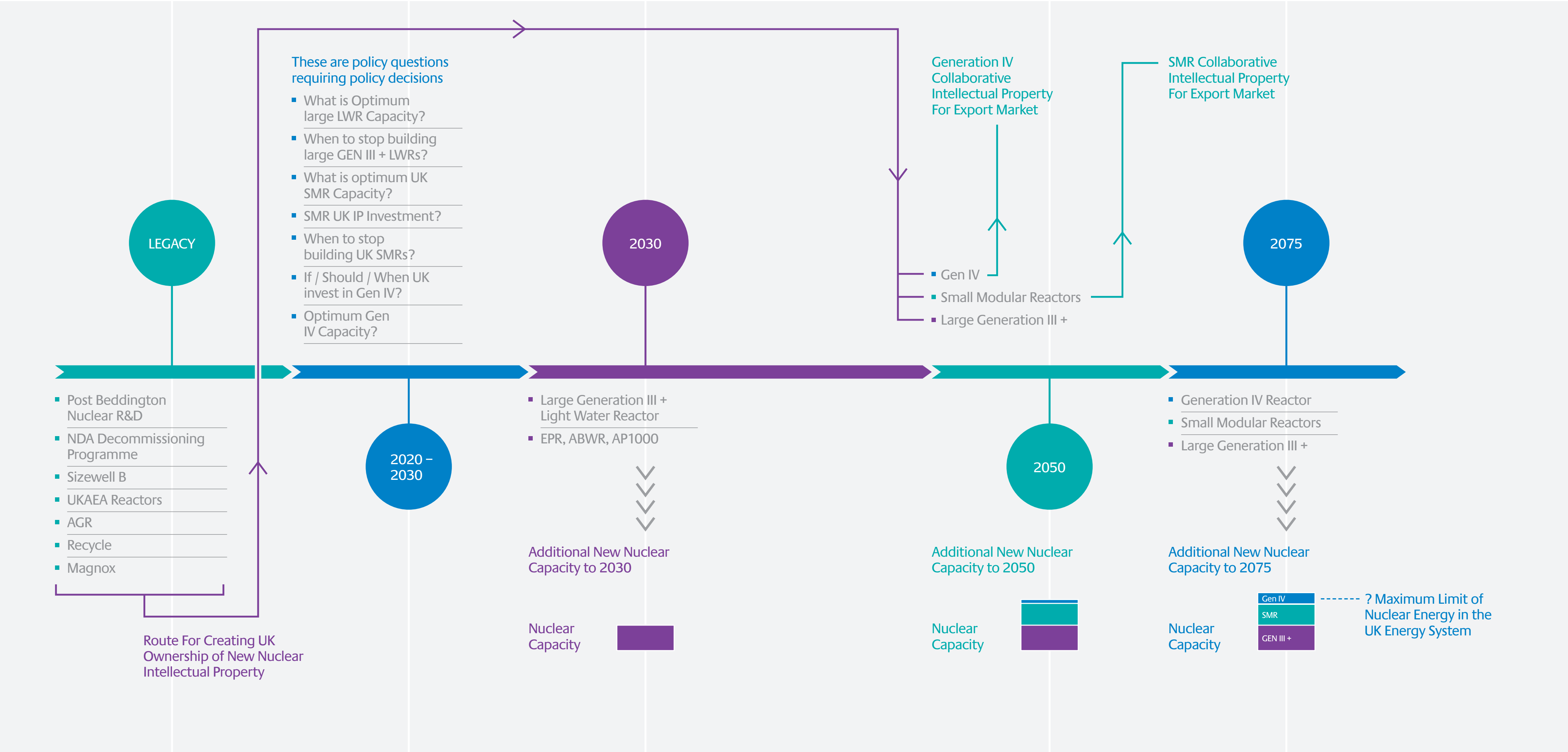
FIGURE 2

UK Nuclear Mix and Policy Decision Timeline



Siting issues and potential UK opportunities for SMRs

Whilst the ETI's Clockwork scenario includes 40 GWe of nuclear capacity by 2050, actual deployment will be influenced by a number of factors including:

- Access to sufficient affordable capital, which in turn will reflect the energy policy environment and nature of policy support for new nuclear
- The programme delivery experience of the early projects, particularly against the potential for schedule and cost over-runs
- Resource capability and capacity to continue to expand amongst supply chain, nuclear utilities and regulatory authorities
- Broader understanding of the optimum contribution from nuclear energy within the UK energy mix.

One of the less well developed constraints is the total stock of suitable sites in England and Wales for new nuclear power station development over the longer term. The requirements or criteria for such sites are set out in the National Policy Statement (NPS) EN-6 for Nuclear[5] Volumes 1 and 2.

The site capacity limit for large nuclear is also influenced by Scottish Government policy which does not support new nuclear power plants and focuses on renewables instead, and by the potential requirements for new power plants with CCS. New CCS plants will require a large construction area, a grid connection, access to water for cooling, and ease of access to potential CO_2 storage locations that have been identified in the Irish Sea and North Sea[6]. New CO_2 storage and transport infrastructure is likely to be located on the coast or river estuaries near these sites, and at key locations transport pipelines may be deployed inland away from the coast. Potential deployment of CCS pipelines along the coastline is highlighted in dark blue in Figure 3. On the coast in these areas there may be potential competition for development sites between nuclear power, thermal plants with CCS and other applications.

One of the opportunities for SMRs is that they could be deployed at a wider range of sites than large nuclear. But to be commercially successful, SMRs need to be developed and deployed in a way that overcomes the diseconomies of scale associated with smaller reactors. Potential attributes include more extensive modularisation, shorter site construction times, and manufacture and assembly of the reactor system in a factory with associated quality and productivity benefits. Other designs of SMRs seek competitive advantage by moving away from established LWR technology, including High Temperature Gas Reactors and Molten Salt Reactors.

FIGURE 3

Sites restricted to England and Wales with coastal and estuary regions of potential competition for development sites between nuclear and new thermal plants with CCS

Installed Capacity	Site Capacity For Large Reactors
16 GW	✓
40 GW	?
75 GW	✗

Key

- Scottish policy for no new nuclear
- Potential CO_2 coastal pipeline and potential for competition for development sites
- Existing nuclear power stations
- Civil nuclear process and research reactor sites

[5] https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/37051/2009-nps-for-nuclear-volumel.pdf

[6] http://www.eti.co.uk/wp-content/uploads/2014/03/A_Picture_of_Carbon_Dioxide_Storage_in_the_UKUPDATED1.pdf

Siting issues and potential UK opportunities for SMRs

Continued »

Some of the advantages and disadvantages between SMRs and large reactors are illustrated in Figure 4, but to substantiate deployment each type of reactor must find a respective role in a 2050 UK low carbon energy system which they can deliver more cost effectively than any other available technology. To achieve this, the combination of performance, emissions, deployment timescales and cost must make each of the technologies attractive to vendors, developers, investors, taxpayers and bill payers.

Large nuclear reactors are best suited for baseload electricity production and the level of capacity ultimately deployed will be influenced by a range of factors. This traditional role is shown on the left of Figure 5, where baseload reactors run at a steady maximum output between planned outages of minimum duration. As part of the electricity generation process, the heat transferred to the condensers under the turbines is discharged to the environment through the cooling water.

The diagram on the right of Figure 5 suggests the potential for a different role for SMRs. This role shows three separate outputs with three potential revenue streams:

- Some baseload electricity
- Some variable electricity, adjusted when necessary to assist with the balance of supply and demand on the grid
- Re-use of some of the heat otherwise rejected to the environment. This is mostly waste heat but heat removal at higher and more useful temperatures reduces the efficiency of the steam turbine with some small loss in power output.

The combination of the PPSS and ANT projects and subsequent analysis of the results within ESME, the ETI's national energy system design and planning capability, was designed to better understand the relationship between large reactors and SMRs, and their potential combined contribution within the ETI Clockwork scenario.

FIGURE 4

The balance of choice between large reactors and SMRs

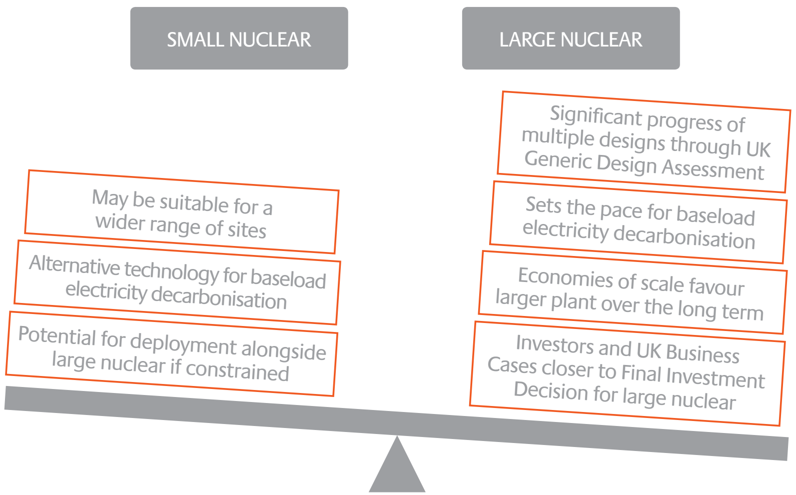
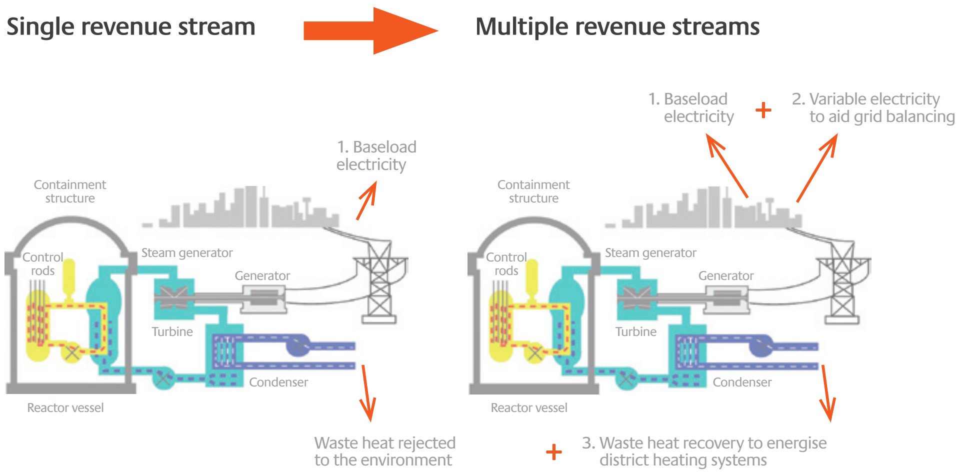


FIGURE 5

The traditional role for large baseload reactors and the potential combined roles for SMRs



ETI projects and results

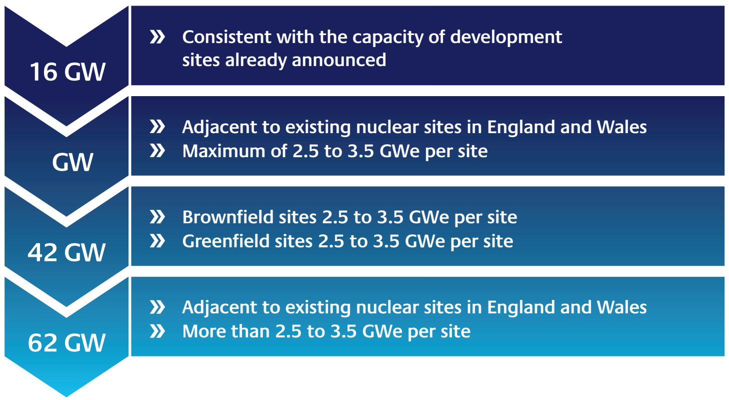
Power Plant Siting Study (PPSS) results for large reactors

The PPSS project explored the theoretical upper capacity limit for large nuclear power stations in the UK by applying the existing siting criteria from the NPS For Nuclear EN-6.

For sites for large reactors examined in the PPSS, the theoretical site capacity limit from the incremental cumulative steps identified in Figure 6 limit is around 62 GWe. This is an indicative limit established from the data in the PPSS and summarised here. Determined developers could be successful, with strong stakeholder support, at sites which fail on more than one of the discretionary criteria. This would be a change in the method of application of the criteria from NPS EN-6, and if applied could increase the theoretical capacity limit above 62 GWe.

FIGURE 6

Cumulative incremental theoretical capacity for large reactors in England and Wales



However detailed sensitivity analyses suggest that this is an unrealistic upper bound capacity for credible deployment for the following reasons:

- A number of large reactor sites encroach on buffer zones to ecologically designated areas and would require mitigation and compensation cases to be accepted
- The capacity analysis assumes deployment of 1.65 GWe units wherever possible whereas an average unit output of 1.4 GWe may be more realistic, reducing the available theoretical capacity by around 15%
- The likelihood of some sites being used for CCS in preference to nuclear power
- The unattractiveness of developing more than 2.5 to 3.5 GWe of identical units per site for reasons of grid reinforcement and system resilience
- With a limited number of sites suitable for large reactors, it is necessary to consider holding back some site capacity for the later deployment of subsequent generations of large reactors
- The PPSS identified no long term opportunities to substantially increase future large reactor capacity utilising water cooling, including opportunities from the future potential rationalisation of the MOD landholding in England and Wales. No sound basis was identified for changing or relaxing the existing criteria.

The range of factors reducing the theoretical capacity of around 62 GWe to an upper bounding limit for deployment is illustrated in the flow chart in Figure 7. In combination these factors reduce the upper bounding limit for deployed capacity of large reactors to around 35 GWe.

A combination of factors reduces the upper bounding limit for deployed capacity of new large reactors in England and Wales to around 35 GWe.

ETI projects and results

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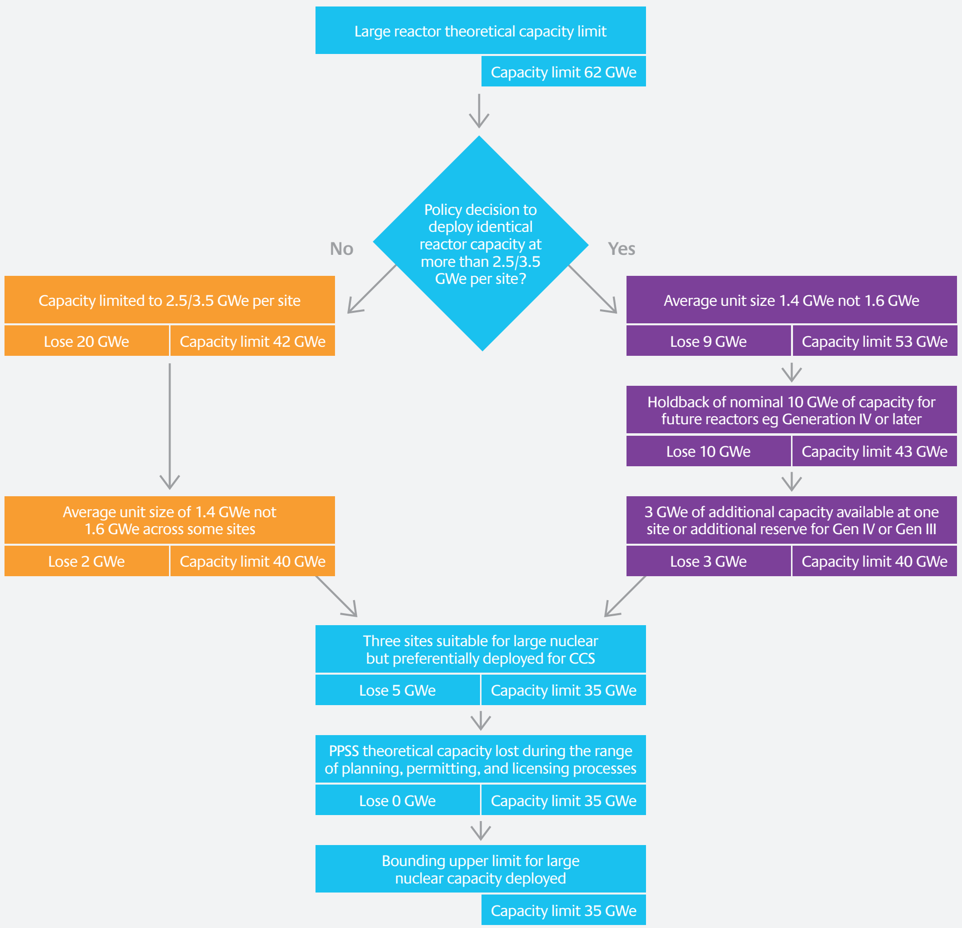
FIGURE 7

Flow chart showing the reduction from theoretical large reactor capacity to an upper bounding limit for generation III+ large reactor capacity deployed by 2050



Power Plant Siting Study (PPSS) results for SMRs

For SMRs an indicative theoretical capacity was found to be 67 GWe. An upper limit was not found as part of the PPSS and further work would be expected to identify additional SMR site capacity.

The same NPS EN-6 criteria were applied consistently with appropriate scaling for size. The SMR operational footprint is smaller and the cooling water flow requirements lower compared with a large reactor due the lower level of reactor power. Some of this SMR capacity also uses an increased distance from the water source to the power plant (when compared with the equivalent distance for large reactors) by pumping cooling water from the source to the reactor site; the maximum distance was increased from 2 km to a 20 km limit for this purpose. The reason for this change becomes clear from the ANT project which explores the application of CHP SMRs for energising city scale district heating systems. In this application a large volume of hot water in insulated pipes is being pumped from the SMR power plant to the district heating systems, whilst a much smaller volume of water in uninsulated pipes is being drawn from a nearby water source. A more cost effective solution is to increase the length of the cooling water pipe and reduce the length of the DH system supply and return pipes; at the same time this increased potential distance from the water source enables a wider choice of sites with potentially reduced flood risk and improved ground conditions.

The charts in Figure 8 illustrate the geographic distribution of SMR site capacity, and show that SMR site capacity is less constrained in England and Wales compared with large reactors.

Inland sites depend on cooling water abstracted from catchments with limited water resource availability such that water abstracted at one location is not available further downstream along the river. Complex inland watercourse modelling, or conjunctive analysis, was used to confirm that around 60 GWe of SMR capacity could feasibly operate alongside the theoretical large reactor capacity identified earlier. The capacity at inland sites is likely to be influenced by the future availability of water resources (reflecting the impact of climate change and potential changes on policy on water abstraction from rivers and other inland sources). The potentially reduced availability of abstractable fresh water was addressed as an uncertainty within the PPSS rather than directly by analysis. However the diversity in SMR site location and associated cooling water supply is evenly split between fluvial and coastal/estuary, which demonstrates diversity and choice in sites and associated cooling water supply. This is relevant for nuclear and other thermal power technologies if diminishing cooling water availability from our rivers becomes a major driver.

ETI projects and results

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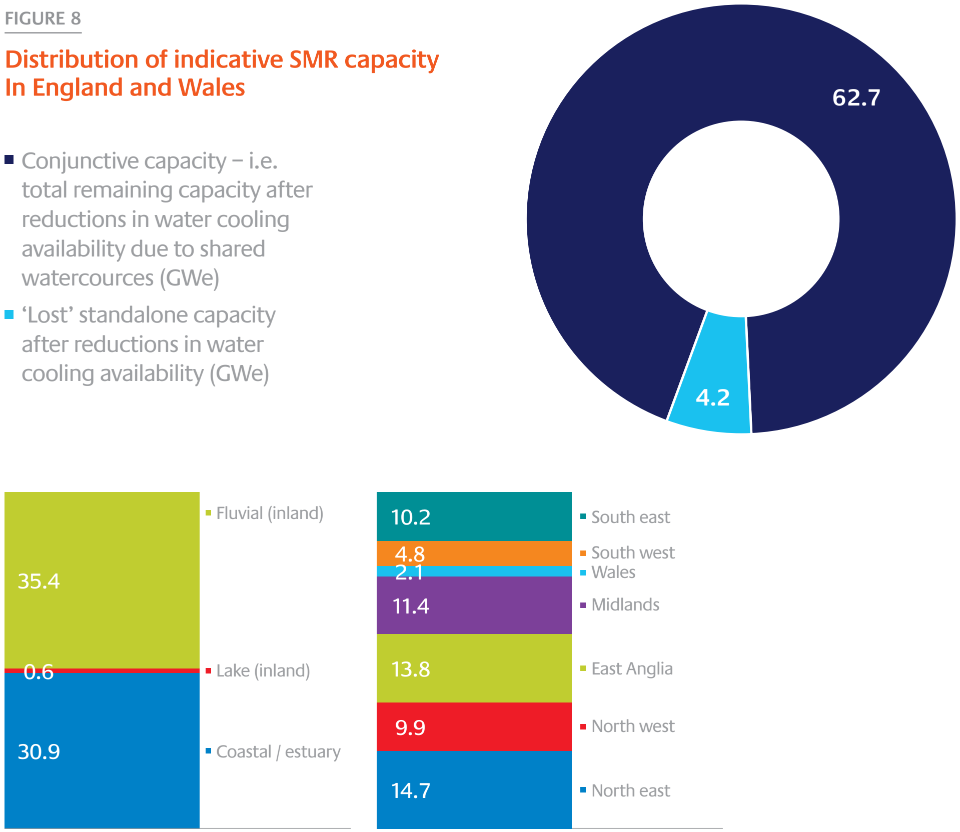
FIGURE 8

Distribution of indicative SMR capacity In England and Wales



WATER SOURCE

REGION

Theoretical capacity vs credible capacity deployed by 2050

The PPSS reflects the type of analysis that would form the first step in selecting a potential site for a nuclear power station in the UK. The next step is expected to lead to one or more of the sites identified in the PPSS being added to the existing list of sites in NPS EN-6 for the purpose of potential development for nuclear power. If a site within the NPS EN-6 list is then selected by a developer, a wide range of local investigations and consultations are commissioned to support the full range of applications necessary for development of a new nuclear power station. These successive steps are illustrated in Figure 9.

It is expected that some of the sites comprising the theoretical capacity will fail during these processes and the developer would withdraw the associated applications. For large reactors, our analysis suggests that the theoretical site capacity has already been reduced from the theoretical limit of 62 GWe to a credible capacity deployed by 2050 of 35 GWe. No allowance has been made for any of the potential sites for large reactors failing during this process; 35 GWe is therefore considered an upper bound limit.

For SMRs an indicative theoretical capacity of 67 GWe has been reduced to 63 GWe through the conjunctive cooling water assessment. Subsequent energy system modelling showed that around 21 GWe was sufficient for most scenarios and so this has been used as an indicative site capacity for SMRs. This limit applied for a broad set of ESME model runs testing SMR deployment levels alongside large reactors. However, modelling results showed higher levels of SMR deployment and demand for SMR site capacity when any of the three of large nuclear, gas turbines with CCS, or wind were significantly constrained below their respective levels of optimum deployment in the ETI Clockwork scenario.

This analysis illustrates that a significant number of SMR sites could fail in the process described in Figure 9 whilst retaining sufficient capacity in the remaining sites. This demonstrates that the overall site capacity for SMRs is much less constrained than for large reactors; consequently there is much more choice regarding potential siting locations. The PPSS explored SMR capacity without finding the ultimate SMR theoretical capacity limit; more work could be expected to successfully identify further SMR site capacity. This finding led to an approach with the PPSS which identified the majority of SMR capacity being identified as "likely to be feasible" across a very large number of sites, compared with the definitive pass or fail established for the relatively small number of large reactor sites. This indicates that the assessed capacity for SMRs is likely to be a lower bound limit.

ETI projects and results

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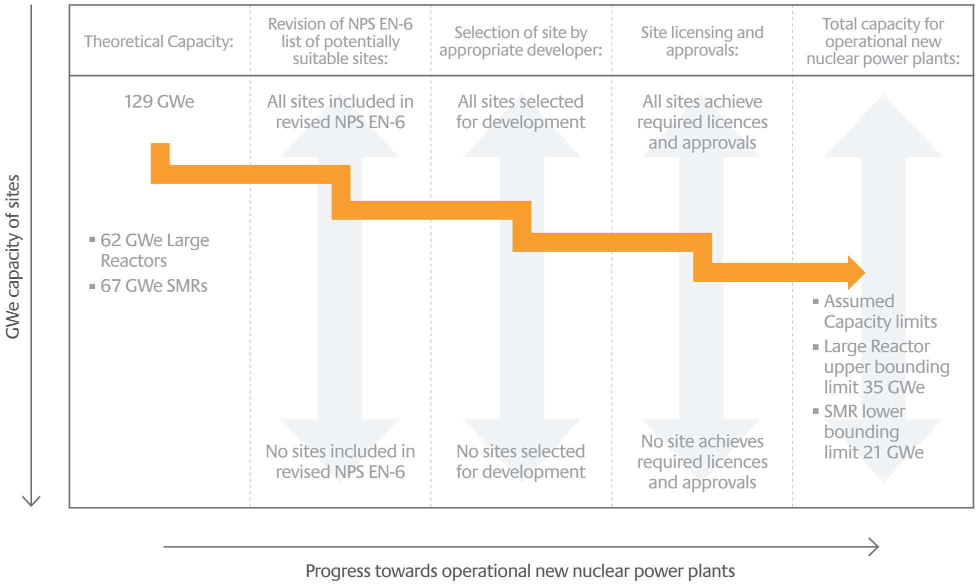
FIGURE 9

Theoretical nuclear site capacity and transition through national policy statement inclusion, site selection, and permitting and site licence application processes to lead to credible assessed capacity limits for deployment by 2050



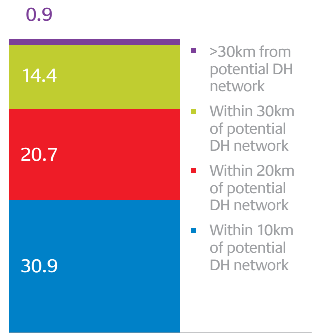
Summary from the PPSS

For large reactors, a total theoretical capacity of 62 GWe from the PPSS was assessed to provide an upper bound limit of deployed capacity of 35 GWe. It is unlikely that this level of deployed capacity would be realised due to application of the processes illustrated in Figure 9.

For SMRs, a total theoretical capacity of 67 GWe from the PPSS was assessed to provide a lower bound limit of deployed capacity of 21 GWe which was found to be sufficient for most of the scenarios tested as described on page 21. It is possible that the upper bound limit for SMR capacity is higher than 67 GWe, and that further work to identify additional sites would also increase the upper bound limit. Site capacity for SMRs is not constrained in the way it is for large reactors.

FIGURE 10

Distance of SMR capacity established in the power plant siting study to the respective local district heat networks identified in the alternative nuclear technologies project



SITE CAPACITY (GWE)

ETI projects and results

Continued »

Results from the technical workstream from the Alternative Nuclear Technologies (ANT) project

The ANT project established a comprehensive list of key technical requirements for SMRs, to support their deployment in the UK and how they would differ from those for large reactors. Such requirements included the need to transport modules during SMR power plant construction without modification to existing transport infrastructure such as road and rail bridges. Significant benefits were also identified if UK SMR technologies could use the UK nuclear waste and spent fuel infrastructure that is already committed to current and planned large LWR reactors in the UK. Although this issue delivers a cost benefit, the real driver is the certainty that within the timescale for potential SMR deployment the required downstream nuclear infrastructure will be available.

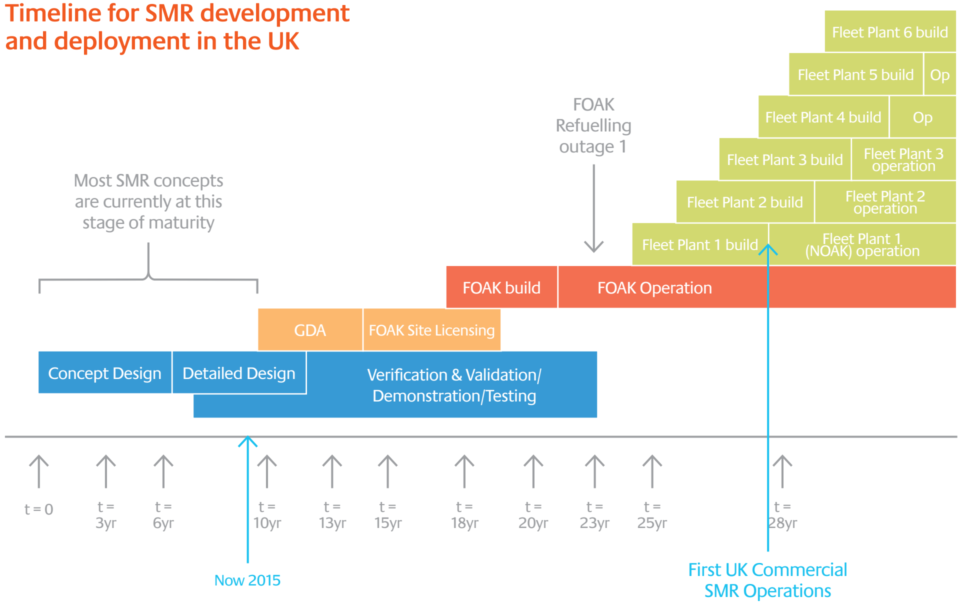
Using heat location demand data provided by the ETI, and economic benchmarks of cost effective district heating deployment elsewhere, the ANT project also established the location and size of potential city scale district heat networks in Great Britain, and identified the subset of networks in England and Wales which would be large enough to use a significant proportion of the heat output from one or more SMRs. The combined heat demand from these networks could create a demand of around 40 GW thermal from SMRs, equivalent to around 21 GWe of SMR electrical generating capacity. SMR plants could be deployed for Combined Heat and Power (CHP) production, using largely waste heat to produce hot water for district heat networks connected through large insulated supply and return pipes. The distance of indicative SMR capacity (in GWe), established through the PPSS, to the local respective district heat networks is shown in Figure 10. Shorter distances improve the economics of district heating energisation through shorter pipes and reduced energy demands for pumping. Significantly longer piping and pumping distances than these have been established as cost effective outside the UK but access to an easy unobstructed pipe route is also important for cost effective pipe installation.

The ANT technical work stream also analysed the timeline for development, deployment and operational demonstration of a First Of A Kind (FOAK) SMR. Figure 11 illustrates that the shortest period from commencement of UK Generic Design Assessment (GDA) to initial operation of the first in a batch of factory built units is around 17 years.

Achievement of the earliest possible deployment date would require selection of an SMR concept in an advanced state of maturity, but not one which has already achieved regulatory approval. The key to success lies in selecting and deploying a technology for which design completion can still be optimised to accommodate regulatory requirements in one or more other countries (non UK) in addition to those from UK GDA. This would enable a factory and associated supply chain that could supply two or more markets in parallel without further later changes to accommodate UK regulatory requirements. If a maturing technology were to progress into the GDA in the near future, then the earliest operational date for a commercial UK SMR is likely to be 2030 or soon thereafter.

FIGURE 11

Timeline for SMR development and deployment in the UK



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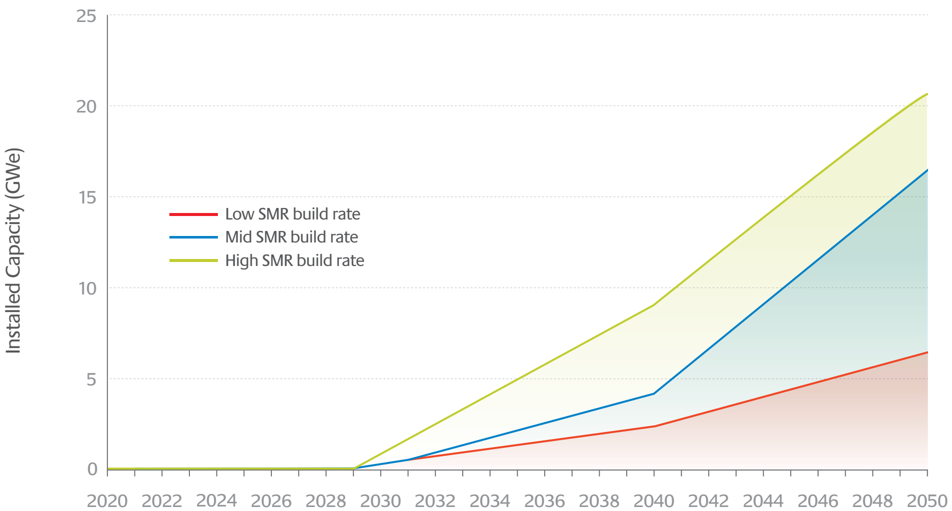
A further output from the ANT project is a build out rate assuming factory production of the reactor system in modules. The chart in Figure 12 shows high, medium and low build out rate scenarios. Each scenario features a first factory operating for a period of about 10 years when manufacturing processes and procedures are developed and improved to yield a positive learner effect, which is reflected in productivity improvements and reduced costs per unit. The next period is then a higher build out rate in a new or reconfigured factory which benefits from learning and improvements implemented. Build out rate is a key parameter within the ETI energy system modelling for which the mid-range build out scenario was used. Other build out rates are possible.

FIGURE 12

Build out rate scenarios for factory production of the reactor system in modules



Analysing the business case for SMRs from the ANT project

The future costs, development timescales and rollout trajectory for SMRs are uncertain so the analysis presented here is intended to provide an indication of the opportunities and challenges for potential future deployment of SMRs in the UK.

A cost model to derive First Of A Kind (FOAK) and N'th Of A Kind (NOAK) capital costs for a generic 100 MW scale SMR was created by adjusting established benchmark costs for diseconomies of scale, and then economies arising from mass production. These estimates shown in Table 1 (page 30) are independent of any specific vendor estimates and should be regarded as indicative because of the uncertainties involved. They are not derived from the traditional bespoke bottom up application of established reactor power plant cost breakdown structures and therefore specific design, manufacture and construction innovations are not directly taken into account.

In parallel, a discounted cash flow model was used to estimate the target Capital Expenditure (CAPEX) required to make a future SMR project commercially viable. The model estimates SMR Operational Expenditure (OPEX) costs and energy sales receipts. For electricity these revenues have been based on other low carbon technologies competing to supply electricity at around £80/MWh. For heat, the prices have been estimated from a range of alternative low carbon sources of heat such as large-scale biomass CHP plant or gas fired CHP plant with CCS. The value for low carbon heat supply has also been benchmarked against the cost of gas fired boilers for district heating energisation with a carbon penalty of £75/tonne of CO_2 in line with DECC's current projections for 2030. Together these suggest a base case price for low carbon heat of around £65/MWh.

The breakeven (target) CAPEX for electricity-only baseload SMR operation is estimated to be around £3,600/kW for NOAK SMR systems. This is illustrated in Figure 13 and suggests that, within the uncertainties of the ETI's analysis, the business case may be challenging for SMRs deployed as baseload electricity providers only. More aggressive cost reduction assumptions (e.g. supported by full scope bottom up estimates) or a higher market value of low carbon electricity could shift this preliminary assessment.

However, the economic case for SMRs becomes much more robust if configured for CHP deployment with commercial exploitation of the value of low carbon heat. Figure 14 shows how the breakeven (target) CAPEX for SMRs increases when SMRs are used in CHP mode for different amounts of heat recovery and for varying market values of heat. The heat Annual Capacity Factor (ACF) is a measure of how much of the heat output from the SMR is utilised (i.e. 30% ACF means that 30% of the annually available heat is supplied to the customer district heating system). For the three ACF values considered, three values for the future price of heat are shown (£85/MWh, £65/MWh and £45/MWh).

ETI projects and results

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The analysis shown in Figure 14 suggests that the commercial viability of SMRs will be greatly enhanced in CHP configuration. With ACFs of 30% or higher and market values for heat of between £45/MWh and £65/MWh, it appears likely that SMRs would be commercially viable based on comparison of the required CAPEX for viability and the estimated NOAK CAPEX. This is shown as £5,200/kWe in Figure 14, which is based on the 1st Factory CAPEX of £5000/kWe shown in Figure 13 with an uplift of £200/kWe for conversion from electricity only to CHP. This analysis and the subsequent ESME modelling allows for a 20% reduction in turbine power output and associated revenues when operating as CHP. However CHP SMR deployment viability is also predicated on there being suitable district heating infrastructure available to accept the heat available from such CHP SMRs. The availability of district heating systems in the timeframes when SMRs are likely to be initially deployed is consistent with the energy system transition pathways detailed in the recent "Options, Choices, Actions" ETI publication. The cost of this infrastructure has also been included in the in-house energy system modelling performed by the ETI which is summarised later in this paper.

FIGURE 13

Cost model projections and breakeven capex levels for electricity only generic SMRs of 100 MWe Scale

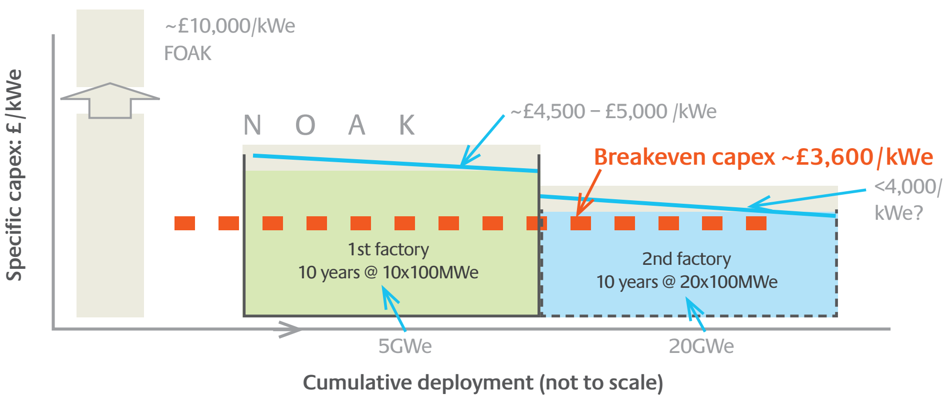
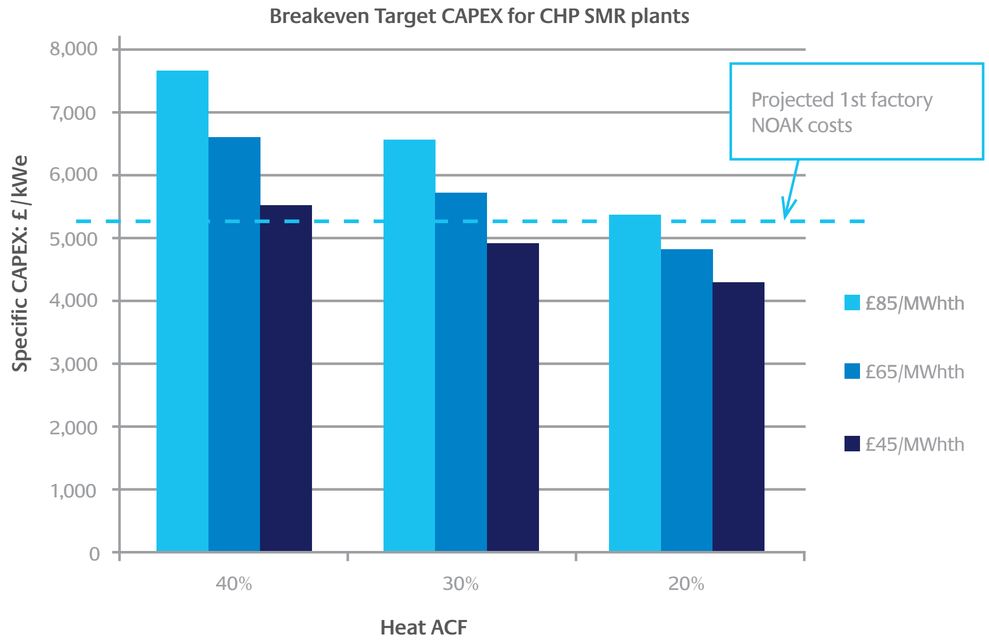


FIGURE 14

Breakeven Target CAPEX vs indicative cost scenario for a baseload CHP SMR plant



ETI projects and results

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Summary From The ANT Project

Within the significant uncertainties involved in this approach our preliminary analysis, summarised in Table 1, suggests that the commercial viability of electricity only (traditional baseload) SMRs is likely to be challenging and would require design innovation and aggressive cost reduction.

However commercial viability is much more likely to be achieved if UK SMRs are configured and deployed for CHP operation with the supply of heat to city scale district heating systems in combination with electricity generation. Whilst novel to the UK, the Beznau nuclear power plant in Switzerland has been delivering electricity to the grid and heat to the Refuna district heating system for over 30 years[7].

TABLE 1

Indicative NOAK costs for a generic 100MWe scale SMR power plant against likely target costs to achieve commercial viability

100 MWe scale generic smr power plant	Indicative NOAK capital cost	Target cost based on expected future prices and revenues
Electricity Only	£4500 to £5000/kWe	£3600/kWe
Combined Heat and Power	£4700 to £5200/kWe	£6300/kWe (40% ACF and heat price at £65/MWh) £4800/kWe (30% ACF and heat price at £45/MWh)

[7] https://www.axpo.com/content/dam/axpo/switzerland/erleben/dokumente/axpo_KKB_prospekt_en.pdf.res/axpo_KKB_prospekt_en.pdf

Results From ETI Energy System Analysis and Sensitivity Studies Within The ETI Clockwork Scenario

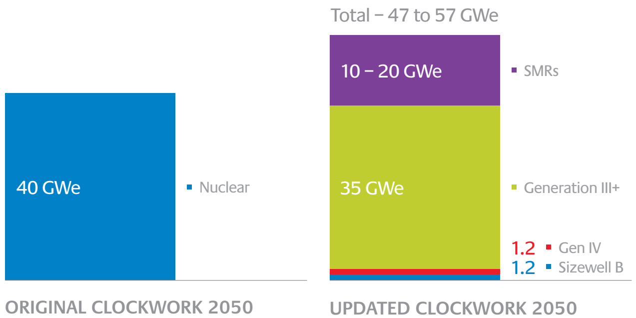
The ETI has published scenarios for a UK energy transition. Further adjustments were made to the "Clockwork" scenario, incorporating data derived from the PPSS and ANT analyses. The results of this energy system analysis showed relatively little overall change in the transition timelines and technologies deployed during the transition, but with some small shifts in contribution from individual technologies within the mix.

The 2050 contribution from nuclear in this updated scenario analysis illustrated in Figure 15 is delivered by:

- 1.2 GWe of legacy generation from Sizewell B which is assumed to operate for a life of 60 years from a first operations date of 1995
- 35 GWe of large Generation III+ reactors deployed to the site capacity limit
- 16 GWe of SMRs deployed as a dispersed fleet around the larger cities of England and Wales providing CHP. These deliver hot water via pipelines up to 30 km long to city scale district heating systems as well as electricity generation to supply the grid
- 1.2 GWe from a single Generation IV power plant deployed in the 2040s as a signpost back to the Government Nuclear Industrial strategy.

FIGURE 15

Updated contribution from nuclear within the Clockwork scenario using PPSS & ANT Project Results



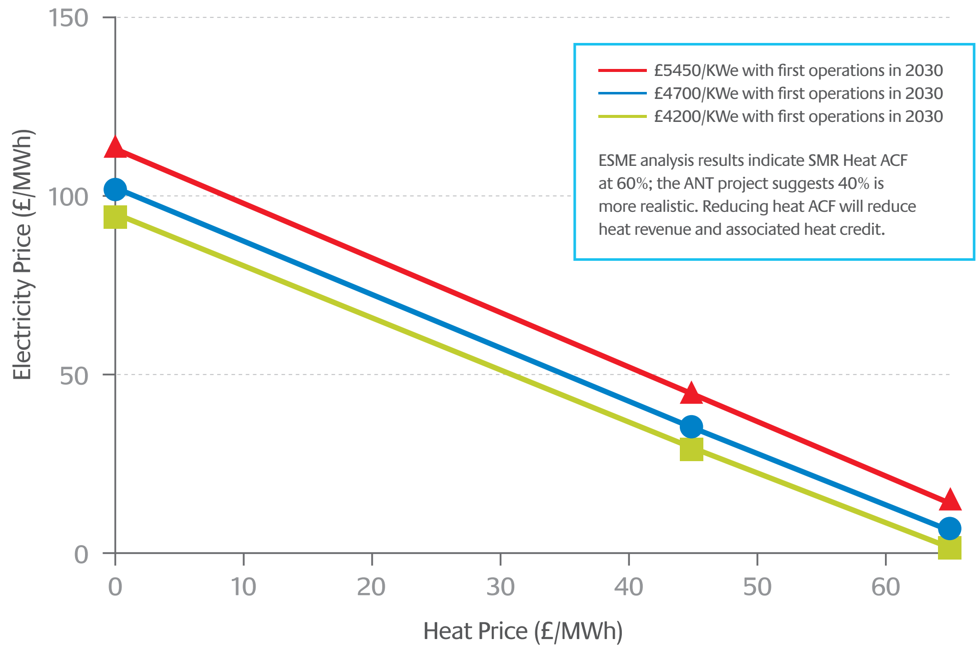
There is additional learning from ESME sensitivity studies which is not shown in Figure 15:

- » The two dimensions which most strongly influence the levels of SMR deployment are first operations date for a UK commercial SMR (i.e. speed to deployment) and level of CAPEX for n'th of a kind deployment (i.e. cost of deployment). At lower levels of CAPEX for CHP SMRs and combined with an earlier first operational date of 2025, CHP SMR deployment increases to around 20 GWe. At higher levels of CAPEX for CHP SMRs and combined with a later operational date of 2035, CHP SMR deployment decreases to around 10 GWe
- » Electricity-only SMRs are not generally deployed because reductions in our assumptions for capital cost are required to make them cost competitive for baseload electricity. When they are deployed, the deployment dates are generally later in the energy system transition when additional electricity generation capacity is required in the late 2030s and 2040s. This conclusion is strongly influenced by the assumed capital costs which remain subject to considerable uncertainty
- » In daily periods of lower electricity demand, such as summer nights, the electrical output from SMRs could be required to ramp down and up to aid balancing of the grid. This emphasises the requirement for flexible generation with the required capability to deliver a shaped power delivery profile to match system demand and the availability of other sources of generation.

ESME calculates the Levelised Cost of Electricity (LCoE), but for a CHP plant provides no credit for heat supplied. Using the ESME LCoE and the total annual electricity supplied, annual breakeven revenues have been calculated. By maintaining the CHP plant breakeven revenue at the same level, the heat supply revenue using the ANT future heat prices are applied creating a discounted price for electricity. This is the norm for applying heat credit to electricity prices in 2050, as shown in Figure 16 for three different CHP CAPEX levels. These CHP SMR heat supply results from ESME show a consistent Annual Capacity Factor for heat in 2050 at around 60% whereas the ANT project anticipated an upper limit of around 40%. This accounts for the more favourable discounted prices for electricity in Figure 16 compared with the breakeven revenues anticipated in the ANT project. Greater understanding of the transition to low carbon heating and the fundamental link between local implementation and strategic system planning is an important part of the ETI Smart Systems and Heat Programme; this will further inform estimates for the future values for Heat ACF for CHP plants.

FIGURE 16

SMR breakeven LCoE derived from electricity revenues and heat offtake results from ESME and application of heat credit using heat prices from the ANT project



The role for nuclear in a low carbon energy system

Table 2 shows the differing roles and deployment dependencies between large reactors and SMRs. There are no technical characteristics of large reactors which preclude them from being configured and deployed as a combined heat and power plant. The differentiation is about timing and markets:

- The design and layout of the first three large reactor designs is fixed and committed within the GDA process. A UK SMR is yet to enter the GDA process and the design is not yet fixed
- The large reactor sites are generally more remote from cities creating longer piping distances and higher pumping loads
- The thermal output from large reactors is vast and few UK city scale district heat systems could absorb sufficient heat to justify compromising the electrical generating capacity and operating efficiency of a large reactor.

TABLE 2

Roles and deployment dependencies for large reactors and SMRs in a 2050 UK low carbon energy system

Characteristic	Large generation III+ nuclear power stations	Small modular reactors configured as combined heat and power plant
Role	Baseload electricity generation	Flexible electricity generation to complement baseload. Supply of heat to city scale district heating systems
Site capacity	Upper bounding limit of 35 GWe across 12 to 14 locations	Lower bounding limit of around 21 GWe. More capacity likely to be available if required. Dispersed portfolio of sites around England and Wales at distances of up to 30 km from potential city scale district heating networks
Capacity deployed in cost optimised "Clockwork Scenario"	35 GWe at CAPEX and OPEX cost assumptions used within ESME	Between 10 and 20 GWe depending on CAPEX levels, speed of deployment of first commercial plant in the UK, and availability and competitiveness of other low carbon sources of heat. Analysis suggests around 16 GWe of CHP SMRs based on a first UK commercial CHP SMR operating in 2030 and with NOAK CAPEX cost of around £5000/kWe
Dependencies In ETI Clockwork Scenario	» Rate and scale of deployment is influenced by the access to affordable capital, the achievement of positive Final Investment Decisions (FIDs), and the FID interval between successive power station projects launched by each developer » Assumes that all of the 35 GWe of site capacity can be realised	» The rate and scale of deployment is influenced by the access to affordable capital, the achievement of positive Final Investment Decisions (FIDs), and the FID interval between successive CHP SMR energy plants launched » Future heat markets arising with district heat networks and the associated contractibility of heat supply will be crucial in potential business cases for CHP SMRs » Progress with key enablers needs to begin now if SMRs are to be available in the mid 2020s as one of a range of technologies for potential deployment. This includes early SMR entry into the UK GDA process » Flexible power delivery required
Public acceptability	Optimised deployment of UK new nuclear would be expected to move beyond the group of existing nuclear power sites. This in turn requires a strategic approach to siting and the associated phases of public consultation. SMR siting is likely to raise a new set of public acceptability challenges and opportunities	

Enabling activities to make progress towards UK SMR deployment

Considerable uncertainties remain regarding costs and schedules for the deployment of a first of a kind commercial SMR plant in the UK. Our analysis suggests that it may be challenging for SMRs to be cost competitive for baseload electricity generation only, particularly if large reactors are being deployed successfully in the UK market at regular intervals. However, given uncertainties around costs and schedules for SMR development and deployment, it is too early and inappropriate to rule out the viability of SMRs for cost effective baseload generation.

Our analysis shows that the UK could deploy SMRs at the earliest by 2030 or soon thereafter, and that SMRs are likely to deliver the greatest benefit to the UK energy system when configured for CHP operation. Scenario analysis also shows that timescales to deployment and capital costs are the primary influences on the level of deployment (and associated benefit to the UK energy system). Progressing enabling activities in parallel with further refinement of SMR costs and schedules is needed to enable the earliest deployment of SMRs.

Our work on the ANT project also touched on the policy considerations and enabling activities needed to support SMR development. This is shown in the form of an indicative timeline in Figure 17 setting out some of the deployment issues which are specific to CHP SMRs.

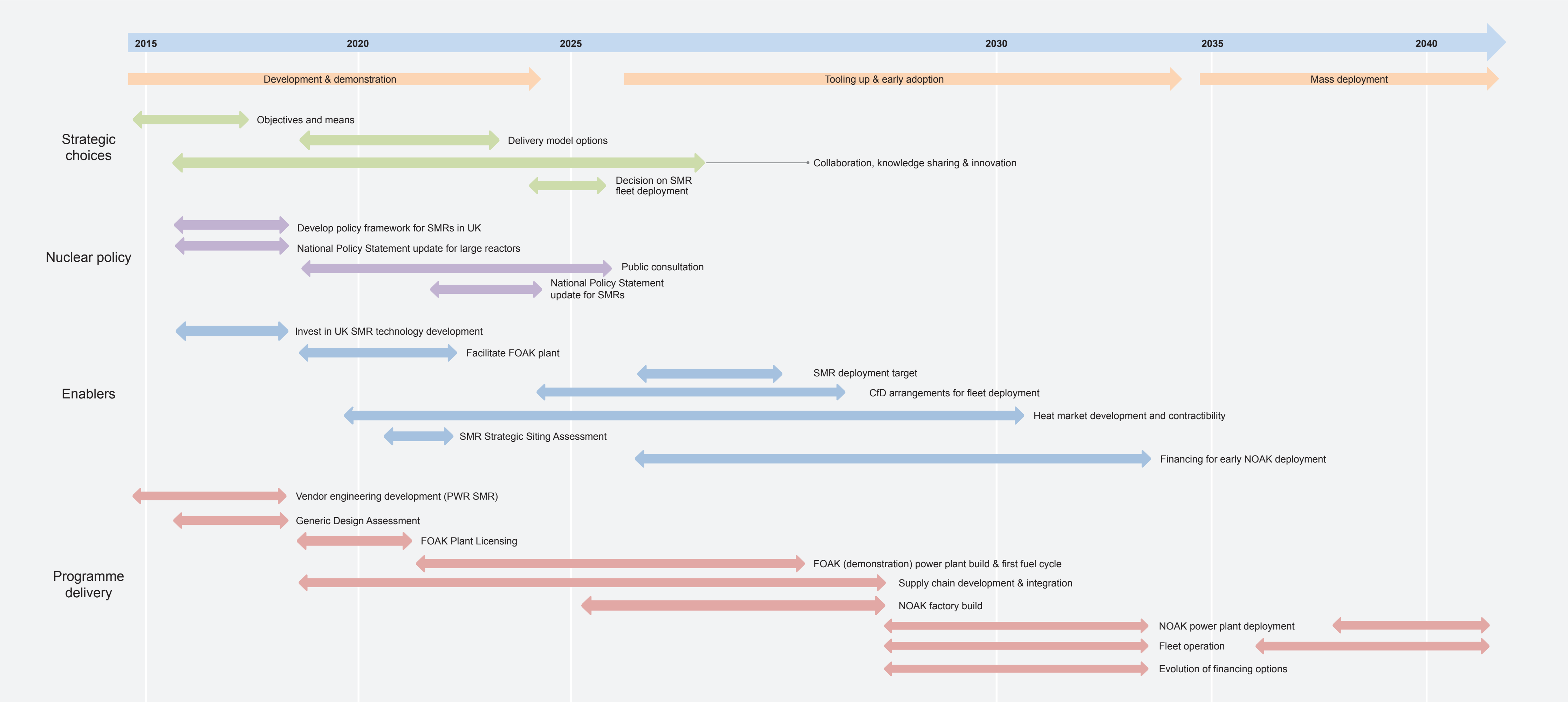
Uncertainties also remain with the rate of city scale district heating deployment and the enabling transition activities necessary to deliver them. District heat networks could be developed initially with conventional heat sources such as gas CHP or biomass, and gradually extended and linked to lower carbon heat sources such as marine heat pumps, geothermal or low carbon heat from thermal plants such as SMRs. District heat network deployment can go ahead of CHP SMRs as there are already available low or zero carbon technologies to energise them. However deployment of CHP SMRs is likely to be dependent on the ready availability of district heat networks as potential markets for low carbon heat.

Enabling activities to make progress towards UK SMR deployment

Continued »

FIGURE 17

Indicative timeline for SMR development & deployment in the UK



Conclusions

A range of analyses by the ETI and others suggest that new nuclear power, along with conventional power stations with CCS and renewables are likely to be key in delivering low carbon electricity in the future in the UK.

Large nuclear reactors (typically 2-3 GWe per power station) are best suited for continuous electricity production; the amount ultimately deployed in the UK by 2050 will reflect a range of factors, including the availability of suitable sites. New ETI analysis concludes that the upper bounding limit for these large nuclear power stations in England and Wales (to 2050) is around 35 GWe based on the availability of sites. Other factors, including financing, rollout profile and cost trends during construction, may combine to constrain eventual deployment to less than 35 GWe.

ETI analysis has also shown that a fleet of Small Modular Reactors (SMRs), typically of the order 50-300 MWe per unit and deployed as multiples where required, could complement large nuclear plants within a future low carbon UK. SMRs could deliver a combination of heat and electricity generation CHP at appropriate locations. Low carbon heat from SMRs could make a major contribution to the decarbonisation of energy use in buildings, particularly within cities where other solutions such as electric heat pumps may prove to be less cost effective, as identified in ETI's insight report on decarbonising heat for UK homes.

Given their scale, SMRs offer greater flexibility to site and deploy compared with large reactors, creating the potential to deliver heat into cities via hot water pipelines with a length of up to 30 km. Within England & Wales, around 60 GWe of SMR site capacity has been identified as being theoretically feasible. ETI's energy system modelling suggests that between 10 and 20 GWe of CHP SMRs In England and Wales could be competitive. Considerable uncertainties remain around SMR costs, their cost reduction potential and first deployment dates.

In addition, if large reactors are providing baseload electricity, SMRs will be required to deliver power flexibly, following a daily power profile when necessary to aid balancing the grid when power supply exceeds demand. This will also be required within a system which includes a significant capacity of intermittent renewables.

The next 10 years will be critical in developing the deployment-readiness of key technology options for the UK's low carbon transition to 2050. New nuclear plants can form a major part of an affordable transition, with both large nuclear and SMRs potentially playing a significant role. New large scale reactor designs are already being deployed outside the UK and are suitable for deployment in the UK. But action needs to be taken now if the option to deploy SMRs as part of the UK's low carbon transition is not to be closed off. Progressing critical enabling actions now, in particular SMR entry into the UK Generic Design Assessment process, will retain the option of deploying flexible SMR technology and offer the greatest potential benefits for any UK low carbon transition.

Optimising deployment of both large scale and SMR nuclear power is also likely to require a strategic approach to siting and the associated phases of public consultation. Optimised deployment is likely to include brownfield and greenfield sites in addition to existing nuclear power locations.

Appendix A

ESME modelling approach

The ETI has developed its Energy System Modelling Environment (ESME)[8] – an internationally peer-reviewed national energy system design and planning capability – to identify the lowest cost decarbonisation pathways for the UK energy system. This involves running hundreds, even thousands of simulations, exploring the variation on cost optimal designs within a range of assumptions and constraints in order to identify robust strategies against a broad range of uncertainties.

ESME covers the whole energy system for the UK, meaning the ETI can look in detail at possible designs for infrastructure, supply and end use technologies for heat, electricity, personal transport, freight, industry and so on.

We have tested the designs by removing and adding certain technologies and adjusting their cost and performance characteristics. The runs allow us to understand which are the most valuable (combinations of) technologies under different conditions, which are the most robust, and which technologies act as effective insurance options in case a first technology fails to deliver.

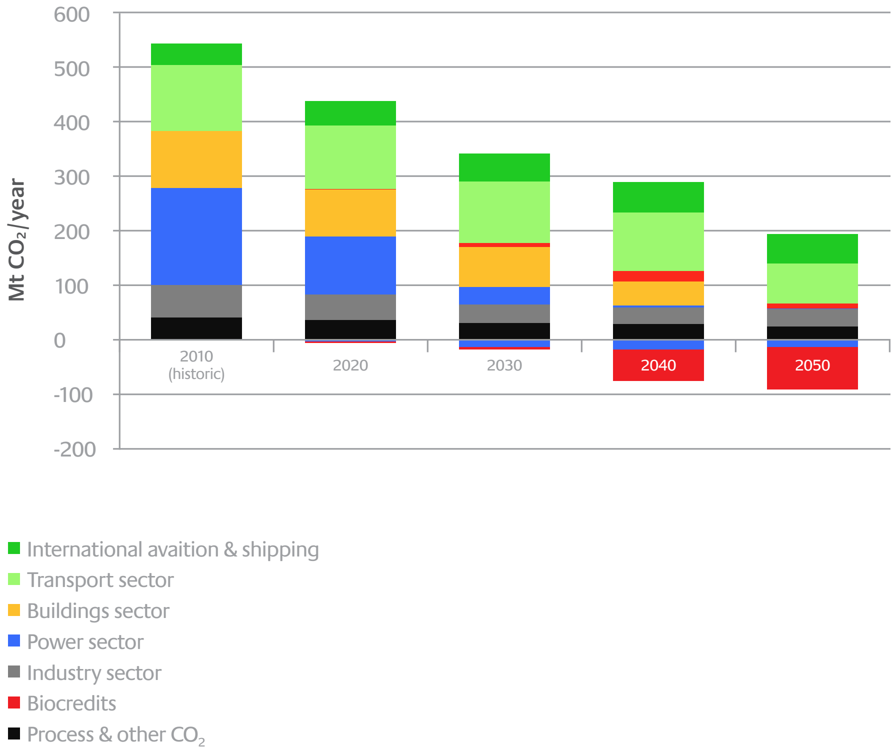
We recognise that techno-economic optimisations are imperfect. Many low carbon solutions have benefits and drawbacks that cannot be easily represented in this fashion. That is why the ETI analysis is supported by detailed research around consumer needs, environmental impacts, business models and more across our entire portfolio.

A typical ETI decarbonisation transition scenario for the UK

A typical UK energy system transition scenario generated by the ETI is shown in Figure A1, which demonstrates the full range of sectors to be considered within the transition to achieve compliance with the legal requirement for abatement of Green House Gases (GHG) by 2050. This transition shows a substantial decarbonisation of power by 2030, followed by the use of decarbonisation of energy use in buildings. The creation of "bio-credits" by combining biomass use with carbon capture and storage technologies becomes increasingly important if significant levels of carbon emissions are to continue within the sectors of international aviation and shipping, and transport.

FIGURE A1

CO$_2$ emission reduction in a typical ETI ESME transition scenario



[8] https://www.eti.co.uk/project/esme/

Glossary

ACF	Annual Capacity Factor
AGR	Advanced Gas Cooled reactor
ANT	System Requirements For Alternative Nuclear Technologies
BWR	Boiling Water Reactor
CAPEX	Capital Expenditure
CCS	Carbon Capture and Storage
CfD	Contract for Difference
CHP	Combined Heat and Power
DECC	Department of Energy And Climate Change
DH	District Heating
ESME	ETI's energy modelling system – Energy System Modelling Environment
FID	Final Investment Decision
FOAK	First Of A Kind
GDA	Generic Design Assessment
Gen III+	Generation III+; generic grouping of current designs of reactor
Gen IV	Generation IV; future designs of reactor for deployment from around 2040
GHG	Green House Gases
GWe	Giga Watts of electricity
LCoE	Levelised Cost Of Electricity
LWR	Light Water Reactor
NDA	Nuclear Decommissioning Authority
NOAK	Nth Of A Kind
NPS	National Policy Statement
OPEX	Operations Expenditure (non-capital)
PPSS	Power Plant Siting Study
PWR	Pressurised Water Reactor
SMR	Small Modular Reactor
Solar PV	Solar Photo Voltaic
UK IP	Intellectual Property held by UK organisations

Relevant ETI documents available online

Options, Choices, Actions

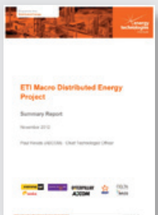
http://www.eti.co.uk/options-choices-actions-uk-scenarios-for-a-low-carbon-energy-system/

Decarbonising Heat for UK Home – an insights report by the ETI

http://www.eti.co.uk/wp-content/uploads/2015/03/Smart-Systems-and-Heat-Decarbonising-Heat-for-UK-Homes-.pdf

ETI's Smart Systems and Heat Programme

http://www.eti.co.uk/wp-content/uploads/2014/03/7763_ETI_SSH-Updated-November-12.pdf



ETI's Macro Distributed Energy Project

http://www.eti.co.uk/macro-distributed-energy-project/

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