NUCLEAR FOR NET ZERO

A UK WHOLE ENERGY SYSTEM APPRAISAL

PROJECT SUMMARY REPORT

June 2020

Part of Energy Systems Catapult's
Net Zero programme, funded by:

Innovate UK

es.catapult.org.uk

Contents

1. Executive summary

This report sets out the findings from whole energy system analysis of the potential roles and contribution from nuclear energy in supporting different decarbonisation pathways to achieve UK Net Zero.

The analysis summarised in this report is the most recent analysis in a series of nuclear techno-economic assessments undertaken using ESC's Energy System Modelling Environment (ESME) since 2015.

The underlying nuclear technology related data and assumptions incorporate the learning from engagement with the nuclear sector and the knowledge from the Energy Technology Institute's portfolio of knowledge building projects within its nuclear programme. The ETI closed in December 2019 and ESC now owns, operates and updates ESME.

The key conclusions from this new analysis, known as Nuclear for Net Zero (NFNZ) are:

1. Nuclear is potentially an important part of the future Net Zero energy system in the UK but nuclear cost reduction is a necessary pre-requisite. Cost reduction is baked into the N'th-of-a-Kind cost assumptions used in this analysis. One of the key enablers to nuclear cost reduction is the intentional commitment to programmes of capacity rather than individual unconnected projects. In the absence of credible plans to realise nuclear cost reduction, a UK net zero energy system without nuclear is possible but targeting such a system is risky (unlikely to get to Net Zero) and potentially expensive. Such a non-nuclear scenario might require significant bioenergy and land use change, as well as a vast quantity of renewable energy.

2. Energy from wind is the key technology for decarbonising power. There are important potential roles for nuclear and multiple applications for Carbon Capture and Storage (CCS). CCS deployment should be targeted at various applications for hydrogen production; Bioenergy with Carbon Capture and Storage (BECCS) is important to counter the impact of residual emissions (mainly in aviation and livestock but also fossil CCS).

3. If District Heating (DH) is to be deployed at scale in cities for decarbonising heat in homes and domestic hot water production, then low grade heat from low carbon thermal power plants including nuclear is a very cost-effective heat source.

4. One of the challenges with deploying city-scale DH is the installation of piping. All reactor types are capable of cogeneration deployment to supply the lower grade heat required; light-water nuclear SMRs are a good match for thermal energy demand and can be deployed closer to the centre of demand meaning shorter connecting pipes and lower costs for many potential DH locations.

5. Hydrogen is a very important energy vector for net zero. Hydrogen production methods using fossil fuels with CCS create residual emissions which must be compensated for using accounting methods linked to other technologies with carbon credits. Increasing carbon capture rates to potentially 99% reduces the impact from these residual CCS emissions when used with fossil fuels.

6. Advanced nuclear plants coupled with higher temperature more efficient hydrogen production technology can be a cost-effective source of additional hydrogen with low carbon footprint and relatively low land-take.

7. Nuclear can have an expanded role in power generation as well as supplying heat for DH energisation and hydrogen supply into a future network for multiple applications.

8. Market, policy and regulation analysis within this report indicates the importance of developing and consulting on policy frameworks for domestic heat decarbonisation, industrial heat decarbonisation, and the timing and characteristics of the future UK hydrogen supply market.

9. The potential policy approach for nuclear suggested by this new analysis is to initially launch around 10 GWe of additional new Gen III+ reactor capacity and in parallel to support stage gated development programmes for UK deployment of LWSMR and Gen IV. Optimum levels of further nuclear capacity additions would be better informed by 2030. **The decision for large Gen III+ reactors is not when to start, but when to stop.** An initial optimised programme of around 10 GWe of new Gen III+ capacity beyond HPC is a decision of low or no regret provided construction duration and costs continue to reduce as predicted by the findings of the ETI Nuclear Cost Drivers project. The ETI project indicated the importance of a handful of relatively simple concepts in enabling nuclear cost reduction including commitment to a programme of capacity rather than individual unconnected projects, and the benefits from deployment of multiple units in an uninterrupted construction sequence on the same site. This additional capacity can be expected to potentially commence operations between 2028 and 2035 if suitable projects are committed at the right time. Over the next 5 years, staged gated reviews of LWSMR and Gen IV development programmes would provide a clearer indication of the likelihood of realising the anticipated benefits from these two technologies. This additional understanding, accompanied by progress in the development of other low carbon energy technology programmes, would support further periodic policy reviews and decisions in the period 2025 to 2035 regarding policies for deployment of LWSMR, Gen IV, and the continued deployment of Gen III+ with reducing costs.

10. Change is required if the UK is to get on track for Net Zero by 2050. If nuclear is to fulfil its potential role in decarbonising the energy system, then the policy framework must change and both UK Government and the nuclear sector (represented by the Nuclear Industries Association) have a role to play in leading and enabling such a change.

2. Introduction

2.1. Introduction to Energy Systems Catapult

Energy Systems Catapult was set up to accelerate the transformation of the UK's energy system and ensure UK businesses and consumers capture the opportunities of clean growth.

The Catapult is an independent, not-for-profit centre of excellence that bridges the gap between industry, government, academia and research.

We take a whole system view of the energy sector, helping us to identify and address innovation priorities and market barriers, to decarbonise the energy system at the lowest cost.

2.2. ESME Whole Energy System Model

Energy System Catapult has benefitted in its growth and capability from the transfer of people, tools and intellectual property from the Energy Technologies Institute (ETI) which closed in 2019. The ETI was a UK partnership that operated between Government and six energy companies from 2007 to 2019. In 2010, the ETI developed its whole energy system model known as ESME, which has been benchmarked and internationally peer-reviewed. ESME models the combinations of technologies to be deployed up to 2050, meeting decarbonisation targets at least cost. ESME covers the whole of the UK, including power, heat, transport, industry, international aviation and shipping.

The ETI strategy was to execute a £500M programme of projects to advance valuable low carbon technologies and acquire Intellectual Property (IP) to refine the ESME model representing low carbon energy technologies. From September 2017, and in anticipation of ETI closure, the ESME model, the supporting knowledge, and around 20 subject matter experts were transferred from the ETI to Energy Systems Catapult (ESC).

2.2.1. The Insights from Scenario Modelling Using ESME

ESME was developed for the purpose of examining decarbonisation pathways with multiple low carbon technologies. It was purposefully designed to be technology and policy neutral. It characterises particular technologies using only "Nth of a kind" data for construction, operational performance and costs. By examining multiple scenarios and pathways, its principal purpose is to identify technologies that are repeatedly selected amongst the least cost solution sets produced by the model. Such technologies emerge as potential deployment choices of little or no regret.

Given that so many uncertainties are associated with future technologies yet to be deployed, ESME employs a probabilistic (Monte Carlo) feature to undertake many simulations and again identify technologies that are repeatedly selected amongst the least cost solution sets produced by the model. To identify such technologies of little or no regret, it is good practice to combine deterministic analysis with Monte Carlo probabilistic analysis to develop more resilient conclusions.

2.2.2. Transferring the Learning from ESME Scenarios into Potential Development Recommendations for Markets, Policy and Regulation

ESME does not provide blueprint solutions for future energy systems. The insights from ESME can be valuable for policymakers in identifying the most beneficial technologies to be brought forward into commercial deployment. This happens through the application of policy and regulation to stimulate and enable the deployment of such new technologies through market frameworks.

2.2.3. ESME is not a Commercial Market Model

A key point in considering the learning from ESME scenario outputs is that ESME is not a commercial market model, in that it does not:

- include or account for the cost of technology development prior to deployment
- include or account for the transition in cost from First of a Kind (FOAK) to Nth-of-a-Kind (NOAK)
- differentiate between the Weighted Average Cost of Capital (WACC) that may apply to a FOAK multi-billion pound energy infrastructure development with associated perception of risk, and the WACC attributable to the relatively routine deployment of renewables such as solar Photo Voltaic (PV)

There is a need for a parallel market model to understand the commercial challenges of first deployment and subsequent transition towards wider deployment leading to representative NOAK cost for deployment. Market, policy and regulatory initiatives are necessary to stimulate development and deployment by addressing these commercial challenges.

ESME is not a commercial market model, and the inputs and outputs should not be considered as if ESME was a commercial market model.

2.2.4. ESME Development By ESC

ESC has continued to develop ESME with its associated scenarios and technology sets since transfer from the ETI. The technical development enabling net zero analysis is described in more detail in section 4.

2.3. The Energy Technologies Benchmarking Project Funded by IUK

ESC has delivered a programme of work packages exploring the implications of Net Zero across a portfolio of technologies and solutions. In March 2020, ESC launched its "Scenarios Report"[1], as Work Package 1, alongside the development of six further deep dive work packages:

2. Offshore wind
3. Storage and flexibility
4. Gaseous systems in buildings
5. Public understanding and attitudes to Net Zero
6. Evaluating digital technologies
7. Nuclear technologies – Work Package 7

[1] Innovating to Net Zero. Energy Systems Catapult 10th March 2020. https://es.catapult.org.uk/reports/innovating-to-net-zero/

2.4. Introduction to the Nuclear for Net Zero Project

An ESME sensitivity work package was designed in October 2018 to incorporate the learning from the ETI's Nuclear Cost Drivers (NCD) project and inform the ETI's final nuclear insight report. Given the trajectory for the ETI's closure in 2019, the ETI was unable to support the delivery of a full further ESME sensitivity analysis, but the ongoing requirement was reported in pages 30 and 31 of the ETI's final nuclear insight report released in June 2019 (see section 3 for more details). This requirement was incorporated as Work Package 7 within the scope of the IUK funded ESC Energy Technologies Benchmarking project. This project is reported as "Nuclear for Net Zero" (NFNZ) through the inclusion of the following scope as shown in Figure 1:

- The introduction of an additional nuclear technology dataset into ESME for the cogeneration of power and production of hydrogen
- The task of providing the dataset for the new technology and updating the datasets for large Gen III+ plants and light-water nuclear Small Modular Reactor (LWSMRs)
- Designing the series of ESME sensitivity runs to test the potential role and contribution from the different nuclear technologies within the model
- Reporting of results
- The consideration of potential action with respect to markets, policy and regulation

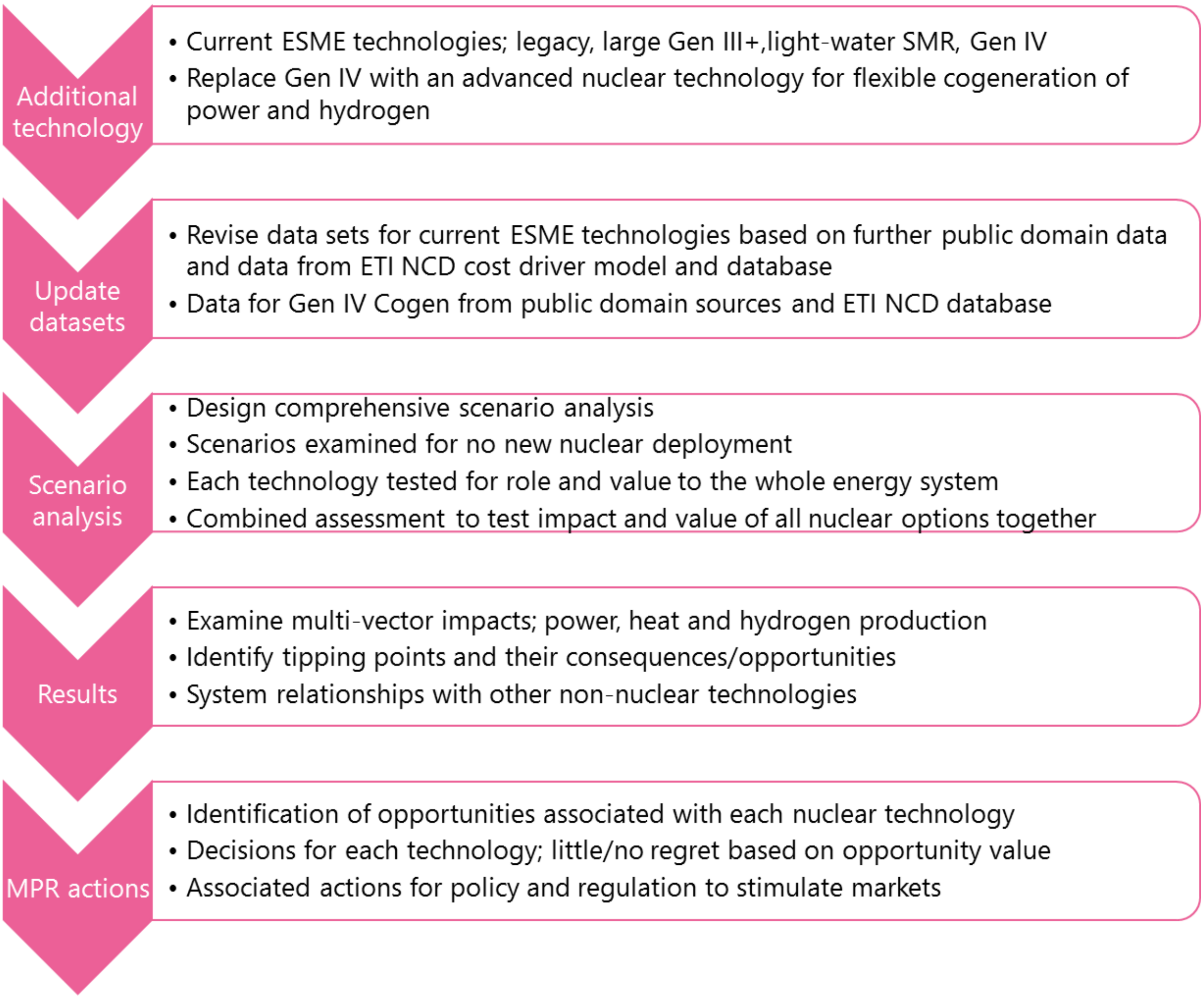

Figure 1 – Approach to Delivering Nuclear for Net Zero

More detail on the approach and methodology for delivering the scope of NFNZ is in section 5.

3. Background

3.1. ETI's Nuclear Insights and Associated Knowledge Building Projects

Nuclear for Net Zero (NFNZ) is not the first nuclear technology appraisal to be undertaken using ESME. In 2013, nuclear as a low carbon technology source was represented as a single technology. Section 3 of this report summarises the development and implementation of a number of nuclear technology types and data sets over the previous 7 years. This was realised from the ETI's investment in a portfolio of knowledge building projects; these projects are also briefly mentioned here.

The ETI's first nuclear insight[2] released in 2015 was built on the learning from the ETI's Alternative Nuclear Technologies (ANT) project and the Power Plant Siting Study (PPSS). The ANT project developed the outline economic and technical performance characteristics of a light-water nuclear Small Modular Reactor (LWSMR), with the potential for steam extraction from the power turbine for energisation of a city scale district heating system. The PPSS delivered a siting study for large reactors and LWSMRs in England and Wales to examine the locations and regional capacity limits for each type of reactor. A site capacity cap of 35 GWe was introduced, which prevented deployment of a much higher level of large new nuclear plants. At this time a generic advanced nuclear reactor technology was introduced into ESME with first deployment around 2040, and the assumption that a future technology with further developments in safety requirements and performance would involve higher costs than large Gen III+ reactors being deployed in a similar timeframe. This reflected the prevailing view of some long established institutions such as the Alternative Energies and Atomic Energies Commission (CEA) in France that the continuing pusuit of newer technologies and higher safety standards could only continue to escalate costs for future designs.

The second nuclear insight[3] released in 2016 was built on the learning from a further phase of the ANT project and the SMR Deployment Enablers (SDE) project. The SDE project examined the scope and requirement for the various necessary enabling activities and the feasibility of deployment of a UK SMR by 2030.

The final nuclear insight[4] released in June 2019 reported the learning from the ETI's Nuclear Cost Drivers study together with some limited ESME sensitivity testing, but the associated data was not incorporated into the periodic ESME updates at the time. This insight summarises the significant UK nuclear sector developments from 2015 to June 2019 and reports progress at the time with BEIS' Advanced Modular Reactor (AMR) competition.

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[2] The role for nuclear in a low carbon energy system. ETI 5th October 2015. https://www.eti.co.uk/library/the-role-for-nuclear-within-a-low-carbon-energy-system

[3] Preparing for deployment of a UK small modular reactor by 2030. ETI 29th September 2016. https://www.eti.co.uk/library/preparing-for-deployment-of-a-uk-small-modular-reactor-by-2030

[4] Update to the role for nuclear in the transition to a low carbon economy. ETI 19th June 2019. https://www.eti.co.uk/insights/update-to-the-role-for-nuclear-in-uks-transition-to-a-low-carbon-economy

3.2. Nuclear Technology Terminology Used in this Report

This project summary report is intended to report the learning from the NFNZ project including the associated ESME modelling and sensitivity studies. All the ESME modelling reported here involves 4 nuclear technology streams which are consistently reported as:

- Legacy; which includes the UK fleet of Advanced Gas-cooled Reactors (AGRs) and the single PWR at Sizewell, which are all operated by EDF Energy
- Gen III+; which represents UK nuclear new build reactors with electrical capacity greater than 1 GWe; the first of these is the twin EPR under construction at Hinkley Point (HPC)
- Light-water nuclear Small Modular Reactors (SMRs). These use the same Gen III+ nuclear heat supply systems as the large scale reactors, but are designed and delivered as smaller units. These technologies are consistently referred to in this report as light-water (nuclear) SMR (abbreviated to LWSMR) to distinguish from Steam Methane Reforming (SMR) plants which represent a technology deployed in ESME for hydrogen production
- Advanced reactors; this is a generic grouping intended to represent the next generation of nuclear heat supply systems more widely known as Generation IV. For the purpose of ESME, advanced reactors are characterised by a dataset comprising inputs and outputs, with associated economic and deployment parameters. ESME is blind to which particular Generation IV nuclear technology might be deployed. The datasets used in ESME NFNZ project do not explicitly include nuclear fusion technology.

Table 1 – Nuclear Technologies and Designs; Alignment to the Four Nuclear Technology Groups Modelled in ESME

ESME Grouping	Nuclear Technology Type	Description
Legacy	AGR	Advanced Gas-cooled Reactor; a Gen II design.
	SZB	Sizewell B. A four loop Pressurised Water Reactor (PWR). Operations began in 1995 with a nominal 40-year operating life. A life extension programme is anticipated to extend operations to 2055.
Large Gen III+	Gen III+	Generation III+ represents an incremental development in light-water reactor technology with features which are now common in many designs. As well as additional safety features, there are operability improvements. "Large" is a descriptor for plants of typical electrical generating capacity above 1.0 GWe, to distinguish them from light-water nuclear Small Modular Reactors (LWSMR)
	PWR	Pressurised Water Reactor. The EPR, AP1000 and CGN Hualong 1 are all Gen III+ designs delivering above 1 GWe.
	BWR	Boiling Water Reactor. The ESBWR and ABWR from Hitachi-GE are Gen III+ designs delivering above 1 GWe. No ESBWR plants have been constructed to date, but the ABWRs in Japan demonstrate cost-effective fleet deployment experience.
SMRs	Light-water nuclear SMRs	There is no universally accepted definition for Small Modular Reactor. The IAEA refers to small and medium reactors with capacity up to 700 MWe. Modular can refer to methods of manufacture (ie method of construction), or method of deployment (sequential, but not necessarily continuous, deployment at the same site)
	PWR	NuScale and UKSMR are both vendors of LWSMRs which employ Gen III+ Nuclear Heat Supply Systems
	BWR	The GE BWRX 300 is a 300 MWe design based on the Nuclear Heat Supply System technology in the ESBWR already licensed by the NRC.
Advanced Nuclear	Gen IV	Generation IV is the grouping applied to more advanced nuclear technologies which are not yet in commercial deployment. The Generation IV International Forum (GIF) is an international

ESME Grouping	Nuclear Technology Type	Description
		collaboration programme intended to support the 6 leading sub-groups identified below.
	VHTR	The Very High Temperature Reactor is primarily dedicated to the cogeneration of electricity and hydrogen, the latter being extracted from water by using thermo-chemical, electro-chemical or hybrid processes. The high outlet temperature makes it attractive also for the chemical, oil and iron industries. The original target outlet temperature of 1000°C can support the efficient production of hydrogen by thermo-chemical processes.
	HTGR	The High Temperature Gas Reactor is another name for a VHTR. The Chinese twin HTR-PM reactor is the latest variant of Chinese VHTR/HTGR development plant with a pebble bed core expected to begin operating in 2020. The HTR-PM operates with an outlet temperature of 750°C. In parallel, The Japanese Atomic Energy Authority (JAEA) has been operating its High Temperature Test Reactor since 1999 and operates with an outlet temperature of 950°C. It is the intended heat source for JAEA's demonstration hydrogen production plant which utilizes the sulphur-iodine thermo-chemical cycle. This HTGR has a prismatic core.
	GFR	The Gas-cooled Fast Reactor is a VHTR designed to operate with a fast neutron spectrum. Its benefits are associated with closed nuclear fuel cycles for long term sustainability of uranium resources and waste minimization.
	LFR	The Lead-cooled Fast Reactors feature a fast neutron spectrum with high temperature operation, and cooling by either molten-lead or a lead-bismuth eutectic.
	SFR	A Sodium-cooled Fast Reactor uses liquid sodium as the coolant with a fast neutron spectrum. Although not deployed commercially, there is significant development and operating experience of this technology in UK, France, USA and elsewhere.
	MSR	Molten Salt Reactors are distinguished by a core, or the fuel within the core, being dissolved in molten fluoride salt. The technology was studied and demonstrated by the United States more than 50 years ago at the Oak Ridge National Laboratory.
	SCWR	The SuperCritical-Water-cooled Reactors are high temperature, high pressure, light-water-cooled reactors that operate above the thermodynamic critical point of water (374°C and 22.1 MPa).
	AMR	Advanced Modular Reactor. It is presumed that future advanced reactors designs will all incorporate a modular construction philosophy rather than being stick built. The category of "AMR" was introduced by BEIS to segregate advanced nuclear technologies from modular reactor designs which use water as the primary reactor coolant. AMRs are not necessarily small.

A range of literature and project sources has been used to inform the nuclear technology datasets used in the ESME analysis. This wide range of sources describes numerous designs and reactor types, but the terminology is not necessarily consistent across these sources with the 4 nuclear technology categories used within ESME. For completeness, Table 1 is intended to be an introduction into the various nuclear technologies and associated designs, and how these fit into the four technology categories modelled in ESME.

3.3. Previous Nuclear Techno-Economic Appraisals by the ETI and ESC

Previous techno-economic appraisals have been undertaken by the ETI and ESC using ESME including:

- an initial sensitivity study[5] in 2015 using ESME which examined the potential benefits of using lower grade heat from nuclear power plants to energise potential city scale district heating systems
- ETI's delivery of Project 2[6] of DECC's SMR Techno-Economic Appraisal
- a limited sensitivity analysis using ESME version 4.4 which was reported in the final ETI nuclear insight
- inclusion on nuclear technologies in multiple iterations of the Clockwork and Patchwork scenarios developed by the ETI and then ESC.

3.4. Updating Nuclear Technology Data Sets from Earlier ESME Releases

The updated technology datasets used to deliver NFNZ are summarised in Section 6. These datasets are principally based on the cost model, cost database and learning derived from the ETI's Nuclear Cost Drivers project which reported[7] in April 2018.

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[5] ESME Sensitivity Studies for Nuclear ETI 6th October 2015. https://www.eti.co.uk/library/nuclear-sensitivity-study/

[6] DECC SMR TEA Project Technical Report. 20th May 2016. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/665265/TEA_Project_2_Technical_Report_-_Systems_Optimisation_Modelling_SMRs.pdf

[7] ETI Nuclear Cost Drivers Project April 2018. https://d2umxnkyjne36n.cloudfront.net/documents/D7.3-ETI-Nuclear-Cost-Drivers-Summary-Report_April-20.pdf?mtime=20180426151016

4. ESC's Net Zero Scenarios

4.1. Introduction to ESME Net Zero

ESME has been significantly upgraded so that credible transitions to Net Zero can be explored. These upgrades have drawn upon internal ESC expertise, key sources in the literature, and a series of workshops with sector experts.

The previous options in ESME were sufficient for exploring 80% pathways. However, with tighter targets, ESME reached a limit of about 90% before running out of options for further abatement. This portfolio of options has now been enhanced and expanded. New options have been added for ships fuelled by hydrogen/ammonia, and options for decarbonisation of industry, via electrification or hydrogen, have been extended. Options for off-road mobile machinery to transition away from fossil fuels have also been added, as well as a small deployment of early plant directly capturing CO_2 from the air known as Direct Air Capture of CO_2 (DACC).

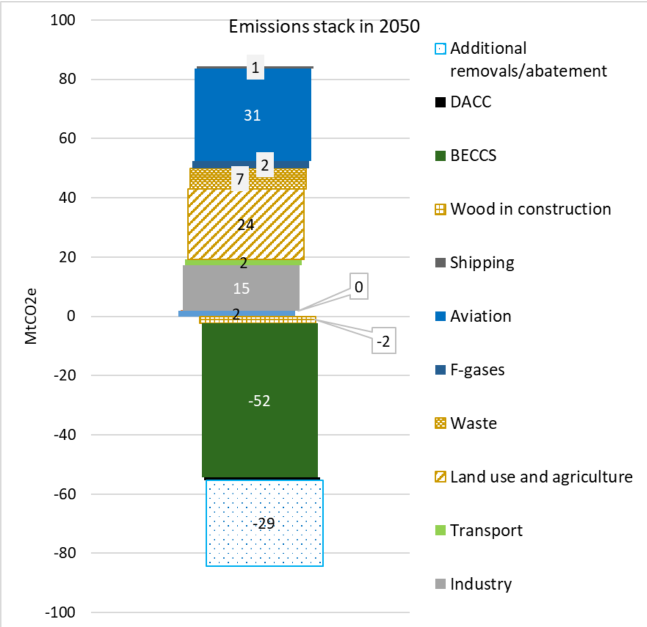


Figure 2 – 2050 Emissions and Removals in 96% Decarbonisation Case

This new 'robust' option set enables ESME to reach a 96% target, similar in progress to the CCC's Further Ambition position. From here, even further measures (removals or abatement) are needed to reach Net Zero as illustrated in Figure 2. The energy transition picture for the 96% case is similar in overall ethos to previous 80% scenarios, with a phase-out of fossil fuel use (replaced by primary energy from wind, nuclear power and biomass) and a transition in end-use away from gas and petrol/diesel, as illustrated in Figure 3. Costs and technology availability will, of course, affect the choice of technologies deployed (for example, the balance of electricity from wind, solar and nuclear power).

The final energy balance clearly indicates the requirement to transition from the incumbent fossil-based systems to electrification, hydrogen and district heat. This indicates the potential role of nuclear technologies to support a Net Zero target, with large Gen III+, LWSMR and Gen IV plant being able, as a group, to support all three of these needs. In particular, Gen IV higher temperature nuclear plant is fairly uniquely placed in being able to supply all of these three energy vectors, and the ability to co-locate such plant on industrial sites (which may require all three energy carriers on-site) is potentially an additional benefit.

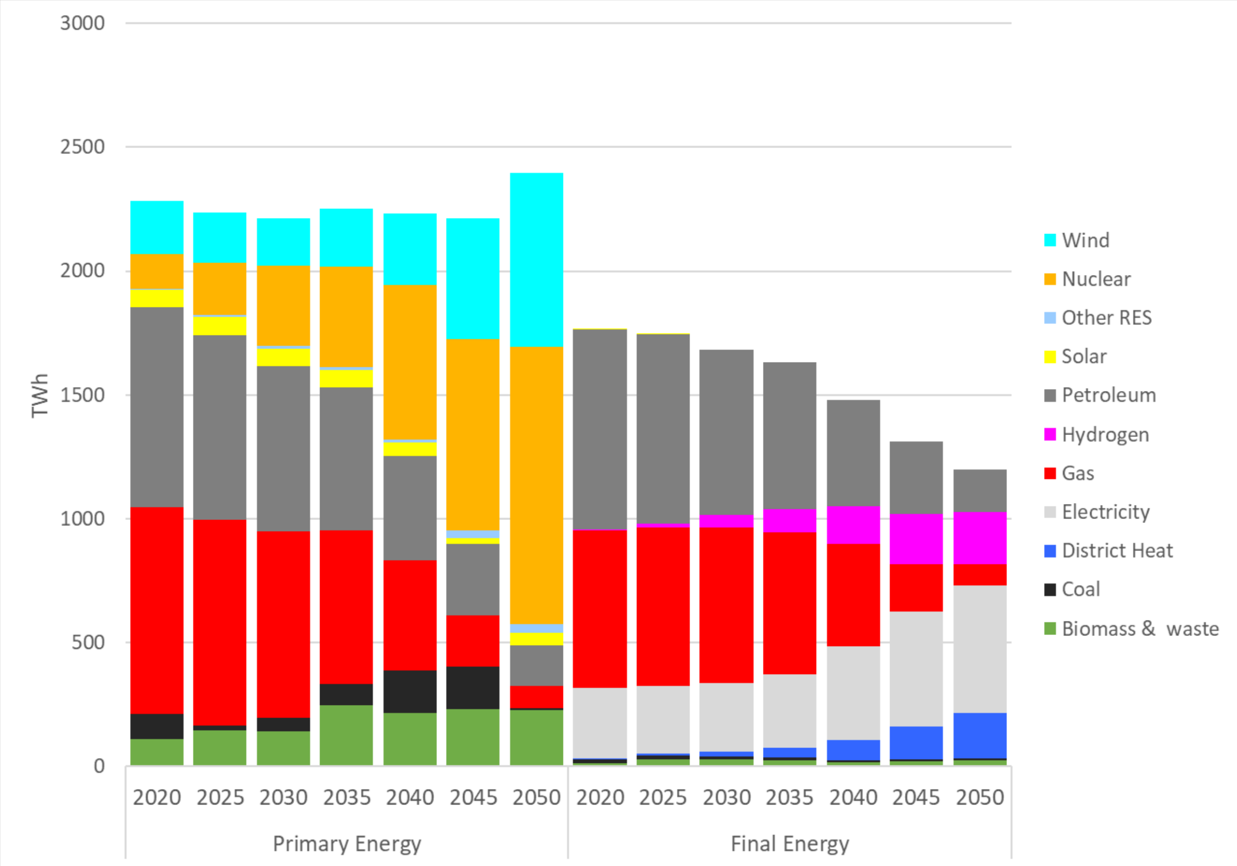


Figure 3 – Example Primary and Final Energy in 96% Decarbonisation Case

4.2. Speculative Options and Scenarios

To further develop the model to be able to produce pathways that are consistent with a Net Zero target in full, it is necessary to go beyond the upgrades delivering a 96% decarbonisation target. These additional steps are deemed "speculative" in that they rely on innovation in technology or changes in consumer behaviour beyond even currently ambitious assumptions. Potential speculative measures include:

- Mass deployment of DACC
- Enhanced carbon capture rates, beyond 95%
- Greater availability of UK or global biomass resource
- Greater levels of UK afforestation
- Reduced livestock (based on an assumed decline in meat/dairy consumption)
- Slower aviation demand growth
- Successful development of synthetic fuels for like-for-like replacement of fossil fuel consumption.

These speculative measures can be crudely broken down into measures which are technology-based or societal/behaviour-based. A scenarios philosophy treats these two sources as independent controls to be explored separately: this leads to a proposition of four energy system scenarios as illustrated in Figure 4.

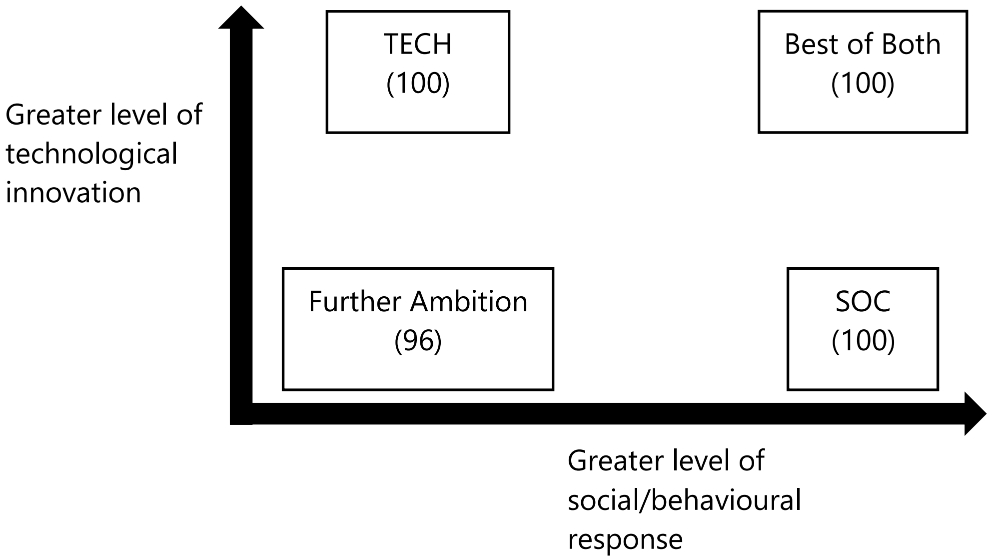


Figure 4 – Scenario Space Utilised Within ESME

The scenarios can be summarised as follows:

- **Further Ambition (FA96)** – aligned to Further Ambition 96% target only, with no speculative measures.
- **TECH100** – Net Zero target with more technology-based measures: direct air capture, higher capture rates and extra biomass resource.
- **SOC100** – Net Zero target with more society-based measures: more UK forestry, reduced livestock and slower aviation growth, and societal trends in line with "Sharing Economy" projections
- **Best of Both (BOB100)** – Net Zero target with the 'best of both': technology and society-based measures.

These scenarios, and the context for their development, are described in more detail in ESC's report titled Innovating to Net Zero which has been referenced earlier.

5. Project Approach to Nuclear for Net Zero

5.1. Introduction of Advanced Nuclear with Cogeneration

ESME 4.5 and earlier versions already include the potential for cogeneration (cogen) from light-water nuclear SMRs for the flexible production of electricity to supply the grid and heat via turbine steam extraction to energise potential city scale district heating systems. The value of cogen light-water nuclear SMRs is partly that they are smaller scale baseload electricity generation plants. During the summer months there may be the potential for periods of lower load factor because of the differences in inter-seasonal electricity demand, but these periods are compensated for by the addition of a second revenue stream from annual heat sales to sustain a viable case for investment.

The concept of introducing advanced nuclear with cogeneration of power and hydrogen is to make available a further technology to deliver firm or mid merit electricity to complement that generated by renewables. This would be modelled by a plant within ESME which can:

- Be represented by a steady state operational mode of electricity generation with additional co-located plant and equipment for the production of hydrogen
- Flex between energy vectors such that when renewable electricity generation is low, the plant can produce less or no hydrogen and more net electricity generation for supply to the grid
- Flex between energy vectors such that when renewable electricity generation is high, the plant can produce more hydrogen and less or no net electricity exported to the grid
- Flex at a rate of change consistent with "day ahead planning". It is not assumed for this analysis that such a plant can flex with fast response.

For the purpose of ESME data sets, these are merely represented by numbers in an Excel file; the dataset does not have to be bespoke to a particular technology type. Many research papers now illustrate the potential for multiple nuclear technologies to be deployed as cogeneration for power generation and hydrogen production including the variants shown in Table 2.

Table 2 – Some Potential Combinations of Nuclear Heat Supply Systems and Hydrogen Production Technologies

Nuclear Heat Supply System	Power Generation Technology	Hydrogen Production Technology
Light-water reactor	Rankine cycle steam turbine with shaft driven alternator	Low temperature electrolysis
		Higher temperature electrolysis
High temperature gas reactor	Rankine cycle steam turbine with shaft driven alternator	Low temperature electrolysis
		Higher temperature electrolysis
	Helium gas turbine with shaft driven alternator	Low temperature electrolysis
		Higher temperature electrolysis
		Sulphur iodine thermo chemical process

It was inappropriate to model all these permutations in ESME for this next step within the NFNZ analysis because this is impractical within the bounds of the project budget and duration. For the purpose of creating an initial dataset, public domain technical papers were used to create the inputs. Scrutiny of these papers identifies that nuclear heat supply systems operating at higher temperatures may be a better match for hydrogen production systems operating at elevated temperatures.

For this reason, data has been used to combine an HTGR as the nuclear heat supply system with data from representative higher temperature hydrogen production processes. This does not mean that this combination is the only, or necessarily the most economic combination, for the cogeneration of power and hydrogen from nuclear.

5.2. Updating Datasets for ESME 4.6 or Later ESME Release

The current nuclear technology datasets in ESME 4.5 come from a range of sources and the opportunity has been taken to refresh this data. The NFNZ data sets, including a nuclear data set for Gen IV cogeneration, are described in section 6. There is the potential to incorporate these into the next update and release of ESME beyond version 4.5.

5.3. Deterministic Sensitivity Studies – 3 Product Streams

The sensitivity analysis has been designed to explore the effect on system optimisation from varying a number of parameters:

- Scenarios
  - The initial scenario to be applied is Further Ambition 96 because this is based on the collection of technologies recognised as capable of achieving 80% decarbonisation, but with the scenario stretched to achieve 96% decarbonisation
  - The most widely deployed scenario is TECH100 because this incorporates additional speculative technology measures to enable the model to remain stable and optimise towards a solution for 100% decarbonisation
  - To test solution resilience and assist in the identification of technologies of little or no regret, BOB100 is also applied, which represents the introduction of both speculative technologies and changed societal behaviours to enable 100% decarbonisation
- Technologies in isolation
  - Initially all nuclear technologies are isolated to explore scenarios associated with the deployment of no new nuclear
  - Deployment of large Gen III+ reactors alone without light-water SMRs or Gen IV
  - Deployment of light-water SMRs alone without large Gen III+ or Gen IV
  - Deployment of Gen IV without large Gen III+ or light-water SMRs
- Technologies in combination
  - All nuclear technologies deployed in combination
  - Application of all 3 decarbonisation scenarios
  - Addressing uncertainty through the application of a probabilistic (Monte Carlo) run.

5.4. Market, Policy and Regulatory Considerations

In May 2007 the Department of Trade and Industry published a paper[8] titled "Meeting the energy challenge; a White Paper on energy". This was partly a Government response to the Stern review on the evidence and impact of climate change in 2006. The Energy White Paper identified the proposed policy based on need and available options. The Energy Act of 2008 converted this policy into law and a number of Market, Policy and Regulatory (MPR) actions were initiated to enable companies to develop plans to invest in the development, construction and operation of new nuclear power stations including:

[8] UK Government Policy Paper – Meeting the energy challenge: a White Paper on energy. Published 23 May 2007 by the Department of Trade and Industry https://www.gov.uk/government/publications/meeting-the-energy-challenge-a-white-paper-on-energy

- Waste and decommissioning funding
- Regulatory justification
- Generic Design Assessment
- Site specific licensing and permitting
- The establishment of an Infrastructure Planning Commission to consider planning applications associated with nationally significant infrastructure
- The creation of National Policy Statements including NPS EN-1[9] for energy and the associated Nuclear NPS EN-6 which identifies specific locations for development of new nuclear power stations.

The timeline chart in Figure 5 was regularly updated and periodically published by BERR; this version of the chart is dated November 2009. It is disappointing to note that a timeline from November 2009 showed that operation of the first unit of the first new nuclear power station would begin within 8 years i.e. in December 2017. Ten years later at April 2020, operation of the first unit of the first new nuclear power station is still 5 years away with operation forecast from 2025.

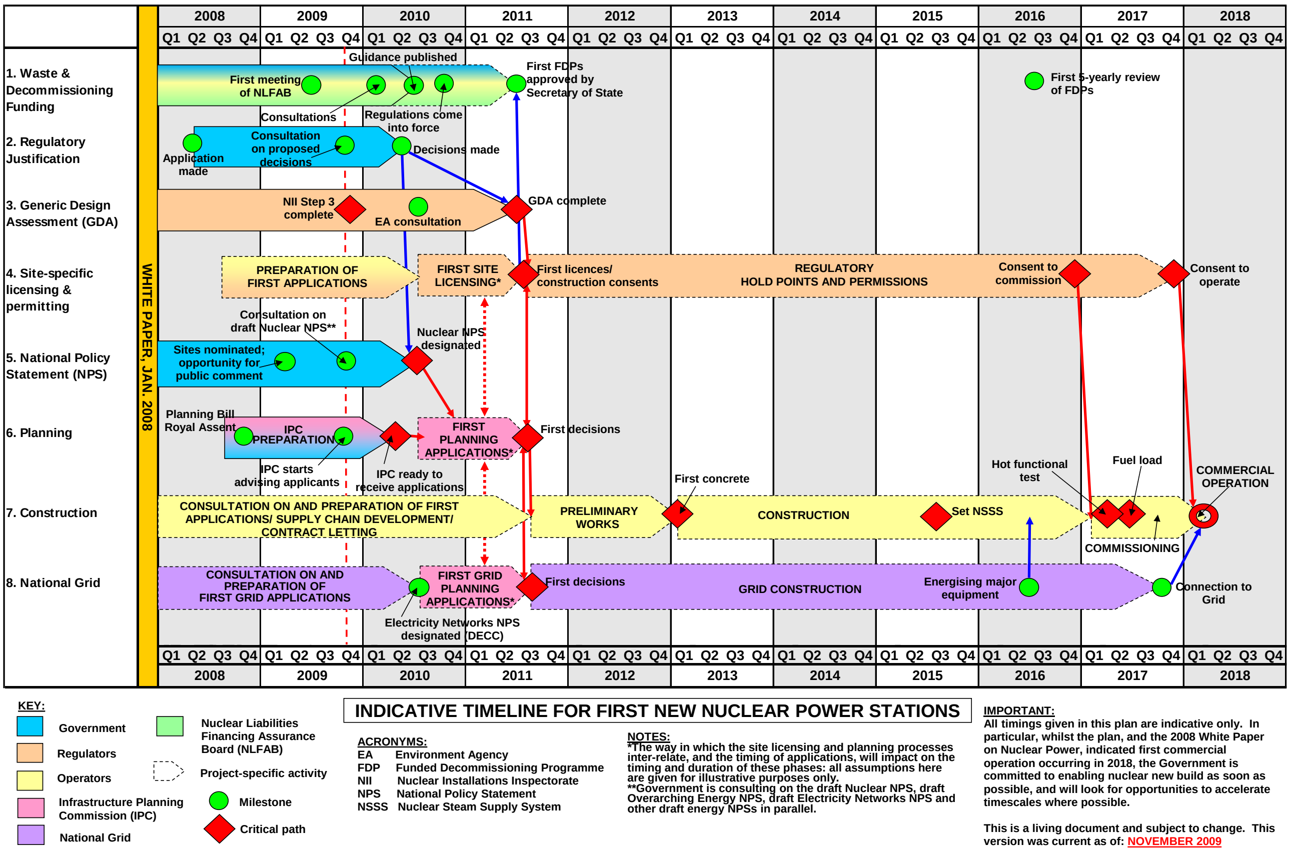


Figure 5 – Indicative Timeline for the First New Nuclear Power Stations Published by the Department of Business, Enterprise and Regulatory Reform in November 2009

9 Over-arching National Policy Statement for Energy NPS – EN1. Published by DECC Jul 2011. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/47854/1938-overarching-nps-for-energy-en1.pdf

6. Updated Datasets for Nuclear

6.1. Basis for Updated Data

ESME modelling is based on the use of technology datasets for which the underlying data and sources are evidence backed. The NFNZ data is strongly influenced by the learning from the ETI NCD project, but also further informed by other publicly available data source and market developments since early 2018. Data used in the NFNZ analysis for Gen III+. LWSMR and Advanced Reactors for cogeneration of power and hydrogen production is summarised in sections 6.2, 6.3 and 6.4 respectively.

6.2. Contemporary Gen III+ Light Water Reactors >1 GWe

The summary of selected key parameters is shown in Table 3.

Table 3 – Selected Key Parameters for NFNZ for Large Gen III+ Nuclear Power Plants

Large Gen III+ (NOAK)	Optimistic	Base	Pessimistic
First Operations (date)	2025	2025	2030
Construction Duration (years)	4.5	5	8
Build Out Rate (GWe/year)	2.1	1.4	0.7
Overnight Capital Cost ($/KWe in 2017 dollars)	$4,000/KWe at 2025 reducing to $3,500/KWe by 2050	$4,500/KWe at 2025 reducing to $4,000/KWe by 2050	$5,500/KWe at 2030 reducing to $5000/KWe by 2050
Site Capacity Limit (GWe or equivalent)		35 GWe	
Notes:	(1) Economic life 60 years (2) Design capacity factor 92% (3) Site capacity limit for England and Wales at 2050 established from the ETI PPSS (4) Electricity only; no heat recovery (5) Different build out rates reflect (PESS) construction at one site at a time, (BASE) concurrent construction at two sites at a time, (OPT) concurrent construction at 3 sites at a time) (6) Data values reflect NOAK rather than FOAK as per consistent treatment within ESME alongside other low carbon technologies.		

6.3. Light Water Small Modular Reactors

The updated NOAK datasets for light-water nuclear SMR are summarised with selected key parameters shown in Table 4.

Table 4 – Selected Key Parameters for NFNZ for Light-Water Nuclear SMR Cogeneration (Flexible Power and Heat)

Cogen SMR (NOAK) Electricity and Heat	Optimistic	Base	Pessimistic
First Operations (date)	2028	2030	2035
Construction Duration (years)	3	3.5	4
Build Out Rate (GWe/year)	2.4	1.2	0.6
Overnight Capital Cost ($/KWe in 2017 dollars)	$3,500/KWe at 2028 reducing to $3,000/KWe by 2050	$4,000/KWe at 2030 reducing to $3,500/KWe by 2050	$5,000/KWe at 2035 reducing to $4,500/KWe by 2050
Site Capacity Limit (GWe or equivalent)		22 GWe	
Notes:	(1) Economic life 60 years (2) Design capacity factor 92% (3) Capex is for cogeneration with steam extraction for DH energisation with power downrate penalty. Costs include $500/kWe Capex increment for CHP which includes pipe runs circa 10 km to connect plant to city scale DH ring main (4) For electricity only plant remove the $500/KWe CHP increment included in the Capex (5) Full DH energisation equated to 22 GWe of LWSMR in England and Wales from ETI ANT project. This limit retained for LWSMR and the “twice-over” PPSS site capacity allocated to Advanced Gen IV high temp. If large Gen III+ reactor sites un-used then this underutilised capacity could be available to LWSMR or Advanced Gen IV high temp in additional sensitivity studies (6) Data values reflect NOAK rather than FOAK as per consistent treatment within ESME alongside other low carbon technologies.		

6.4. Advanced Reactors for Cogeneration of Power and Hydrogen

The updated NOAK datasets for Gen IV cogeneration of flexible power and hydrogen production are summarised with selected key parameters shown in Table 5.

Table 5 – Selected Key Parameters for NFNZ for Gen IV Cogen (Flexible Power and Hydrogen Production)

Cogen Gen IV Electricity and Hydrogen (NOAK)	Optimistic	Base	Pessimistic
First Operations (date)	2035	2040 (but 2035 used in ESME runs to reflect a push for commercialization)	2045
Construction Duration (years)	2	3	4
Build Out Rate (GWe/year)	3.0	1.5	0.6
Overnight Capital Cost ($/KWe in 2017 dollars)	$3,000/KWe at 2035 reducing to $2,500/KWe by 2050	$3,500/KWe at 2035 reducing to $3,000/KWe by 2050	$4,000/KWe at 2035 reducing to $3,500/KWe by 2050
Site Capacity Limit (GWe or equivalent)		22 GWe	
Notes:	(1) Economic life 60 years (2) Design capacity factor 90% (3) Capex is for cogeneration of electricity and hydrogen production. Costs include $500/kWe Capex increment for co-located hydrogen production plant (4) For electricity only plant remove the $500/KWe hydrogen production increment included in the Capex (5) Full DH energisation equated to 22 GWe of LWSMR in England and Wales from ETI ANT project. This limit retained for LWSMR and the "twice-over" PPSS site capacity allocated to Advanced Gen IV high temp. If large reactor Gen III+ sites un-used then this underutilised capacity could be available to LWSMR or Advanced Gen IV high temp in additional sensitivity studies (6) Site capacity limit for England and Wales at 2050 established from the ETI PPSS (7) Data values reflect NOAK rather than FOAK as per consistent treatment within ESME alongside other low carbon technologies.		

7. ESME Analysis and Results

The charts shown in section 7 are intended to collate and summarise key information from the many ESME runs across relatively few pages. These results are then interpreted and discussed in Section 8.

7.1. No New Nuclear

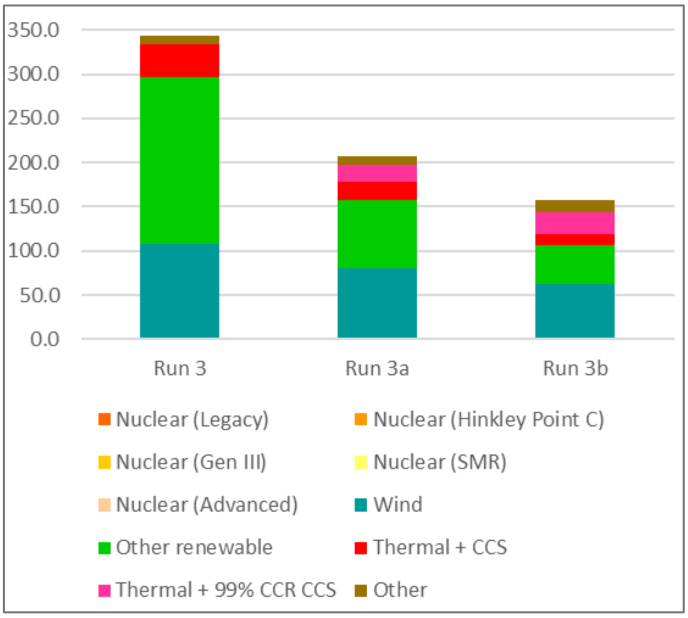


Figure 6 – No New Nuclear; Electrical Generating Capacity in 2050

Run 3	Run 3a	Run 3b
FA96 No new nuclear	Tech 100 No new nuclear	Bob 100 No new nuclear

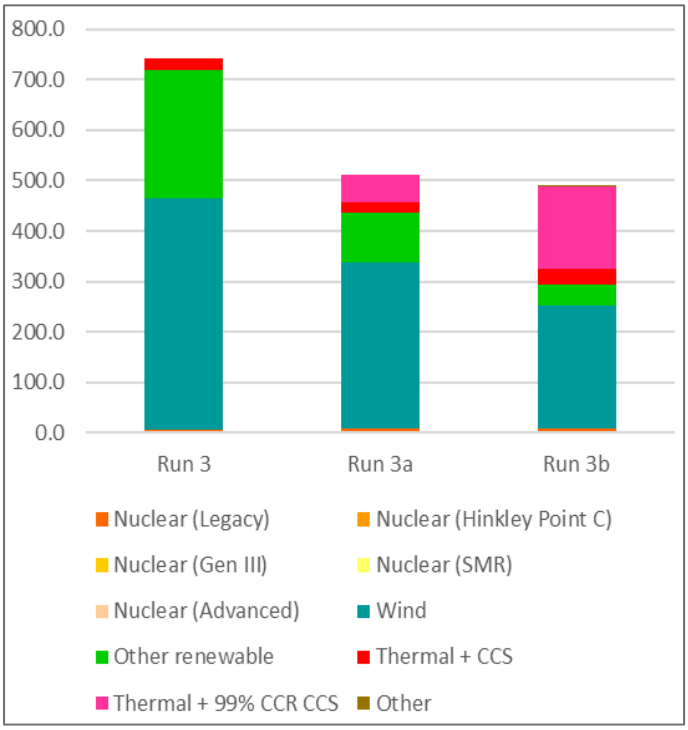
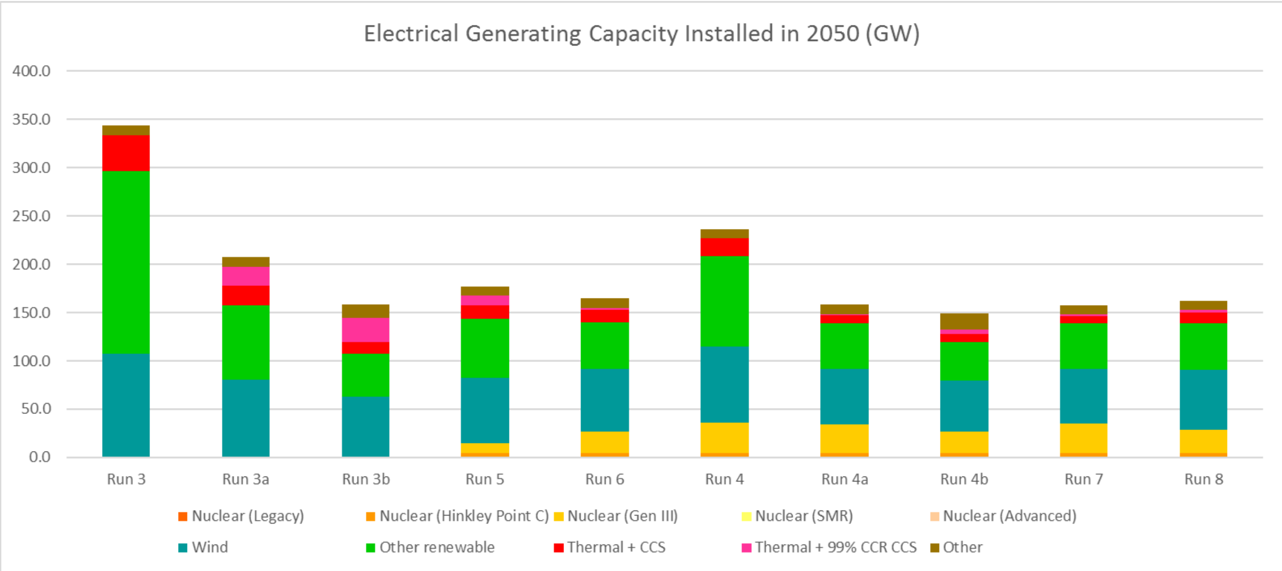


Figure 7 – No New Nuclear; Electricity Generation in 2050

7.2. Contemporary Gen III+ Light Water Reactors >1 GWe

Figure 8 – Gen III+ Electrical Generating Capacity in 2050 Across a Range of Scenarios Without LWSMR or Gen IV



Run 3	Run 3a	Run 3b	Run 5	Run 6	Run 4	Run 4a	Run 4b	Run 7	Run 8
FA96 No new nuclear	Tech 100 No new nuclear	Bob 100 No new nuclear	Tech 100 Policy cap	Tech 100 10y delay to 2035	FA96 Baseline data	Tech 100 Baseline data	Bob 100 Baseline data	Tech 100 Lower CAPEX	Tech 100 Higher CAPEX

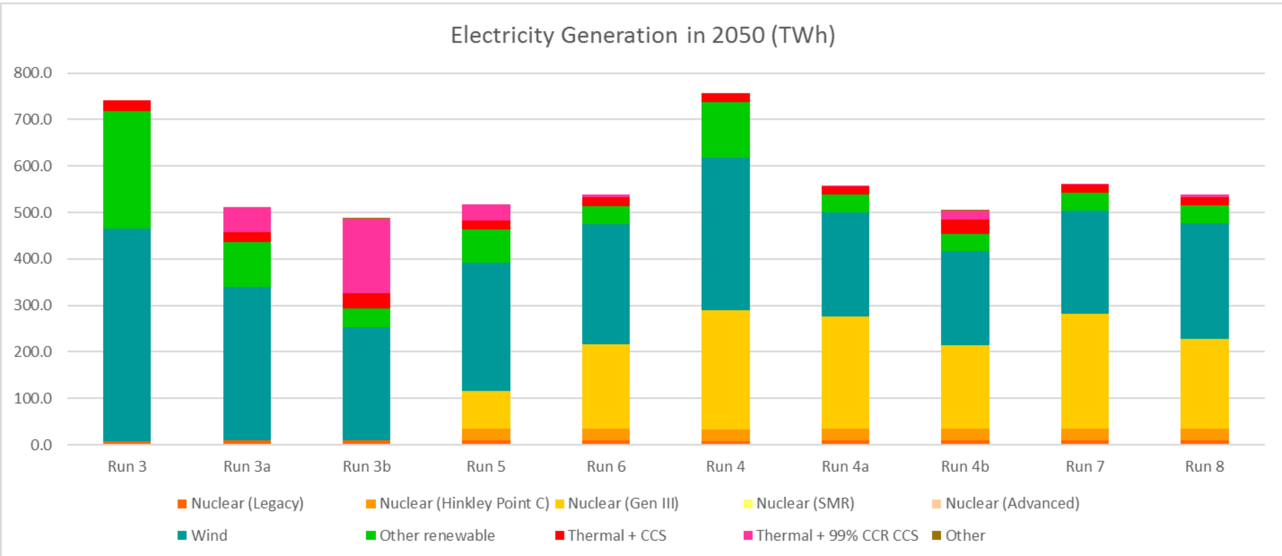
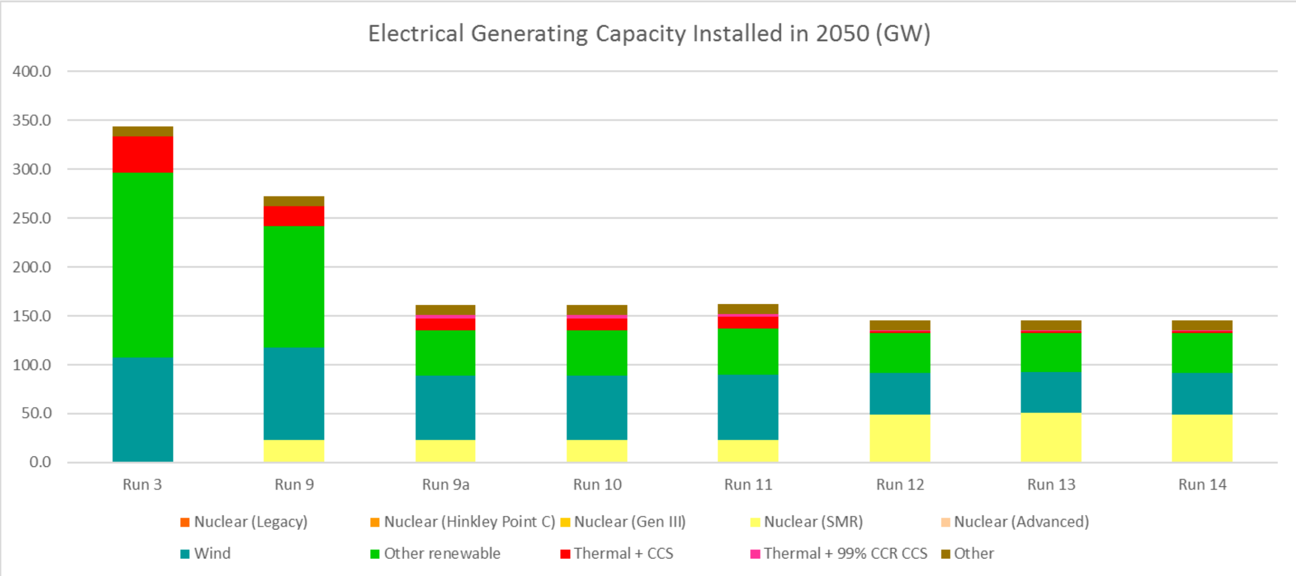


Figure 9 – Gen III+ Electricity Generation in 2050 Across a Range of Scenarios Without LWSMR or Gen IV

7.3. Light Water Small Modular Reactors

Figure 10 – LWSMR Electrical Generating Capacity in 2050 Across a Range of Scenarios Without Large Gen III+ or Gen IV



Run 3	Run 9	Run 9a	Run 10	Run11	Run 12	Run 13	Run 14
FA96 No new nuclear	FA96 Baseline data	Tech 100 Baseline data	Tech 100 lower CAPEX	Tech 100 Higher CAPEX	Tech 100 Elec only; higher roll-out	Tech 100 As run 12 but lower CAPEX	Tech 100 As run 12 & 13 but higher CAPEX

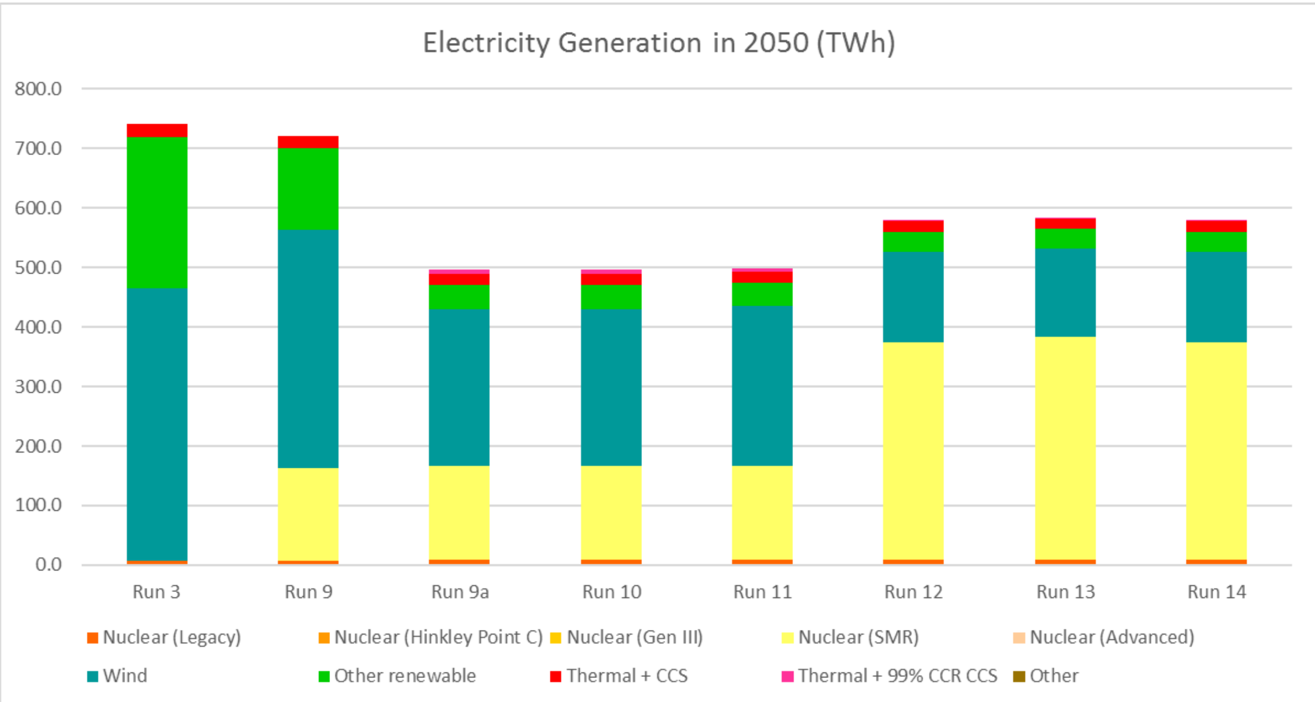
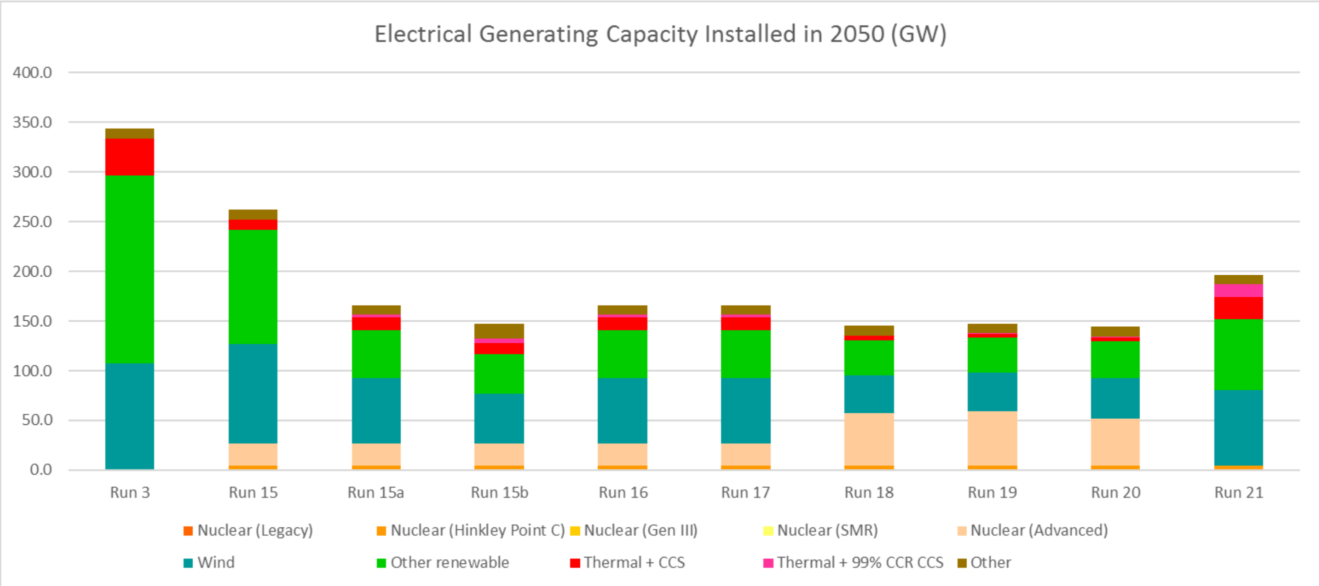


Figure 11 – LWSMR Electricity Generation in 2050 Across a Range of Scenarios Without Large Gen III+ or Gen IV

7.4. Advanced Reactors for Cogeneration of Power and Hydrogen

Figure 12 – Gen IV Electrical Generating Capacity in 2050 Across a Range of Scenarios Without Large Gen III+ or LWSMR



Run 3	Run 15	Run 15a	Run 15b	Run 16	Run 17	Run 18	Run 19	Run 20	Run 21
FA96 No new nuclear	FA96 Baseline data	Tech 100 Baseline data	Bob 100 Baseline data	Tech 100 lower CAPEX	Tech 100 Higher CAPEX	Tech 100 Elec only; higher roll-out	Tech 100 As run 18 but lower CAPEX	Tech 100 As run 12 & higher CAPEX	Tech 100 H2 only; higher roll out

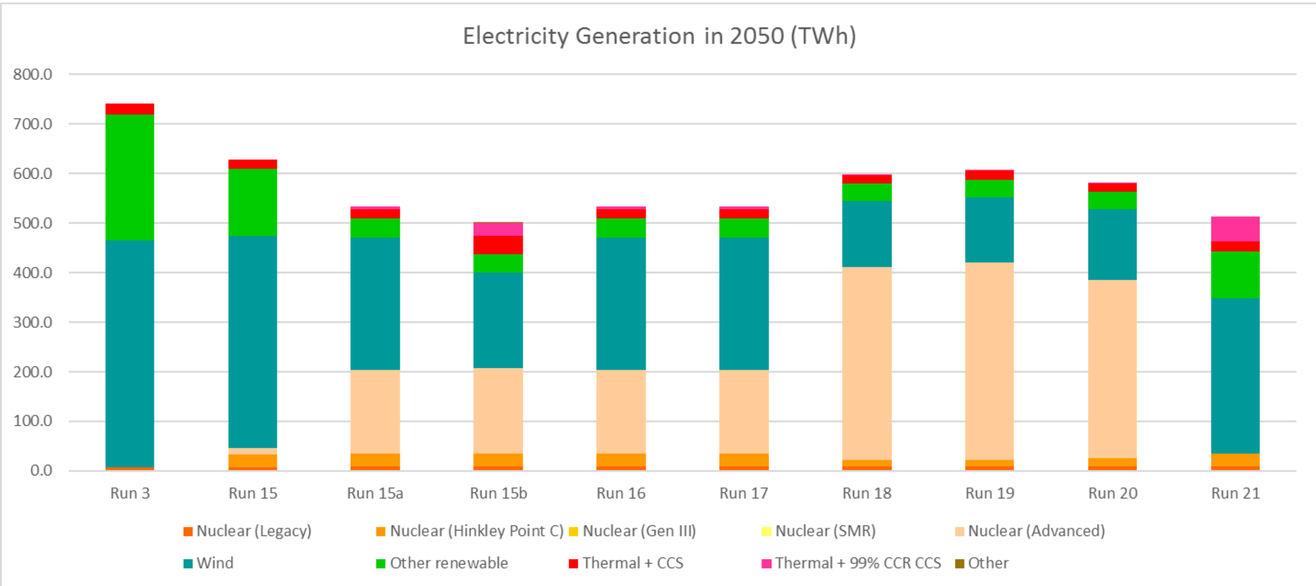
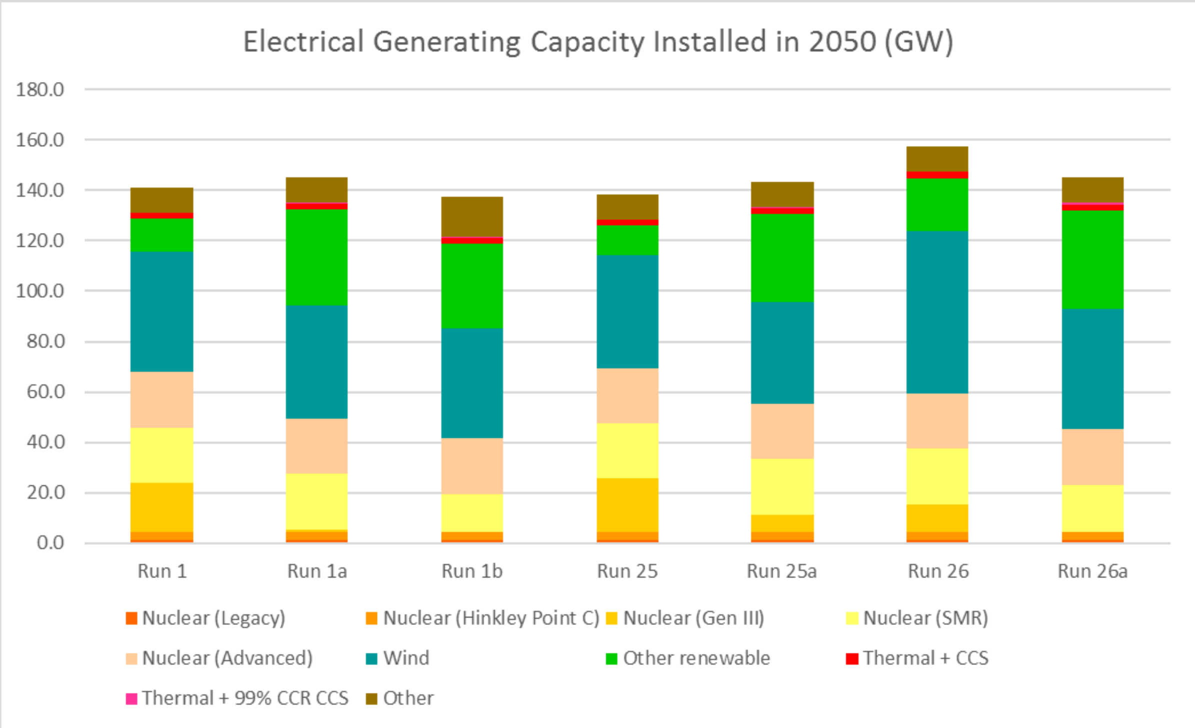


Figure 13 – Gen IV Electricity Generation in 2050 Across a Range of Scenarios Without Large Gen III+ or LWSMR

7.5. Combined Assessment – Inclusion of All Nuclear Technologies

7.5.1. Deterministic ESME Scenarios – All Nuclear Technologies

Figure 14 – Electrical Generating Capacity in 2050 Across a Range of Scenarios Including All Nuclear Technologies



Run 1	Run 1a	Run 1b	Run 25	Run 25a	Run 26	Run 26a
FA96 Baseline data all nuclear	Tech 100 Baseline data all nuclear	Bob 100 Baseline data all nuclear	FA96 Lower CAPEX all nuclear	Tech 100 lower CAPEX all nuclear	FA96 Higher CAPEX all nuclear	Tech 100 Higher CAPEX all nuclear

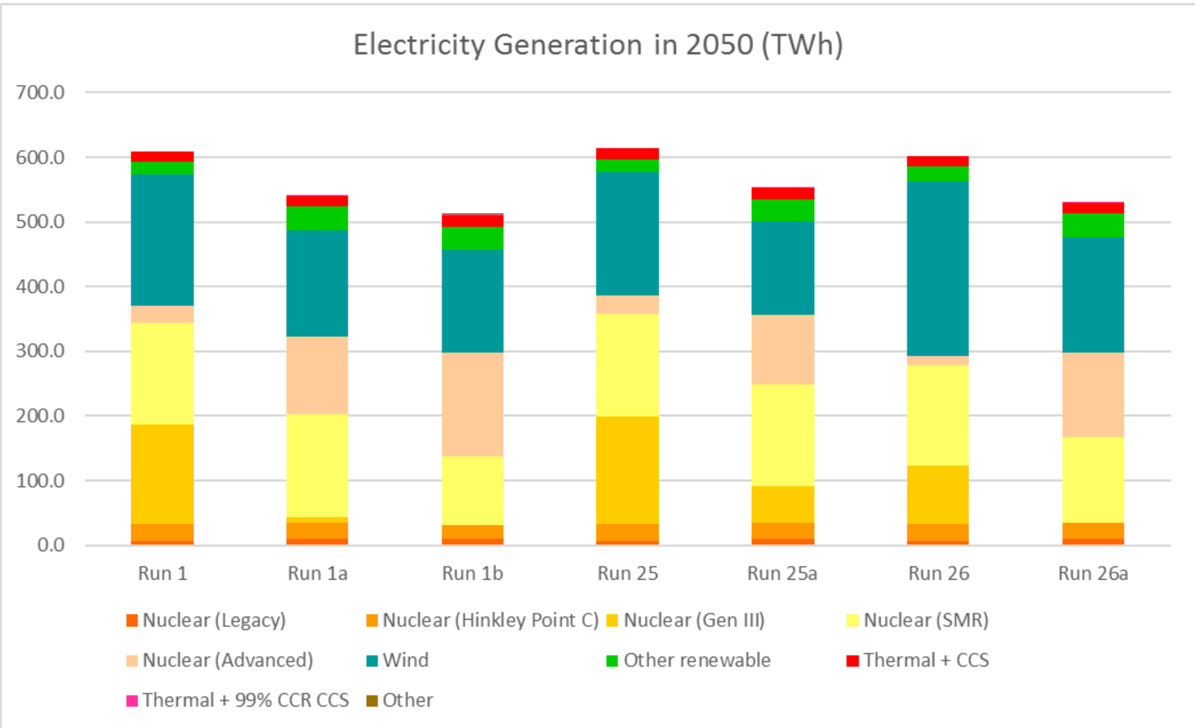


Figure 15 – Electricity Generation in 2050 Across a Range of Scenarios Including All Nuclear Technologies

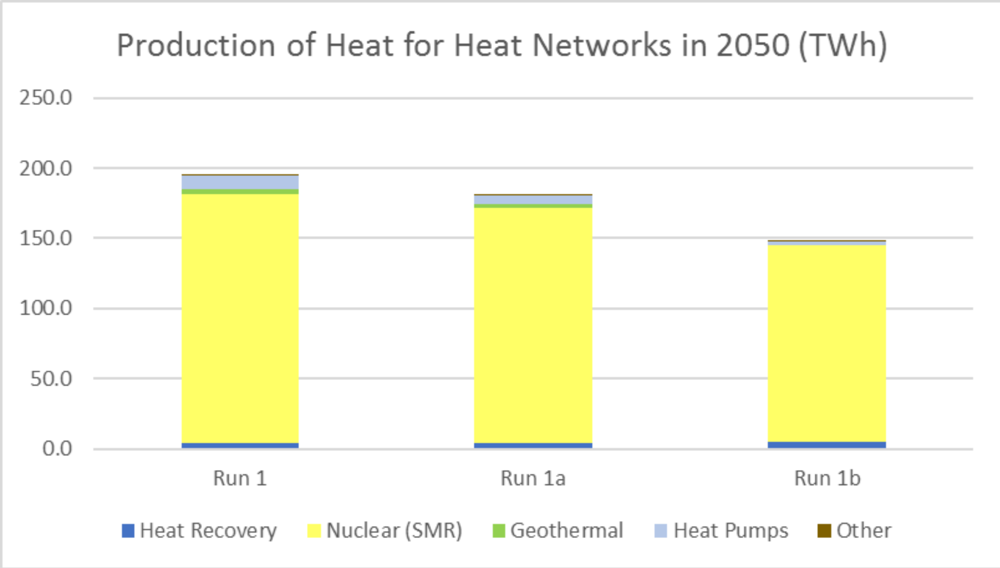


Figure 16 – Sources for Production of Heat for Energising Heat Networks for a Range of Scenarios Including All Nuclear Technologies

Run 1	Run 1a	Run 1b
FA96 Baseline data all nuclear	Tech100 Baseline data all nuclear	Bob100 Baseline data all nuclear

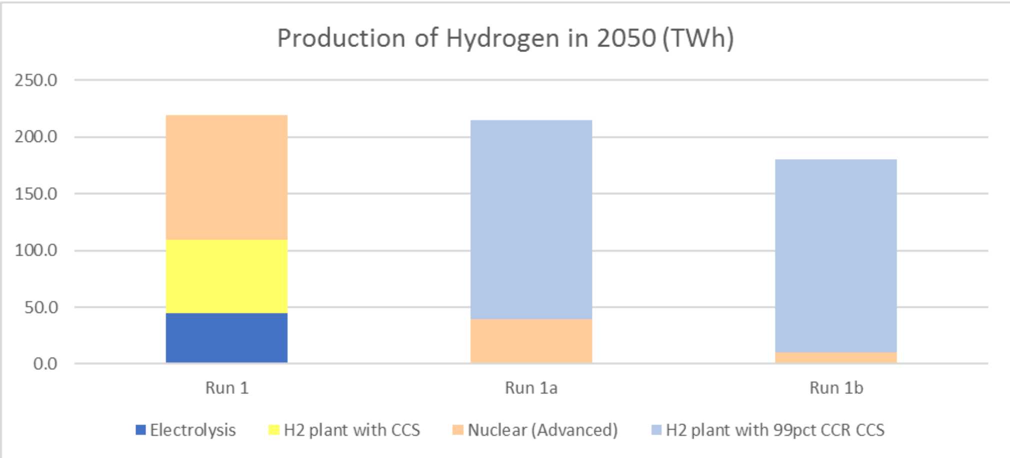


Figure 17 – Sources of Production of Hydrogen for a Range of Scenarios Including All Nuclear Technologies

Run 1	Run 1a	Run 1b
FA96 Baseline data all nuclear	Tech100 Baseline data all nuclear	Bob100 Baseline data all nuclear

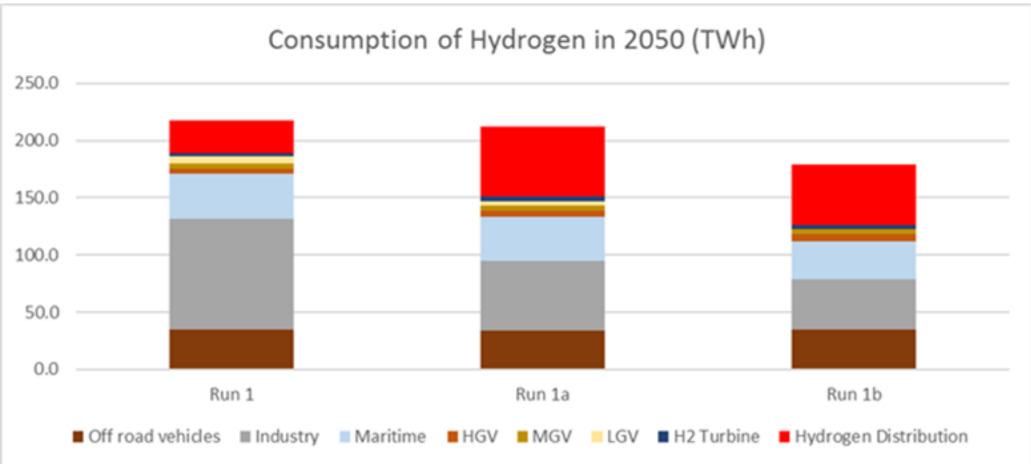


Figure 18 – Sources of Hydrogen Demand for a Range of Scenarios Including All Nuclear Technologies

7.5.2. Probabilistic (Monte Carlo) Assessment Across All Technologies

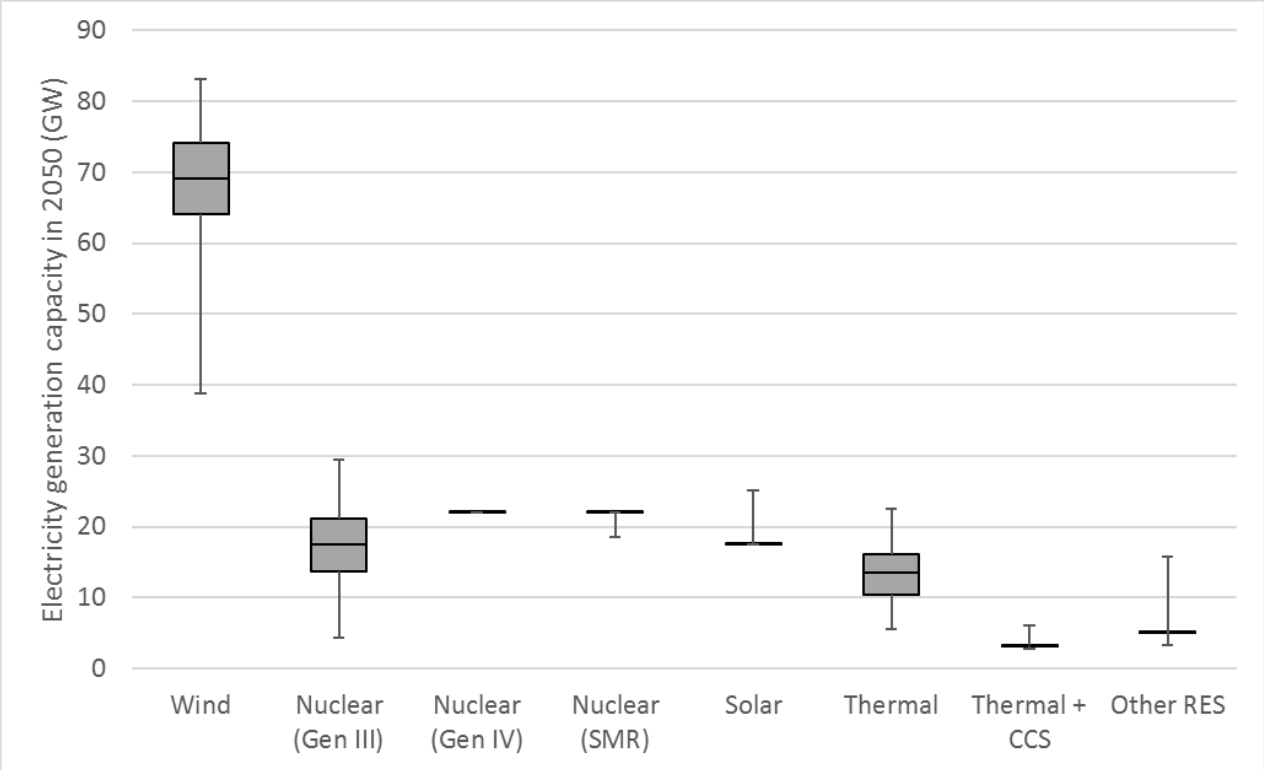


Figure 19 – TECH100 Generation Capacity by 2050 – Recognising Cost Uncertainty with Probabilistic (Monte Carlo) Analysis

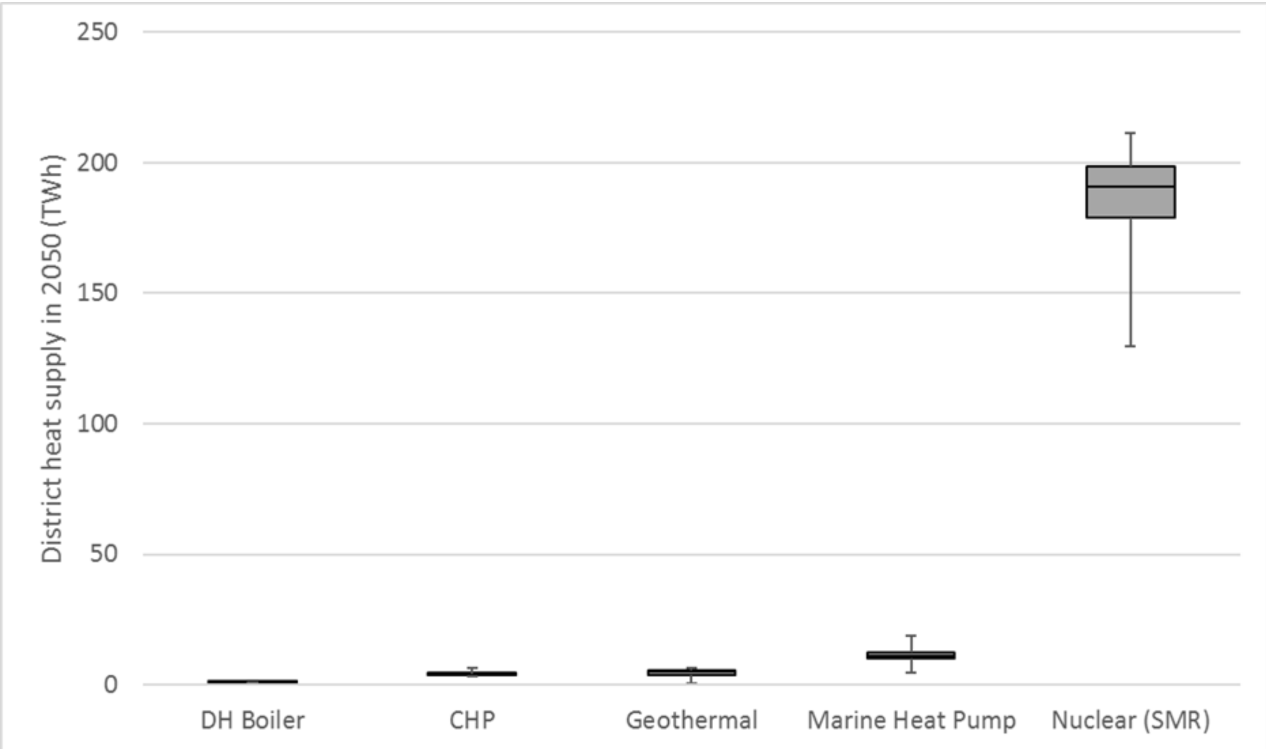


Figure 20 – TECH100 District Heating Supply In 2050 – Recognising Cost Uncertainty with Probabilistic (Monte Carlo) Analysis

8. Discussion

The starting point for considering the results from NFNZ are the initial scenarios described in section 4.2 and using the nuclear technology datasets in ESME 4.5 and earlier:

- FA96 – using core technologies for 80% decarbonisation and stretched to deliver 96%
- TECH100 – introduction of additional speculative technologies to deliver 100% decarbonisation
- SOC100 – introduction of speculative changes to societal behaviours for 100% decarbonisation
- BOB100 – combination of both TECH100 and SOC100

The aspects of electricity generation from nuclear and hydrogen production from all sources are shown in Table 6.

Table 6 – Electricity Generation from Nuclear and Hydrogen Production from All Sources in 2050 for a Range of Scenarios Using Nuclear Technology Datasets from ESME 4.5

Scenario	2050 Electricity Generation from Nuclear (TWh)	2050 Hydrogen Production from All Sources (TWh)			
		Biomass Gasification with CCC	Low Temperature Electrolysis	Steam Methane Reforming with CCS	Total Hydrogen production
FA96	400	60	160		220
TECH100	300	30		220	250
SOC100	170	110		70	180
BOB100	130	30		210	240

The impact on this summary table from using the updated datasets summarised in section 6 with the NFNZ scenarios is shown in the same format in Table 7.

Table 7 – Electricity Generation from Nuclear and Hydrogen Production from All Sources in 2050 for a Range of Scenarios Reported in the NFNZ Analysis

Scenario	2050 Electricity Generation from Nuclear (TWh)	2050 Hydrogen Production from All Sources (TWh)				
		Biomass Gasification with CCC	Low Temperature Electrolysis	Steam Methane Reforming with CCS	Advanced Nuclear Cogen	Total Hydrogen production
FA96	370	65	45		110	220
TECH100	310			175	45	220
BOB100	300			170	10	180

The results from the NFNZ analysis with the revised datasets indicates:

- A strong role for nuclear across the three scenarios of FA96, TECH 100 and BOB100, and
- A varying role across the FA96, TECH 100 and BOB100 scenarios for the Advanced Nuclear technology deployed as a cogeneration plant for electricity generation and hydrogen production. In FA96 Advanced Nuclear is delivering 50% of hydrogen demand; the introduction of the speculative technologies in TECH100 with 99% carbon capture rates enables significant hydrogen production from steam methane reforming. The reduction of energy demand and changed societal behaviour with SOC100 and reflected here through inclusion in BOB100 reduces overall hydrogen demand and the majority of energy produced from Advanced Nuclear is directed towards electricity generation

- Table 6, using the earlier nuclear datasets, indicates a diminishing role for nuclear energy for electricity generation through the 4 scenarios of FA96, TECH 100, SOC100 and BOB100. Table 7, using the NFNZ datasets, indicates a strong and consistent role for nuclear energy for electricity generation through the 3 scenarios of FA96, TECH 100, and BOB100.

8.1. No New Nuclear

The first nuclear deployment scenario to be considered is the extreme of no new nuclear. The FA96 scenario with no new nuclear deployment was examined in a particular scenario known as Run 3. The 2050 electricity capacity and generation data are summarised for Run 3 in the summary charts shown in Figures 6 and 7 respectively. Figures 6 and 7 also show the summary 2050 data from ESME Runs 3a and 3b for the TECH100 and BOB100 scenarios respectively. Inserted between Figures 6 and 7 is an additional legend which provides a "run summary" to aid interpretation of the chart information within the figures. This approach using a "run summary" legend is used consistently through the presentation of results in Section 7.

A comparison of "like-for-like" scenarios with and without new nuclear is summarised in Table 8. ESME is a cost optimisation model and, when using the nuclear technology datasets defined in NFNZ, nuclear deployment occurs within the model whenever such a choice is available. The substantial reduction in grid capacity with FA96 is expected due to the deployment of firm capacity to replace some intermittent renewables. Total generation using the FA96 scenario is also reduced significantly with the introduction of Advanced Nuclear cogeneration because there is no longer the reliance on Low Temperature Electrolysis (LTE) for hydrogen production.

Table 8 – Grid Capacity and Electricity Generation at 2050 From Scenarios with No New Nuclear Generation in Comparison with the Same Scenarios with New Nuclear Technologies Enabled Using NFNZ Nuclear Datasets

Scenario at 2050	No New Nuclear		All Nuclear Technologies Deployed	
	Grid Capacity GWe	Generation TWh	Grid Capacity GWe	Generation TWh
FA96	345	730	140	600
TECH100	210	510	155	540
BOB100	160	490	138	510

The net effect across all like-for-like scenarios, if nuclear technologies are removed as a deployment choice, is a substantial increase in installed electrical generation capacity and associated grid costs. Without the firm electrical generating capacity from nuclear, the capacity and generation gap must be closed to satisfy demand. Across FA96, TECH100 and BOB100 scenarios, power generation is already limited from technologies using CCS emission abatement technology. Through system optimisation using the FA96 scenario, the installed grid capacity is subsequently expanded if nuclear is unavailable to nearly 350 GWe including approximate contributions of:

- 110 GWe of wind including onshore, offshore fixed and offshore floating
- 70 GWe of solar PV (farm) and 50 GWe of solar PV (domestic)
- 25 GWe of tidal stream

Over 86% of electricity generation is delivered in FA96 by renewables but the remainder is delivered through the availability of dispatchable electricity from other sources including 35 GWe from hydrogen turbines and 40 GWe from CCGT with CCS. A significant source of the electricity demand is associated with Low Temperature Electrolysis plants producing 150 TWh of hydrogen.

8.2. Contemporary Gen III+ Reactors >1GWe – Role and Benefits

The results from sensitivity analyses with Gen III+ deployed alone without LWSMR or Gen IV are summarised for electrical generation capacity and electricity generation in Figures 8 and 9 respectively.

8.2.1. Firm Generation Capacity to Complement Intermittent Renewables

Run 5 represents a potential policy of deploying new nuclear up to a fixed capacity cap. The level of this cap is arbitrary but for this analysis is set to correspond closely with a previous peak in UK nuclear generating capacity of around 13 GWe achieved in 1995. The arbitrary cap is equivalent to HPC plus a further 10 GWe of new nuclear build. Together with the anticipated lifetime extension of SZB, this would yield a total of 14.5 GWe of installed nuclear capacity operating at 2050. At this level of deployment, the required nuclear power plant site capacity is consistent with the current National Policy Statement NPS - EN6, and supportable through the parallel policies for waste disposal and a once through fuel cycle.

Run 3a is selected for comparison with Run 5; Run 3a is the TECH100 scenario without new nuclear deployment. The comparison between Run 3a and Run 5 illustrates that the energy systems in both scenarios represented by Run 3a and Run5 are under-provided with firm electricity generation. Run 5 illustrates that the addition of just 13 GWe of new large Gen III+ in TECH100 displaces 42 GWe of renewable and associated dispatchable back-up capacity:

- 11 GWe of wind
- 16 GWe of other renewables
- 6 GWe of thermal power generation with CCS, and
- 9 GWe of thermal power generation with 99% CCR CCS

Run 6 using TECH100 represents a policy scenario of continued delay where additional new plants subsequent to HPC do not come on-line until 2035. Potential 2050 nuclear generation capacity in this scenario is constrained by the build-out rate. The scenario in Run 6 uses the BASE build-out rate of 1.4 GWe/y which permits an additional 22.4 GWe to be added by 2050 to operate alongside HPC and SZB.

8.2.2. Gen III+ Deployment Levels Sensitive to CAPEX Levels

Run 4 represents a cost optimised energy system using scenario FA96 with the capacity cap lifted on deployment of large Gen III+. The corresponding level of Gen III+ deployment is 31.8 GWe by 2050. With the inclusion of HPC this represents 35 GWe of new nuclear Gen III+ which reaches the site capacity limit of 35 GWe applied from the ETI PPSS.

Runs 4a and 4b using TECH100 and BOB100 realise Gen III+ deployment levels of 29.8 and 22.1 GWe respectively. This suggests a strong demand across all three scenarios for the addition of firm power generation capacity from nuclear, and that the addition of this firm baseload capacity improves overall system optimisation from a cost perspective.

Runs 7 and 8 summarised in Figures 8 and 9 are also illustrative for comparison with Run 4a (all TECH100). Run 7 uses the lower CAPEX for large Gen III+ which yields a marginal increase in deployed Gen III+ capacity but still short of the site capacity limit. Run 8 uses the higher CAPEX for large Gen III+ with the result that Gen III+ deployment levels drop by 6 GWe or 20% of capacity compared with Run 4a. The inference from the modelling is that, as an energy source delivering energy through a single vector, deployment levels for Gen III+ are CAPEX sensitive. The charts for

Run 8 in Figures 8 and 9 show that with nuclear deployment capacity eroded at elevated CAPEX levels, the shortfall is made good through additional wind and a marginal increase in capacity and generation from thermal plants with CCS to address the intermittency of wind.

8.3. LWSMR – Role and Benefits

The results from sensitivity analyses with LWSMR deployed alone without Gen III+ or Gen IV are summarised for electrical generation capacity and electricity generation in Figures 10 and 11 respectively.

8.3.1. Firm Generation Capacity to Complement Intermittent Renewables

Run 9 (FA96) and Run 9a (TECH100) summarised together in Figures 10 and 11 tell a similar story to that associated with large Gen III+ deployment alone, in that the availability of cost-effective firm generation displaces some wind, solar PV and tidal stream from the installed capacity previously optimised without nuclear. There is also the incremental reduction in thermal generation capacity with CCS that delivered the necessary mid-merit dispatchable generation capacity necessary with these intermittent renewables.

8.3.2. LWSMR Deployment Levels Insensitive to CAPEX Levels

Runs 12, 13, and 14 all use TECH100 and represent much higher roll-out rates and site capacity limits for LWSMR when deployed as electricity only (i.e. not cogeneration operation for the flexible delivery of heat and power). The nuclear CAPEX data for NFNZ uses the assumption that the 2050 NOAK CAPEX for LWSMR is lower than for large Gen III+. Runs 12, 13 and 14 represent the Base, Lower and Higher CAPEX levels respectively. None of these runs achieves the modelled site capacity limit of 55 GWe, but there is little variation in deployment levels across the 3 Runs.

8.3.3. LWSMR Deployment and Interaction with Energy Vectors Beyond Electricity

The optimised sources of heat for energising heat networks in a TECH100 scenario without the choice to deploy new nuclear include some heat "take-off" from thermal power or industrial plants, but the majority is from geothermal plant or large-scale marine heat pumps. As well as the cost of piping connections to link these plants to the hot water networks, the heat pumps and geothermal plants demand additional CAPEX and OPEX, and the heat pumps require a significant supply of electricity to operate.

Within ESME the default configuration for LWSMRs is deployment as cogeneration plant for flexible supply of electricity to the grid and heat via hot water for the energisation of heat networks. The chart in Figure 16 illustrates for Runs 1, 1a, and 1b the dominance of heat supply from LWSMRs in energising hot water heat networks used for space heating and domestic hot water production. The levels of hot water supply correspond with levels of LWSMR deployment of 22, 22 and 15 GWe across the scenarios of FA96, TECH100 and BOB100 respectively as shown in Figure 16.

The probabilistic analysis for District Heat energisation using the TECH100 scenario is shown in Figure 20 which identifies a significant potential role for Cogen LWSMR for DH energisation should city scale DH networks be deployed at scale.

8.4. Advanced Reactors – Role and Benefits

The results from sensitivity analyses with Gen IV deployed alone without Gen III+ or LWSMR are summarised for electrical generation capacity and electricity generation in Figures 12 and 13 respectively.

8.4.1. Firm Generation Capacity to Complement Intermittent Renewables

Run 15a (TECH100) summarised together in Figures 12 and 13 tells a similar story to that associated with Large Gen III+ or LWSMR deployment alone, in that the availability of cost-effective firm generation from Gen IV displaces some wind and other renewables from the installed capacity previously optimised without nuclear. There is also the incremental reduction in thermal generation capacity with CCS that provided the necessary mid-merit dispatchable generation capacity necessary with these intermittent renewables.

8.4.2. Gen IV Deployment Levels Insensitive to CAPEX Levels

Runs 18, 19, and 20 all use TECH100 and represent much higher build-out rates and site capacity limits for Gen IV when deployed as electricity only (i.e. not cogeneration operation for the flexible delivery of power and hydrogen production). The nuclear CAPEX data for NFNZ uses the assumption that the 2050 NOAK CAPEX for Gen IV is lower than for large Gen III+ and LWSMR. Runs 18, 19 and 20 represent the Base, Lower and Higher CAPEX levels respectively. Run 19 achieves the modelled site capacity limit of 55 GWe, but there is relatively little variation in deployment levels across the 3 Runs with the Higher CAPEX level still achieving 47.8 GWe.

Gen IV nuclear technology is modelled with a Design Capacity Factor (DCF) of 90%; the load factor report for Run 19 shows that with 55 GWe deployed by 2050, the load factor reduces from 90% to 82% in the last decade i.e. from 2040 to 2050. As with LWSMR, system optimisation suggests this is the more cost-effective solution at system level although this technology is operating at an annual load factor below the DCF.

8.4.3. Gen IV Deployment and Interaction with Energy Vectors Beyond Electricity

The concept modelled for Advanced Nuclear Gen IV is illustrated in Figure 21 and described in more detail in section 5.1. For the purpose of energy system modelling, ESME is blind to the particular selection of nuclear heat supply system. The heat supply could be steam from a Gen III+ light-water reactor, or an inert gas used to transport heat from a High Temperature Gas Reactor. This cogeneration plant configuration provides the plant operator with the choice of whether to supply hydrogen to the hydrogen transmission system and for any excess to be sent to store for later “inter-seasonal” use when demand is higher, or to meet a short term need for electricity supply when reserve generation margins are expected to be tight. This change in operating mode does not require a fast response but is consistent with “day-ahead” planning which is sufficient to provide good estimates of renewable generation based on weather forecasts 24 hours ahead.

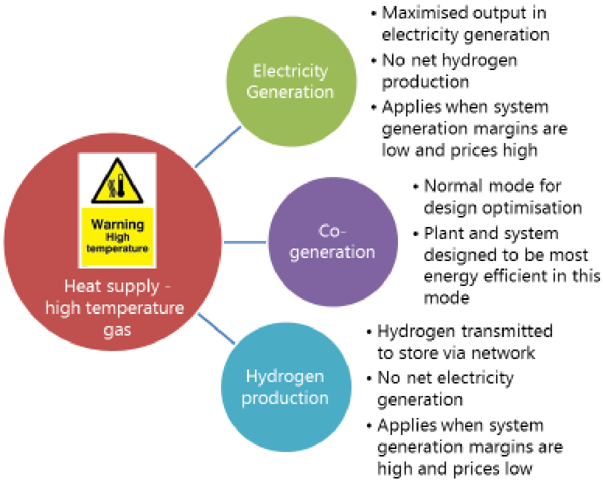


Figure 21 – Cogeneration Configuration for Advanced Nuclear Gen IV Modelled in NFNZ

Figures 12 and 13 provide the Run summaries for Gen IV deployed alone. The very last columns are for Run 21 which is a scenario with Gen IV deployed for hydrogen production only (i.e. not cogeneration) and uses the base level of CAPEX. Run 21 uses a higher deployment rate. Run 22 is the same as Run 21 but uses the lower level for CAPEX and system optimisation through ESME results in deployment of 18 GWe equivalent capacity of "hydrogen only" plants by 2050. The detail within Run 22 reveals an increased use of hydrogen within the hydrogen distribution network. The increased consumption of around 80 TWh is associated with increased heating and hot water production from hydrogen use. There are three key learning points from this analysis of Gen IV cogeneration when deployed as the only new nuclear build technology:

- Collectively the FA96 scenarios reveal the challenge of getting to 96% decarbonisation using only technologies previously considered as "core" for system decarbonisation. The addition of Gen IV cogeneration to other technologies deployable within FA96 is valued for its contribution to hydrogen supply and occasional electricity generation when reserve margins are tight
- With the addition of speculative technologies through TECH 100, including DACC, carbon capture rates raised from 95% to 99%, and additional sustainable biomass resource, then a system solution achieving full decarbonisation or Net Zero becomes possible. This solution to get to net zero demands additional costs (not quantified in this report) as well as changes in land use. There are also system risks associated with the additional uncertainties presented with the speculative technologies. If the uncertainties are resolved, the net impact is to be able to rely heavily on CCS abatement technology with 99% carbon capture rate for hydrogen production through waste gasification, biomass gasification and steam methane reforming.
- With CCS applications and constrained residual emissions prioritised towards hydrogen production, this leave the electricity generating system relatively short of firm and mid merit capacity to complement the intermittent generation from renewables.

8.5. Combination of Nuclear Technologies – Roles and Benefits

The results from sensitivity analyses with Gen III+ deployed in combination with LWSMR and Gen IV are summarised for electrical generation capacity and electricity generation in Figures 14 and 15 respectively.

8.5.1. Electricity Generation

All the Runs summarised in Figure 14 show a substantial contribution from nuclear. The scenario of BOB100 which suppresses energy demand and emissions and combines this with speculative technologies to ease the pressure on residual emissions from technologies using CCS, still deploys over 40 GWe of new nuclear. Figure 15 indicates that this minimum level of new nuclear deployment associated with this scenario would still deliver 60% of electricity generation in 2050.

The scenario of FA96 which achieves 96% decarbonisation without the reliance on speculative technologies or changed societal behaviour deploys over 60 GWe of new nuclear capacity, accounting for nearly 65% of electricity generation in 2050.

All the runs summarised in Figures 14 and 15 additionally show substantial installed capacities of renewables, but renewable installed capacity and electricity generation is dominated by wind generation in its various forms.

All scenarios in Figure 14 have very limited elements of installed capacity from thermal plants with CCS at capture rates of either 95% or 99%, and overall levels of generation shown in Figure 15 are very limited. Section 8.4.3. has shown that with residual emissions constrained from CCS even with 99% capture rates, use of CCS abatement technology within ESME is prioritised towards hydrogen production applications.

This explains why the dominant renewable technology for decarbonising electricity generation is wind and, provided nuclear technologies can be delivered in the region of NOAK CAPEX and other key parameters assumed within this analysis, then ESME analysis indicates that nuclear technologies are the partner to energy-from-wind in delivering firm and mid-merit electricity.

Runs 1a, 1b, 25a, and 26a all sustain high levels of deployment of Cogeneration LWSMR and Cogeneration Gen IV. But across these runs, levels of Gen III+ deployment are lower than in Runs 1 and 25. There are two factors contributing to this:

- Runs 1a, 1b, 25a and 26a include the speculative technologies, with the effect that proven technologies (i.e. Gen III+) are being compared with technologies unproven in terms of performance and economics
- Runs 26 and 26a each use scenarios with higher levels of CAPEX for Gen III+, rather than Base CAPEX values. The use of Base or Lower CAPEX values for Gen III+ restores some Gen III+ deployment, although not to the site capacity limit of 35 GWe when LWSMR and Gen IV are also being deployed in numbers before 2050.

Both of these factors point to the fact that the extent of Gen III+ deployment in this analysis is more sensitive to CAPEX levels than for LWSMR or Gen IV. It should be remembered that the underlying data documented in Section 6 assumes that NOAK costs for both LWSMR and Gen IV will both be lower than for Gen III+. This finding of greater CAPEX sensitivity for Gen III+ is consistent with the earlier analysis in Section 8.2.2.

8.5.2. Heat Supply via Energisation of District Heating Networks

Figure 16 illustrates the potential value of cogeneration from Gen III+ (in this analysis through LWSMR) for supplying electricity to the grid and heat via turbine steam extraction to energise district heating networks. But there are 4 underlying assumptions that need to be realised for this value to be realised:

- The deployment of district heating at scale needs to be a cost competitive option compared with the alternatives
- The implementation of a positive policy choice that district heating networks are a preferred choice for decarbonising space heating unless disproportionately expensive compared with the other options
- That nuclear plants are deployed as DH capable, which will provide future optionality to upgrade plants at upgrade outages during their operating lives when market conditions make this economically attractive. The cost of including this future optionality is low if done at the time of initial construction. Given that some light-water power reactors in the USA are now licensed for

commercial operating lives of 80 years, the small incremental cost at initial construction may be a valuable long-term hedge
- If DH networks are deployed at scale, the greatest cost for the upgrade to DH energisation of a cogeneration capable plant is associated with the pipeline connection to the DH ring main or spur. Such costs would be minimised if new nuclear plants, typically LWSMR, are located as close as possible to centres of DH demand consistent with the prevailing nuclear plant siting criteria.

8.5.3. Hydrogen Supply

The potential value of hydrogen supply from nuclear is described in detail in section 8.4.3. Hydrogen supply should not be considered in isolation as a single vector.

Figure 18 summarises the hydrogen consumption from Runs 1, 1a, and 1b using scenarios FA96, TECH100 and BOB100 respectively. The categories of consumption are listed in greater detail in Table 16 which identifies that across these 3 scenarios:

- Hydrogen demand is relatively consistent across maritime use for ammonia fuel, off-road vehicles, heavy and medium goods vehicles and peaking power generation through hydrogen turbines
- Hydrogen demand varies for industrial applications and other applications suppled from a distribution network.

The scenarios shown in Figure 18 each benefit from the availability of all 3 new nuclear technologies for the ESME cost optimised calculation of scenario solutions. This includes the Gen IV Cogeneration technology for electricity generation and hydrogen production.

Figure 17 shows how the Further Ambition 96% decarbonisation scenario in Run 1 optimises the use of the Generation IV cogeneration technology differently from the scenarios which have incorporated the additional speculative technologies. Despite the differences in optimised use, the high level of deployment of Gen IV across all 3 scenarios illustrates the value of a multi-vector technology in enhancing overall system flexibility and efficiency.

8.5.4. Addressing Uncertainty Through Probabilistic (Monte Carlo) Analysis

Figure 19 shows electrical generation capacity by technology in 2050 using the TECH100 scenario for the probabilistic (Monte Carlo) analysis. This chart suggests the following conclusions:

- Wind turbine generation in its various forms is the dominant technology for decarbonising electricity generation by 2050
- Deployment of CCS emission abatement technology for the purpose of power generation is consistently very low across multiple simulations. Analysis earlier in this report has indicated that CCS use is prioritised towards sources of hydrogen production
- Cogeneration LWSMRs are consistently deployed to (or close to) the applied site capacity limit of 22 GWe. This is explained by the associated chart in Figure 20 which is the corresponding chart for district heating energisation in 2050. LWSMR is the dominant source of heat supply via steam turbine heat extraction because of the low levels of additional CAPEX and OPEX associated with this solution compared with the alternatives
- Cogeneration Gen IV is deployed to the applied site capacity limit of 22 GWe in all simulations. The high level of deployment is linked to the dataset assumptions that Gen IV is the lowest cost source of firm power generation and has the capability to divert to hydrogen production when electricity generation reserve margins are very high because demand is low or because there is significant generation from intermittent renewables

- Generation III+ is valuable as a source of firm generation but deployment does not reach the applied site capacity limit across any of the simulations. The level of deployment includes HPC (3.3 GWe) and SZB (1.2 GWe) with a statistical distribution:
    - Lower quartile – 14 GWe
    - Mean – 18 GWe
    - Upper quartile – 21 GWe
- The variation in level of Gen III+ deployment (4.5 GWe to 30 GWe) is closely matched to the variation in deployment of wind (39 GWe to 83 GWe) once the difference in load factors have been taken into account. This relationship is probably related to the sensitivity of Gen III+ deployment to CAPEX levels. This infers that failure to achieve early and continuing long term cost reductions in Gen III+ projects can be expected to result in less Gen III+ deployment, with the "lost" capacity being made good by continued deployment of wind and associated back-up generation

Figure 20 suggests that if there is a likelihood of district heating systems being widely deployed at city-scale, then there is long term whole-system advantage of deploying LWSMR so that they are DH capable and at locations where it is feasible and more cost effective to install connecting water supply and return pipework. Such a plant upgrade for DH hot water supply and the associated pipework would only be implemented when there is a market need and if it is cost-effective to do so.

8.6. Maintaining A Focus on Market Needs and Costs

All except one of the UK's existing nuclear power stations is scheduled to be shut-down by 2030. The first unit of the twin EPR under construction at Hinkley Point is currently forecast to begin operations in 2025 and there is an expectation that a lifetime extension programme for the single unit at Sizewell B will enable operations to continue until 2055.

At the same time, the NDA's decommissioning programme continues across its estate comprising the nuclear research sites, the shutdown Magnox reactor sites and at Sellafield. The UK nuclear sector will soon experience a further shift from operations to decommissioning with a schedule of 10 years of AGR shutdowns[10] which is being planned by EDF Energy and the UK Government.

In 2018 the leadership of the UK Nuclear Sector and the Government jointly agreed the UK Nuclear Sector Deal[11] (NSD) through the forum of the Nuclear Industry Council. The NSD supports the UK Government's aims for a modern industrial strategy through:

- growth of a highly skilled workforce
- a globally unique stock of technology and skills which will benefit other industries and services and which has significant potential in overseas markets
- a lasting contribution to the communities that are host to nuclear facilities, both current and future.

The long-term future of the nuclear sector depends upon the elements of new plant construction and reactor fleet operation to complement existing fuel supply operations and plant decommissioning. More than ever before, the potential for the sector to expand out of the last bastion of nuclear decommissioning depends on delivering productivity, value for money and the products and services required by the market.

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[10] Advanced AGR decommissioning. BEIS 9th September 2019. https://www.gov.uk/government/publications/advanced-gas-cooled-reactor-agr-decommissioning

[11] Nuclear Sector Deal. Developed by the UK Nuclear Industry Council and published 27th June 2018. https://www.gov.uk/government/publications/nuclear-sector-deal/nuclear-sector-deal

The analysis documented in this report makes assumptions about long term reduction in the CAPEX requirements for new nuclear plants, along with other key parameters used in the analysis. These cost reduction assumptions are evidence based, with more certainty around the cost reduction potential for the sequential programmatic build of large Gen III+ reactors, and the less certain but evidence based assumptions for LWSMR and Gen IV, neither of which are yet approved for construction by regulators nor construction ready.

Failure to materialise these cost reductions and thereby bring forward the products and services which offer economically competitive solutions to market needs will continue the long-term decline of the UK nuclear sector in terms of products, services, capabilities and skills.

The market needs for new nuclear products for the UK civil nuclear sector are summarised by:

- new nuclear energy to complement electricity generation from renewables and wind in particular
- products which are cost competitive, which is realistic and achievable if the learning is implemented from the ETI Nuclear Cost Drivers study
- a build-out rate of new plants providing sufficient capacity to make a meaningful contribution towards decarbonising the UK economy to achieve Net Zero by 2050
- products which address the challenges of the market, with market need presented by the delivery of Net Zero. The potential markets for nuclear are in electricity, heat and hydrogen production.

8.7. Launching the Three Programmes

The evidence from the analysis documented in sections 5, 6, and 7 of this report, together with the associated discussion in section 8, identify that if the cost reduction assumptions can be realised, then there are significant potential roles for nuclear in a cost optimised pathway to deliver UK Net Zero. It is identified that there are potential roles for 3 new nuclear programmes in this decade:

- deployment of large Gen III+ reactors which are capable of delivering against the levels of firm electricity generation requirements identified in the CCC Net Zero report. These designs and associated projects are available for deployment now with the support of the right policy framework
- LWSMR reactors which, depending on the success of a number of vendor-led designs under development in the UK, USA and elsewhere, may be capable of delivering further firm electrical generation capacity at lower cost. If the designs are developed in the right way and these reactors deployed in the right way at the right locations, these plants may also have a potential role in the decarbonisation of domestic heat and hot water production through the energisation of district heat networks. This additional role depends on the economics of DH deployment compared with the alternatives, and a policy framework that encourages DH deployment at scale. A development programme is necessary to bring such designs to market which would require a UK Government policy framework delivering enabling activities and further support to enable early private sector investment. A first commercial LWSMR could be operating in the UK around 2030
- Gen IV reactors which have the potential to deliver further firm electrical generation capacity at lower cost. The higher operating temperatures of Gen IV nuclear heat supply systems compared with light-water systems increases their potential for cogeneration operations in the supply of high temperature heat. There may be a number of applications for high temperature heat, but the greatest need identified in this study is for hydrogen production. A Gen IV plant configured for cogeneration has the potential for switching energy delivery between two or more energy vectors. This creates the economic potential to operate such plants for supply of mid-merit electricity to complement electricity generation from wind. This again reflects a strong market need identified from this analysis. The ESME analysis is blind to which specific Gen IV technology is best suited to deliver this potential. However, parallel technical analysis identifies that High Temperature Gas Reactor technology is the most favoured Gen IV Nuclear Heat Supply System for this application. A development programme is necessary to bring such designs to market which would require a

Government policy framework delivering enabling activities and support to enable early private sector investment. The analysis in this report assumes that a first commercial UK HTGR could be operating in the UK around 2035.

The scope of the analysis in this report is bounded by time and budget. There are more potential nuclear technologies, energy applications, and cogeneration options which could be modelled in ESME. In particular, it is acknowledged here that Gen III+ reactors, whether deployed as large Gen III+ designs or LWSMRs, can be capable of supplying heat, flexible power and other non-electricity baseload applications including hydrogen production. There is also currently no explicit inclusion of nuclear fusion technology within ESME; estimates of timescales to commercial deployment for fusion vary significantly. However, the Gen IV technology dataset could represent a “target market” for fusion technologies, as the Gen IV dataset in ESME assumes a higher temperature supply of heat which is consistent between HTGRs and fusion technologies. There is the potential for modelling such potential applications in future ESME-based Net Zero sensitivity studies when there is more techno-economic evidence and budget made available to fund ESC.

9. Implications for Markets, Policy and Regulation

9.1. No New Nuclear

The expansion of the nuclear sector as part of the solution to achieving UK Net Zero should be recognised by policymakers as an option within a basket of technologies recognised as offering little or no regret. This in turn is made easier for policymakers if an expanded nuclear contribution is also recognised as part of the least cost solution to deliver against Net Zero. These conditions are necessary for policymakers because nuclear, amongst all the low carbon technologies, is the technology least suited for the Government to set the conditions for a long-term market change, and allow the private sector through private sector investment and classic competition amongst potential market suppliers to bring the most consumer attractive and winning solutions to market.

The 13 years' experience since the Energy White paper of 2007 of trying to bring forward investment in nuclear power stations is evidence of why this approach is least suited to new nuclear. After 13 years' experience, policymakers with responsibility for energy now better understand the Government role and effort necessary to enable delivery of a cost effective new nuclear programme, rather than a number of more expensive and unconnected individual projects. But the Departmental bandwidth and associated political leadership required to deliver such a programme is significant. Investment in such effort and political capital must be based on the expectation that commitment to such a programme would deliver social good and long-term benefit to the taxpayer and consumer. If the UK civil nuclear sector (meaning in this case vendors, developers, workforce, supply chain businesses and all associated investors) is unable to provide the required leadership and commitment, then these are the circumstances that could force UK Government to consider policy options for UK Net Zero involving no new nuclear. The analysis documented in this report indicates that a policy of no new nuclear could be characterised as:

- <u>Landscape detrimental</u>. The environmental impact in terms of change in land use to deliver a vastly expanded renewables-based net zero energy system, including bio-energy crops for processing with CCS emission abatement technologies, could be significant.
- <u>More risky</u>. Without nuclear, there are fewer options to complement energy from renewables. Such an approach may be characterised as "betting the farm" with the reliance on the combination of 99% capture rate CCS technology combined with BECCS, increased forestation and DACC to manage the residual emissions. This may present a greater risk to the achievement of net zero.
- <u>Potentially more expensive</u>. Although system deployment costs associated with particular scenarios are not quantified in this report, Run 3 in Figures 8 and 9 can be compared with Run 1 in Figures 14 and 15. The first FA96 scenario with no new nuclear has a grid capacity of 350 GWe to deliver 2050 electricity generation of 730 TWh. The second FA96 scenario cost optimised including new nuclear has a grid capacity of 140 GWe and 2050 electricity generation of 600 TWh.

But this analysis of no new nuclear described in Section 8.1 indicates that UK Net Zero without new nuclear is technically possible.

9.2. Constrained New Nuclear

Two approaches to a policy of constrained nuclear are described in section 8.2.1. The first is to continue Gen III+ reactor deployment for additional new plant connections post completion of HPC and within an initial "cap" for new nuclear deployment. This is an enabling option because it leaves the door open for other programme additions to support the achievement of UK Net Zero. It also builds on and takes benefit from investor commitment to HPC to stand up a new nuclear supply chain capability and kindle nuclear power plant delivery experience.

The second approach is to delay, which is effectively to select nuclear technologies as a collective "option of last resort" to deploy should all other options fail. The existing plant operations and maintenance capability resident in EDF Energy will have largely disappeared by this time. The "wait and see" approach leaves insufficient time to enable and deploy other nuclear technology options so effectively becomes "nuclear Gen III+ as the last resort".

The comparison between TECH100 scenarios "no new nuclear" (Run 3a) and "nuclear constrained by policy cap" (Run 50) illustrates that the energy systems each optimised without nuclear in TECH100 (as well as FA96) are under-provided with firm electricity generation. The addition of just 13 GWe of new large Gen III+ in TECH100 results in an overall grid capacity reduction of 30 GWe and displaces 42 GWe of renewable and associated dispatchable capacity:

- 11 GWe of wind
- 16 GWe of other renewables
- 6 GWe of thermal power generation with CCS, and
- 10 GWe of thermal power generation with 99% capture rate CCS.

The benefits of introducing such a development into policy, informed through such a scenario, are:

- This level of new nuclear deployment is suggested by the probabilistic (Monte Carlo) analysis as on option of little or no regret provided that nuclear deployment costs continue to fall as expected from the ETI NCD study
- It maximises the benefit of shareholder investment in HPC and gives consumers and taxpayers some return for the nuclear construction risk premium within the HPC strike price contract
- It enables other options through increasing the capability and experience of UK supply chain and regulators; committing to LWSMR or Gen IV development and deployment without the experience of recent Gen III+ construction can be expected to add further risks and costs associated with these further potential technology development and deployment programmes
- It also enables the nuclear sector to demonstrate than nuclear plants do not need to be risky or expensive, to thereby influence investor risk perception and create the potential for greater private sector investment in further nuclear technology development and deployment.

9.3. Unconstrained New Nuclear - the Base Case

The base case can be considered as an extension to an initial deployment programme constrained by the arbitrary policy cap. In addition to an initial progamme of 10 GWe of Gen III+ to follow HPC and the SZB life extension, the following additional programmes would be launched;

- The policy framework and enablers necessary to continue potential Gen III+ deployment from 13 GWe to a level yet to be determined, but within an upper limit of around 35 GWe based on site capacity availability in England and Wales
- The launch of a stage-gated development programme to realise a first UK LWSMR for operation from around 2030, together with the policy framework and enablers to support a fleet deployment programme of up to 25 GWe and consideration of potential cogeneration deployment options
- The launch of a stage-gated development programme to realise a first UK HTGR for commercial operation from around 2035, together with the policy framework and enablers to support a fleet deployment programme of up to 25 GWe and consideration of potential cogeneration deployment options.

Regular stage gate reviews would inform ongoing policy options and decision making:

- The continuation of UK Government support to the development programme for the UK deployment of LWSMRs
- The continuation of UK Government support to the development, demonstration and deployment programme for HTGRs, and
- When to bring the ongoing Gen III+ deployment to a close.

9.4. The Limits of ESME Analysis

It is necessary to remember that the new analysis reported here is based on the use of the ESME model which was designed and developed for a specific purpose but does have limitations in that ESME is:

- Not a full economic model as it excludes development and FOAK costs
- Not a market model
- Policy and technology neutral
- For the intended purpose of identifying technologies and deployment decisions of low/no regret.

The output from ESME modelling should be interpreted and can be used to inform market, policy and regulation frameworks to create and regulate markets, and to stimulate investment.

9.4.1. System Optimisation Model

There is a role for another different model to support system optimisation through to 2050. This needs to be a full economic model recognising that different risks and shareholder returns may apply to different technologies, and it does not need to be policy or technology neutral. But it must be more than a single vector electricity dispatch model, and it must recognise the opportunities and benefits of multi-vector technologies which can introduce flexibility, efficiency and resilience to the overall energy system.

9.4.2. NOAK Cost Model

ESME is a NOAK model which means that upstream technology development costs and transitional costs associated with FOAK to NOAK are not recognised. However, in reality the cost transition from FOAK to NOAK is important, particularly for technologies that are deployed in fewer numbers with relatively long operational lives. Large nuclear plants might be built and connected to the grid at the rate of one a year in an optimised sequential build programme. They might operate for 60 or 80 years before replacement. This deployment rate and rate of replacement might be contrasted with light vehicles or domestic boilers, which are produced in millions and likely to see two generations of replacement between now and 2050.

Therefore, the rate of migration from FOAK costs to NOAK costs is even more important for new nuclear. One element of learning from the ETI Nuclear Cost Drivers study was that an intentional commitment to a nuclear programme, not just the next project, is an important factor in influencing the rate and extent of cost reduction[12]. It would be beneficial for both industry and UK Government to better understand how to optimise a programme to drive long term cost reduction including the individual and collective impact associated with a range of informed policy choices.

9.4.3. Clean Growth Is More Than Just Energy System Optimisation

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[12] ETI NCD Project Additional Task 10 - Applying the ETI NCD Cost Model to Explore Selected Scenarios. Version 2 dated 26th March 2019.

The current UK Government's strategy for Clean Growth[13] looks to job creation and associated economic growth, plus regional focus to bring economic development where it is needed most. These wider economic aspects are not considered by ESME, but strongly relevant in UK and regional Government MPR considerations.

9.5. New Nuclear Deployment – MPR Experience to Date

The initial MPR actions related to new nuclear deployment within the first two years following the 2007 Energy White paper are described in detail in Section 5.4. Since 2009, the following further UK MPR actions have been taken in support of new nuclear build:

- Regulatory reform and the creation of a new independent statutory body known as the Office for Nuclear Regulation. Set up as a non-statutory agency of the health and Safety Executive (HSE) on 1st April 2011 and transitioned to a Public Corporation from 1st April 2014 under the Energy Act 2013
- Electricity Market Reform (EMR) with Contracts for Difference from 2011
- Industrial Strategy Nuclear Sector Deal 2018
- Consultation on Regulated Asset Base (RAB) as a mechanism for funding further nuclear projects

All of these MPR steps are relevant to the potential development and deployment in the UK of LWSMR or Gen IV nuclear technologies. The next anticipated step in UK energy policy is the 2020 Energy White paper, yet to be published. A UK Government response is also awaited to the RAB consultation; this may be anticipated through the 2020 Energy White paper or published elsewhere.

It is important to note that, for new nuclear deployment up to an arbitrary cap of around 14.5 GWe (including HPC and lifetime extension for SZB), the collection of existing MPR steps including the identification of an appropriate mechanism for funding new nuclear plants remains consistent with extant policy mechanisms including public consultation, the identification of sites through NPS – EN6 subject to realignment of the timing of site development[14], and the assumption of a once through fuel cycle.

9.6. New Nuclear Deployment – Policy Issues for Further Development

The new analysis in this report indicates the potential for nuclear to support decarbonisation beyond just the power sector into decarbonisation of buildings, specifically heating via district heat networks, and also the potential for hydrogen production.

9.6.1. Support for Development and Deployment of LWSMR and AMR Designs

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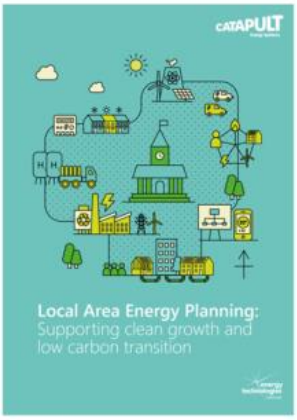
[13] Clean Growth Strategy. A policy paper published by BEIS with first release 12th October 2017. https://www.gov.uk/government/publications/clean-growth-strategy

[14] Government Response - Consultation on the siting criteria and process for a new national policy statement for nuclear power with single reactor capacity over 1 GWe beyond 2025. BEIS dated July 2018. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/727628/NPS_Siting_Criteria_Consultation_-_Government_Response.pdf

The ETI's SMR Deployment Enablers Project mentioned in Section 3.2.3 describes the fundamental requirements for a strong and transparent policy framework to encourage investor confidence and accelerate programmes with overlapping/parallel activities commenced at risk. This is relevant to potential development programmes relevant to both LWSMR and Gen IV.

The UK policy for Clean Growth seeks to derive sustained economic growth (e.g. job creation) from low carbon technology and deployment; this means seeking potential for growth through exports (e.g. technology and expertise) which in turn means an attractive product at the right time and at the right price. Waiting until commercial designs are demonstrated up to and including a first refuelling outage won't give the economic gains or early mover advantage anticipated through Clean Growth. The policy framework will need to enable and support technology development without an existing proven commercial design operating elsewhere in the world. Governments in the USA, Japan and elsewhere see a significant role for State investment in bringing potentially disruptive technologies to market, evidenced by US Government support for NuScale's LWSMR design and the Japanese HTTR design as part of JAEA strategy for a commercial HTGR design.

9.6.2. Potential Heat Requirement for Energisation of DH Networks



It is expected that the power sector will be largely decarbonised ahead of the transport and heat sectors in the transition through to 2050. Whilst decarbonising power is challenging, a national transmission and distribution system is already in place and central co-ordination and regulation involves relatively few actors. This enables and requires a strong decision making and leadership role for central government.

For decarbonising transport and heat, the prescription of fixed solutions from central government is less likely to support a successful transition. This is because many more actors are involved from suppliers to millions of consumers. Local solutions which best match local opportunities are expected to be more successful, particularly as changes impact consumers and to be successful will require changes in consumer behaviour.

As part of the ETI's Smart Systems and Heat (SSH) Programme delivered by ESC, the importance of Local Area Energy Planning (LAEP) was recognised in testing solutions and providing options for local decision making. Whilst decision making for such plans is best made locally, there is benefit for enabling frameworks and policies from regional and national Governments to support such decision making. Denmark is often cited as a leader in DH deployment with policies and frameworks to support and enable local decision making. A recent IEA article on district heating[15] identified that municipal and city level policies are important and that national level support also strengthens local initiatives significantly.

DH economics and the costs for DH deployment are known from international norms; the most favoured locations are dense conurbations where the density of demand is high and the average pipe-length to connect properties to a distribution system are low. It would be helpful for UK Government to provide a centralised view of:

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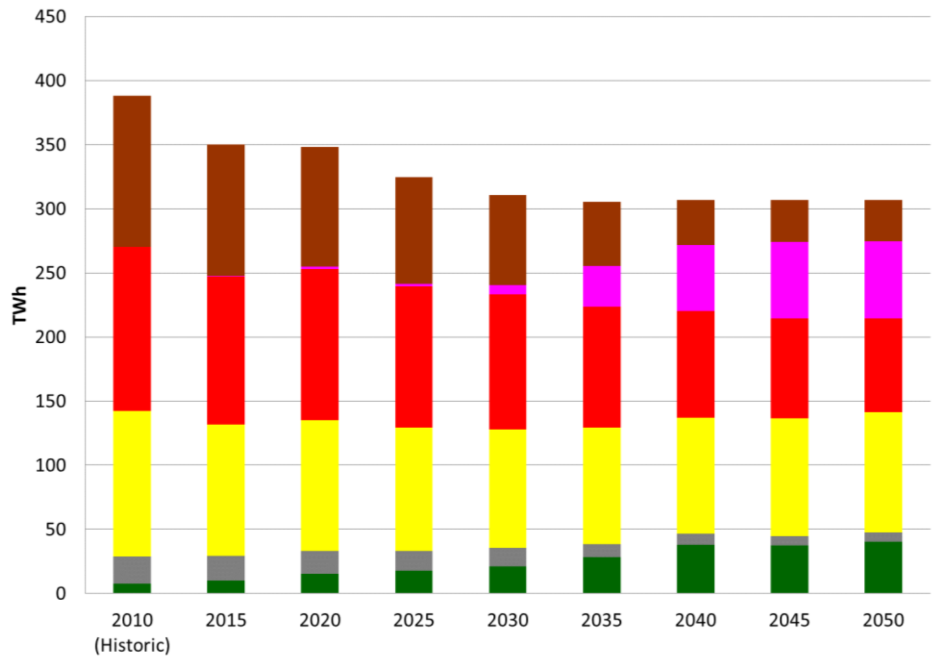
[15] How can district heating help decarbonise the heat sector by 2024. An IEA article dated 21st October 2019 https://www.iea.org/articles/how-can-district-heating-help-decarbonise-the-heat-sector-by-2024

- the developing policy and associated updates on decarbonisation of domestic heat use, including a regulatory framework for DH (e.g. with clarification on the role and responsibilities associated with regulation)
- where networks are more likely to be deployed based on DH economics
- upper and lower bounds of heat energisation requirements for each of the larger potential networks.

An additional but related potential policy consideration is the requirement that all new thermal energy plants including nuclear are to be designed and built to be “heat supply capable”. This future optionality could enable a subsequent plant upgrade for heat supply for DH energisation, should a future market emerge and the economics including the cost of the pipework connection be deemed favourable.

9.6.3. Potential Requirements for High Temperature Heat for Industry

There are diverse requirements for the use of high temperature heat across the industry sector. Figure 22 illustrates how ESME approaches the decarbonisation of the industrial use of heat towards 2050 from Run 1a using the TECH100 scenario. Significant reductions are evident in the use of liquid fuels, natural gas and coal but with increases in the use of biomass and hydrogen.



Fuel type	Key	TWh at 2050
Liquid fuel		30
Hydrogen		60
Gas		83
Electricity		95
Coal		4
Biomass		34

Figure 22 – Industry Fuel Consumption with Scenario TECH100 (Run 1a)

The opportunities for decarbonisation of energy use in industry include:

- energy efficiency measures through insulation or process improvement
- CCS emission abatement technology, but many applications of high temperature heat use are unlikely to be in CCS clusters therefore precluding this as a widespread option
- electrification, depending on local infrastructure requirements
- naked flame hydrogen as a replacement for natural gas.

Specific opportunities have been identified where significant energy demand at existing nuclear sites might be cost effectively delivered and decarbonised through the on-site cogeneration of high temperature heat and power. U-Battery[16] has promoted this a potential solution for the energy demand at Urenco's UK uranium enrichment plant at Capenhurst. High temperature heat supply is an area of interest for a number of vendors of Advanced Reactors, either for the embedded heat and power supply within industrial complexes, or for remote off-grid industries and communities.

It would be helpful for UK Government to provide a centralised view of the policy options for the decarbonisation of the industrial use of heat. High temperature heat which is low cost and low carbon is also a necessary requirement for reducing the cost of hydrogen or syngas manufacture.

9.6.4. Potential Requirements for Hydrogen Supply

It would be helpful for UK Government to identify the expected timing and scale of the UK market for the supply of hydrogen with a low carbon footprint, and also the expectations of the volume of hydrogen that can be sustainably delivered through steam methane reforming given the need to manage the impact of residual emissions, even at 99% carbon capture rates.

Given the attractiveness of hydrogen as an energy vector for long distance heavy haulage transport, maritime use, peaking power, industry applications and hard-to-treat heating applications, it would be useful to understand the timing, scale and indicative market price expectations for new sources of low carbon hydrogen to drive the growth of the hydrogen economy and make decarbonisation choices simpler and easier for consumers.

As with District Heating, potential hydrogen suppliers will require regulatory consideration and supportive policy frameworks to enable investor confidence.

9.6.5. Designation of Potential Sites for Nuclear Development

The list of sites designated in NPS EN-6 is sufficient for a new nuclear build programme with a capacity cap of up to around 16 GWe, and UK Government has already consulted on the potential process for updating NPS EN-6 for deployment from 2025 onwards of nuclear power with single reactor capacity greater than 1 GWe. These designations are relatively specific in terms of the size and type of nuclear power plants that can be built together with timescales for their development. Further policy work is needed should:

- the requirement for the number of sites change
- the timeframe for development change
- there be a change to the proposed type of nuclear technology to be deployed at one or more of these sites

If the scale of nuclear deployment and generation is to increase beyond historic levels, then a strategy for designating further sites will be required. There is time to develop this strategic approach and framework to the next phase of nuclear siting consideration because the list of sites in the current version of NPS EN-6, subject to the addition of a new site adjacent to the existing decommissioning Magnox reactors at Trawsfynydd, is likely to be sufficient until around 2025. But it will be necessary to show that there is active policy development on further site designation to maintain investor confidence amongst vendors, developers and associated supply chains.

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[16] U Battery website https://www.u-battery.com/why-u-battery

9.6.6. Commitment to Programmes of Capacity Rather than Just the Next Project

This report references the evidence from the ETI's NCD project which shows that the intentional commitment to a programme of capacity is a key enabler to unlocking nuclear cost reduction in a sequential build of new nuclear power plants. This is true for all new nuclear technologies across large Gen III+, LWSMR and Gen IV.

Given the complexities of safety regulation of technologies, sites, organisations and prescribed activities through the Nuclear Installations Act 1965 (as amended), it is unrealistic to plan for the expectation of off-shore wind style auctions in the short to medium term for new nuclear capacity. However, finding a framework which gives developers, vendors and their supply chains confidence in a pipeline of projects is a vital step in unlocking the full potential of cost reduction from the optimised replication of reactor designs and projects, together with the necessary learning from one project to the next to maintain a programme of continuous learning and improvement. It is vital that such a programme of improvement remains focussed on cost reduction in deployment, rather than design enhancement.

Accessing an affordable route to financing a programme of new nuclear plants is an imperative element within such a programme commitment. There are significant benefits to consumers and taxpayers in socialising nuclear construction risk, even if such a step is to be limited to a transitional measure.

To provide transparency and be successful, a programme approach needs to be developed which generates a target cost curve for the short, medium and long-term. Such a curve would need to recognise the realism in the transition from FOAK to NOAK and more specifically:

- Recognise the realism in transition between LCOE for "in-country FOAK" to genuine "NOAK" for a common WACC (6%), consistent with a solution for financing new nuclear construction which benefits consumers and taxpayers
- Apply to electrical generation deployed with high capacity factor eg 90% plus (to level the playing field for technologies that could also be deployed for multi-vector cogeneration options delivering mid-merit electricity)
- Create a target curve illustrating the trajectory where high capacity factor generating assets deliver value to the grid by adding resilience and flexibility whilst reducing costs. Such a curve is useful in countering the perception that intermittent renewables and high capacity factor firm generation assets should be compared using LCOE as the only mechanism for demonstrating consumer value
- Periodically review and update the cost curve based on performance and costs of intermittent renewables, energy transmission, and energy storage. This is important to reflect on the general state of the electricity market to ensure that new nuclear projects are genuinely led by market need and consumer value.

A programme-led approach to nuclear deployment should be driven by this target cost curve that includes the expectation of long-term cost reduction. Such a cost curve should be produced and led by a market model rather than a NOAK cost model. A stylised illustration of such a cost curve is shown in Figure 23. Similar target cost curves should be generated for lower grade heat, high temperature heat for use in industry, and hydrogen supply with a low carbon footprint.

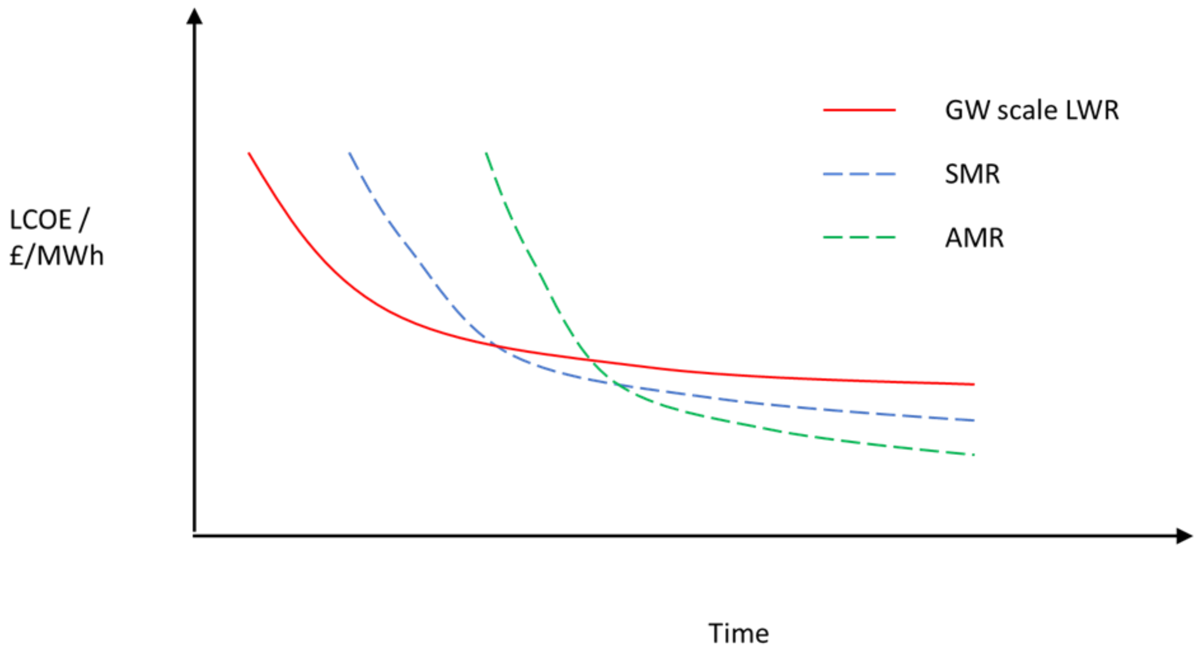

Figure 23 – Stylised Nuclear Technology Cost Curve That Should be Informed by a Market Model Rather Than a NOAK Model

UK Government and economic regulators could use these target cost curves, and competition where practicable, to determine value for money for a particular element in a nuclear programme, rather than more heavily relying on a confidential assessment through a bottom up appraisal of a developer's "books" for the next project in the pipeline.

9.7. Ongoing Issues Requiring Continued Management by Government and Industry

Section 9.5 summarised the historic enabling frameworks which were put in place from 2007 to enable new nuclear development, and how these frameworks have been amended or added to since 2007. Section 9.6 identified some of the additional MPR issues to be addressed if the some of the potential opportunities identified in this analysis are to be realised. This section highlights other ongoing issues requiring ongoing continuing management by both Government and Industry because, if resolution of these issues is seen to fail, then they could become significant barriers to new nuclear deployment.

9.7.1. Confidence in Progress with Waste Management and Disposal

The Energy White paper from 2007 proposed that the opportunity for new nuclear deployment should progress, but also recognised the conditionality associated with progressing a long-term solution for nuclear waste and spent fuel. Given the need to demonstrate progress against the requirements of this test, some might consider that actual progress made over 13 years since the 2007 Energy White paper is less than might have been anticipated. In this field within the nuclear sector, UK Government is responsible for policy, NDA is responsible for delivering associated programmes through the Radioactive Waste management Directorate, and CoRWM[17] provides independent scrutiny and advice to the UK governments on the long-term management of higher activity radioactive wastes.

Failure to make progress on this issue carries the risk of triggering legal proceedings prepared by Non-Governmental Organisations for consideration by the courts with the aim of creating the requirement for Judicial Review.

9.7.2. Sector Perception as a Good Steward of Public and Investor Funds

Public opinion and associated support for the nuclear sector across new build, power generation and decommissioning are both influenced by a range of factors including:

- Recognition of the benefits of nuclear power as a clean low carbon energy source alongside renewables
- Recognition of the value of the sector to the UK economy and potential for export for technology and skills
- Perception of value for money from activities which are taxpayer funded.

Maintaining a perception of delivering good value for money from direct taxpayer funding or other Government support is a vital enabler for new nuclear energy because commitment to a programme of new nuclear plants can be expected to require Government support in a number of ways. To maintain a social licence to operate and expand the nuclear sector's activities to support the achievement of Net Vero, the sector needs to be perceived as a good steward of taxpayer and investor funding. The offshore wind sector illustrates behaviours which would be positive for the UK nuclear sector to emulate including:

- Commitment to long-term cost reduction for the benefit of taxpayers and bill payers
- Innovation across the breadth of operations to reduce cost
- Growth through private sector investment with a good understanding of project and programme risks to enable a competitive WACC
- Regional economic benefits through the creation of long-term skilled employment
- Stakeholder engagement to enable widespread social recognition and acceptance.

UK nuclear decommissioning has been a growing element within the sector since vesting of the NDA in April 2005. The NDA, its subsidiaries, and associated supply chains will operate through financial year 2020/21 with a budget[18] of around £3.4 Bn with taxpayer funding of £2.8Bn. The NDA's mission is to clean up the UK's earliest nuclear sites safely, securely and cost-effectively. The way the NDA delivers this will have an influence on the perception of the nuclear sector and its success at expanding its operations. The NDA should do more on developing and explaining its narrative of cost-effective delivery including its programme of improving business efficiency. The ETI Nuclear Cost Driver study exposed the reality that it can be the indirect costs within projects and programmes which often explain the variation in costs between similar projects, and also the potential for reducing indirect and direct costs in a programme sequence of similar projects. The NDA should do more to explain its narrative for realising cost efficiencies on similar projects across

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[17] Committee on Radioactive Waste Management. More details can be found from the CORWM website https://www.gov.uk/government/organisations/committee-on-radioactive-waste-management

[18] Draft NDA Business Plan 2020 to 2023 for consultation between 19th December 2019 and 14th February 2020. https://www.gov.uk/government/consultations/nuclear-decommissioning-authority-draft-business-plan-2020-to-2023

its sites and between its sites. Such a narrative aligns with the mission of the NDA and is an expectation from the waste and decommissioning sector's commitment to a 20% cost reduction as part of the UK Nuclear Sector Deal agreed in June 2018.

9.7.3. Ongoing Public Support Through Engagement and Consultation

The 2007 energy white paper was framed on the basis of facilitative action to enable potential investment by developers, rather than to deliver a specified programme of new nuclear capacity. More background detail is provided at section 5.4 but, following consultation and subsequent legislation, the response to this framework was the emergence of developer plans for a programme of around 16 GWe which grew to 18 GWe by 2018. This level of deployment is broadly consistent with nuclear replacement (plus allowing for a little growth).

Commitment to a deployment programme of around 16 GWe of new nuclear is consistent with the policy of each UK Government since 2007 and should require no new national consultation. Developers bringing forward proposals for new nuclear power stations are required to undertake two rounds of local consultation with issues raised and developer responses taken into account through the Development Consent Order planning consideration process.

Ongoing engagement is essential as part of the preparation for the potential expansion of the use of nuclear energy as part of the basket of technical solutions to deliver UK net zero. Further consultations to support such potential expansion will be inevitable and beneficial at both national and local levels. Public attitudes on a range of energy related issues including for nuclear are monitored through regular surveys[19]. Each of the elements within the UK civil nuclear sector influences public attitudes through their performance, how they are portrayed in the media and the nature and impact of their engagement with stakeholders including the public. Proposals for potential expansion of the use of nuclear energy use in the UK will not be considered in isolation from public attitudes; in this sense every element in the nuclear sector has a role to play.

9.8. Specific Issues Relevant to a Managed Transition to UK Net Zero

It was Alistair Darling with Tony Blair as Prime Minister who brought forward the 2007 Energy White paper. Through the 2008 Climate Change Act this committed the UK in law to reducing greenhouse gas emissions by 80% compared with reference levels. In 2019 an amendment was brought forward with Theresa May as Prime Minister to amend the legally required standard of performance of UK Net Zero by 2050. Section 9.8 addresses the opportunities and challenges associated with stepping up to deliver UK Net Zero, particularly in the context of new nuclear energy.

9.8.1. UK Net Zero – Good Progress to Date

To meet the targets associated with the original 2008 Climate Change Act, the government has set five-yearly carbon budgets which run concurrently until 2032. They restrict the amount of greenhouse gas the UK can legally emit in a five-year period. The UK is currently in the third carbon

[19] BEIS Public Attitudes Tracker – Wave 32. Released by BEIS 6th February 2020 dated https://www.gov.uk/government/statistics/beis-public-attitudes-tracker-wave-32

budget period (2018 to 2022); the Committee on Climate Change is expected to publish its recommendations on the level of the Sixth Carbon Budget in September 2020.

However, the UK is not on track to meet the fourth budget (2023 to 2027). Beyond decarbonising the power sector, further progress is needed in decarbonising the use of heat in homes and businesses, transport including long distance, heavy haulage, aviation and maritime trade, and use of energy in industry. To meet future carbon budgets and the 100% target for 2050 will require the government to apply more challenging measures.

9.8.2. Time to Double Down on Technologies of Little or No Regret

Government should increasingly be ready to commit and “double down” on technologies of little/no regret. This does not mean an end to innovation, but a recognition of the need to deliver on solutions of little or no regret whilst innovation continues in all its forms.

Nuclear has a strong role to play in decarbonising and expanding a UK low carbon power generation system. Alongside renewables, the analysis in this report demonstrates that (with a relentless focus on cost reduction) nuclear can contribute by adding resilience and reducing cost through delivering firm power generation as well as mid-merit power (not fast response).

Challenges ahead, in the 4th and 5th carbon budgets and beyond, involve further decarbonisation of the use of heat in homes and businesses, and decarbonisation of energy use in industry and transport. Three important energy vectors for tackling these challenges are electricity, heat supply, and hydrogen production and all are reliant on a low carbon source of energy. Electrifying heat and transport could require double the amount of electricity generation in the UK today. Nuclear has the potential to make a greater contribution to tackling these challenges and energising these vectors through the development of light-water nuclear small modular reactors and advanced modular reactors (Gen IV).

9.8.3. Avoid the Hockey Stick of Late Technology Deployment and Investment

ESME as an energy system modelling tool is designed to be technology and policy agnostic. Its primary use should be in identifying low carbon technologies of little or no regret. The role for policy and regulation is to create markets to realise the desired policy outcomes. An important policy goal should be to deliver an affordable and managed transition which minimises adverse impact on UK economic growth. There can be a temptation to leave difficult decisions until later because they may be politically challenging, or the temptation that continued investment in innovation to enable new technical, system or business opportunities which are more attractive than the solutions available today.

To deliver an affordable and managed transition it is vital that not all of the “difficult to deliver” solutions and associated programmes are left until the decade 2040 to 2050. MPR action should be used to bring forward and smooth some of these technology and deployment challenges. In particular, given the role that low carbon electricity is expected to deliver in the decarbonisation of heat and transport, bringing forward new nuclear can be fundamental to enabling this. However, new infrastructure and innovation does not appear overnight and therefore the markets, policy and regulatory incentives need to be developed and implemented now.

9.8.4. Cumulative Emissions Contributing Beyond the 2 Degree Scenario

As discussed in section 9.81, the UK is not on track to achieve the 4th carbon budget. The impact from this overshoot is that every tonne of CO_2 emitted adds to the total environmental inventory of cumulative emissions. The consequence of this overshoot is that the UK is contributing to the trajectory of exceedance above the two-degree scenario.

Nuclear energy through its different technologies has the potential to help recover this and, based on the new analysis in this report, do so within a UK energy system optimised to achieve Net Zero at least cost (provided that the nuclear sector realises continuous and sustainable cost reduction).

Whilst the final proportion of nuclear within a UK 2050 net zero energy mix is yet to be determined, as well as the relative proportions between large Gen III+, light-water SMRs, and advanced modular reactors (Gen IV), the evidence in this report suggests a new approach for nuclear:

- Commit to the deployment of an initial programme of large Gen III+
- Commit in parallel to the stage-gated development and deployment of LWSMRs and AMRs
- Within 5 to 10 years there will be better evidence of the realised benefits and merits of each
- Make initial assessments of target deployment levels for each of the nuclear technologies within an optimised UK energy system cognisant of the capabilities and benefits associated with other low carbon technologies
- Within 5 to 10 years there will be sufficient evidence of when to bring the programme of large Gen III+ to a close.

Finally, there is one certainty regarding new nuclear. Tony Blair in 2007 and Theresa May in 2019 communicated an imperative and urgency to reduce the UK's greenhouse gas emissions compared to historic reference levels. Since 2007 there has been a consistent policy of enabling the deployment on new nuclear power stations and HPC unit 1 is currently forecast to begin operations in 2025. With 3.3 GWe of new nuclear capacity expected to be achieved after 18 years, if this rate of progress is maintained, then there will be less than 8 GWe of new nuclear generation by 2050. However, if such a rate of progress is maintained then the analysis documented in this report also suggests that the 2050 contribution from nuclear will be sub-optimal and higher cost than it should be. The overall energy system would also be more expensive with greater associated risk due to reduced energy diversity and a dependency on some of the "bet the farm" speculative technologies introduced with ESME scenario TECH100.

If nuclear is to fulfil its potential role in the achievement of Net Zero, then the overarching policy regarding new nuclear can stay the same, but the associated policy framework intended to deliver it must change. Both Government and the nuclear sector, represented by the UK Nuclear Industries Association, have a role to play in this, possibly through the next update to the UK Nuclear Sector Deal.

10. Conclusions

Context - this report sets out the findings from whole energy system analysis of the potential roles and contribution from nuclear energy in supporting different decarbonisation pathways to achieve UK Net Zero. The analysis summarised in this report is the most recent analysis in a series of nuclear techno-economic assessments undertaken using ESC's Energy System Modelling Environment (ESME) since 2015. The underlying nuclear technology related data and assumptions incorporate the learning from engagement with the nuclear sector and the knowledge from the Energy Technology Institute's portfolio of knowledge building projects within its nuclear programme. The ETI closed in December 2019 and ESC now owns, operates and updates ESME.

This new analysis, known as Nuclear for net Zero (NFNZ), benefits from the learning and data from the ETI's Nuclear Cost Drivers project which had not previously been incorporated into the ESME nuclear technology datasets. This new analysis also takes advantage of a new near Net Zero scenario as well as a number of Net Zero scenarios developed by ESC and reported through "Innovating to Net Zero". ESC Net Zero analysis reported in March 2020 was completed by December 2019 and before the analysis in this report was completed. The two reports should be read together; the analysis in ESC's Innovating to Net Zero (ITNZ) report precedes the analysis reported here.

As described in detail within this report in the sections relating to both ESME and MPR, it is made clear that the ESME whole energy system model is not a commercial market model. ESME is intentionally designed as a technology and policy neutral analysis tool using "N'th-of-a-kind" technology data. Analysis through multiple scenarios including Monte Carlo probabilistic modelling is intended to identify technologies which are repeatedly deployed at scale across a broad range of scenario simulations to recognise the subset of technologies for which policy support for development can be considered as a choice of little or no regret. Rather than providing a precise blueprint for an optimised 2050 energy system design, the purpose of ESME is to identify these important technologies and enable ESC to make recommendations regarding markets, policy and regulation to enable timely deployment of such technologies in an energy system transition to Net Zero. Equally, different energy system models developed for other purposes using different data inputs and assumptions can be expected to produce different results.

Market, policy and regulation action by Government is not prompted by energy system optimisation considerations alone, but also through consideration of additional aspects such as energy security, potential impact on the economy nationally and regionally, and wider Government policy such as Clean Growth.

From an energy system perspective, achieving Net Zero is hard; ESME has needed additional help through more speculative solutions to decarbonise beyond 96% of reference levels and realise multiple potential pathways for achieving Net Zero. In the development of its new scenarios described in its March 2020 report, ESC reports that ESME with existing technology datasets and associated scenario assumptions would fail to solve beyond 96% decarbonisation. Substantial progress towards Net Zero could be achieved using these more widely recognised technologies and associated assumptions, although many of these technologies are not yet proven at scale or deployed in volume. This potential for "substantial progress" towards net Zero is recognised through the Further Ambition 96 scenario. Two further scenarios were developed known as TECH100 and SOC100; the first introduces additional speculative technologies with less certainty around their technical performance and economic characteristics, and the second assumes changes in societal behaviour to reduce energy related and other emissions. The combination of these two "new" scenarios, leads to a fourth scenario known as BOB100. This fourth scenario combines changed societal behaviour and associated reductions in demand and emissions with the additional speculative technologies which are less certain. The analysis in this report documents dozens of modelling simulations across 3 of these scenarios (FA96, TECH100 and BOB100, noting that the benefits and impacts of SOC100 are included in BOB100) and finally a probabilistic (Monte Carlo) analysis using the TECH100 scenario. These multiple, diverse scenarios provide insights into the role of cost-effective technologies which are ready to be deployed, or are already in deployment today, alongside the need to support and enable the continuing innovation necessary to close the gap and achieve UK Net Zero.

Conclusion 1 – nuclear is potentially an important part of the future Net Zero energy system in the UK but nuclear cost reduction is a necessary pre-requisite. Cost reduction is baked into the N'th-of-a-Kind cost assumptions used in this analysis. One of the key enablers to nuclear cost reduction is the intentional commitment to programmes of capacity rather than individual unconnected projects. In the absence of credible plans to realise nuclear cost reduction, a UK net zero energy system without nuclear is possible but targeting such a system is risky (unlikely to get to Net Zero) and potentially expensive. Such a non-nuclear scenario might require significant bioenergy and land use change, as well as a vast quantity of renewable energy. The analysis in this report draws on projects and other references to demonstrate circumstances where nuclear power projects have encountered numerous risks during deployment causing delays and cost escalation. These reports and references also describe the circumstances and evidence from other nuclear power projects with shorter construction duration, less risk materialisation and lower costs. Nuclear power plant construction projects do not need to be risky or expensive. The datasets for large Gen III+ reactors represented by the designs currently progressing or previously completed UK Generic Design Assessment have been adjusted to reflect the expectation of cost reduction achievable with replicated construction delivered in the right way. These assumptions are explained within this report, but are not considered overly optimistic if the steps and opportunities described in the ETI Nuclear Cost Drivers report are implemented. A range is identified for overnight capital cost, which recognises and indicates the potential for these costs to fall further. One of the key enablers to nuclear cost reduction is the intentional commitment to programmes of capacity rather than individual unconnected projects. Additionally, the ETI Nuclear Cost Drivers report describes the potential for light-water nuclear Small Modular Reactors, and advanced Generation IV reactors. Neither of these technology groups has commercial reactor designs currently approved by regulators or "shovel ready" for deployment, but the potential is identified for deployment costs even lower than those potentially achievable with large contemporary reactor designs to be deployed in countries with developed economies where wage rates for construction labour and project related professional services are relatively high. These potential further cost reductions attributable to these additional technologies are used in the cost assumptions within this analysis. Failure by reactor vendors with UK developers and UK supply chain, working together and with UK Government, to realise these potential cost reductions will cause project construction estimates to remain higher than they otherwise should be or could be. At these higher costs, ESME modelling identifies that some nuclear technologies move away from inclusion in the many pathways to full decarbonisation through the many scenarios considered in this analysis. A UK nuclear sector without a programme of both new reactor projects and long-term operations faces long-term decline. Potential stakeholder engagement by parts of the sector on the basis that nuclear is unique, requires special treatment, and doesn't need to be cost-competitive is ill-advised; the new analysis in this report demonstrates that it is possible within energy system models to achieve UK Net Zero without new nuclear. A UK net zero energy system without nuclear is possible but targeting such a system is risky (unlikely to get to Net Zero) and potentially expensive. Such a non-nuclear scenario might require significant bioenergy and land use change, as well as a vast quantity of renewable energy.

Conclusion 2 – energy from wind is the key technology for decarbonising power. There are important potential roles for nuclear and multiple applications for Carbon Capture and Storage (CCS). CCS deployment should be targeted at various applications for hydrogen production; Bioenergy with Carbon Capture and Storage (BECCS) is important to counter the impact of residual emissions (mainly in aviation and livestock but also fossil CCS). The new analysis in this report confirms that wind generated energy in its various forms is the key technology for decarbonising power and should be deployed at scale. But there are important potential roles for both nuclear and CCS. Multiple scenarios indicate that for a Net Zero energy system, residual emissions have to be countered by various forms of CO_2 accountancy credits, from technologies including BECCS, additional forestation and potentially Direct Air Capture of CO_2. Modelling suggests that CCS use in 2050 with power generation technologies is relatively low, and that CCS applications are generally directed towards the production of syngas or hydrogen, both of which are valuable as energy vectors. It is well established that for a balanced, resilient and cost-efficient system intermittent renewables should be complemented by additional technologies providing firm and mid-merit generation. With the levels of overnight capital cost explained in this report, and used as the basis for the energy system modelling, nuclear technologies have important potential roles to complement energy from wind in providing electricity generation.

Conclusion 3 - if District Heating is to be deployed at scale in cities for decarbonising heat in homes and domestic hot water production, then low grade heat from thermal power plants including nuclear is a very cost-effective heat source. Based on data incorporated within ESME, district heating is frequently modelled as being deployed as an energy vector for decarbonising heat and hot-water production in homes and light commercial premises. The economics of DH are well established from Scandinavian countries and elsewhere. Deployment is favoured where building density and therefore energy demand density is high because the ratio of piping installation to consumer demand is relatively low. As demand density reduces then piping costs rise until the economics for further DH expansion into lower density housing areas becomes marginal. DH deployment also requires access to a local carbon energy source for the supply of heat, and experience elsewhere indicates the need for a strong policy framework both locally and nationally. Significant DH deployment occurs within ESME modelling scenarios even if there is no low carbon heat available from nuclear. More extensive DH deployment as part of the UK transition to Net Zero will require (1) positive business cases for local system installation, (2) frameworks of policy support at national and local level, (3) access to low carbon heat sources by 2050, with potentially interim heat supply sources during the transition. If these conditions are all met, then energisation with lower grade heat from nuclear plants could be very cost-effective. Many such nuclear heat supply applications exist around the world today; the technology and economics are both proven. District heating and hot water production from nuclear energy was reliably delivered by the UK Calder Hall Magnox power station for many decades.

Conclusion 4 – one of the challenges with deploying city-scale DH is the installation of piping. All reactor types are capable of cogeneration deployment to supply the lower grade heat required; light-water nuclear SMRs are a good match for thermal energy demand and

can be deployed closer to the centre of demand meaning shorter connecting pipes and lower costs for many potential DH locations. The dominant capital expenditure associated with the installation of DH is the piping. This includes system network piping, connections to individual buildings, and the connection of the system to the source of thermal energy, which may be some distance away. All reactor types are capable of providing lower grade heat for DH energisation. There is merit in considering the requirement that all new UK commercial reactors should be designed and configured such they are DH capable. The cost is small if this is engineered-in during initial design and construction. If a future DH market emerges and it is cost effective to do so, a future engineering outage would enable the plant to be upgraded to supply heat via a pipeline connection to a DH system. The costs associated with this piping installation are significant. Greater distances increase costs, but costs can also be strongly influenced by the need to overcome obstructions such as roads, rivers or undulating land which require diversions or tunnelling. Light-water nuclear SMRs could potentially be a good match for DH thermal energy demand and can be deployed closer to centres of DH demand, meaning shorter pipes and lower costs for many potential DH locations.

Conclusion 5 – hydrogen is a very important energy vector for net zero. Hydrogen production methods using fossil fuels with CCS create residual emissions which must be compensated for using accounting methods linked to other technologies with carbon credits. Increasing carbon capture rates to potentially 99% reduces the impact from these residual CCS emissions when used with fossil fuels. Multiple studies identify that hydrogen is a very important energy vector for net zero. Potential applications considered through modelling include long distance heavy haulage, industrial applications, hard-to treat heating requirements, peaking power generation, and conversion to ammonia for use in shipping. For 2050, many scenarios indicate hydrogen deployment from multiple sources include biomass and waste gasification with CCS, and steam methane reformation with CCS. Multiple scenarios indicate that for a net zero energy system, residual emissions from the deployment of CCS have to be countered by various forms of CO_2 accounting credits, including BECCS, additional forestation and potentially Direct Air Capture of CO_2. Increasing carbon capture rates to potentially 99% reduces the impact from these residual CCS emissions when used with fossil fuels. Other methods of hydrogen production include low temperature electrolysis, but at a system level this is a relatively expensive source of hydrogen supply and is frequently de-prioritised in cost optimised scenario modelling. The inference is that hydrogen network supply may be potentially constrained by the lack of additional higher volume and lower cost sources of hydrogen supply.

Conclusion 6 - advanced nuclear plants coupled with higher temperature more efficient hydrogen production technology can be a cost-effective source of additional hydrogen with low carbon footprint and relatively low land-take. The techno-economic analysis described in this report applied a lower-cost nuclear plant combined with hydrogen production technology to model a cogeneration plant capable of producing hydrogen in combination with electricity generation. The cogeneration plant was also modelled to have operational flexibility consistent with day-ahead planning, enabling plant operations to shift between periods of maximum electricity generation when generating reserve margins are low and prices high, to periods of maximum hydrogen production when electricity generating reserve margins are high and prices low. The modelling results indicate that hydrogen from nuclear (at the level of technical performance and economics characterised in this report) can be a cost-effective source of hydrogen production in a 2050 Net Zero energy system. Further sensitivity testing provided an indication of a tipping point where hydrogen from nuclear could shift from merely supplying the hydrogen economy to beginning to drive the growth of the hydrogen economy. Compared with other routes of supply to expand the hydrogen economy, such as more steam methane reformation capacity with CCS (requiring more land-based offsetting via increased forestation or biomass) or more low temperature electrolysis energised by additional renewables, advanced nuclear has the potential for greater energy density, lower costs, and much reduced land take. ESME modelling is blind to specific types of reactor design. All groups of nuclear technologies modelled in ESME are capable of cogeneration for both heat and hydrogen production. The limited time and budget available for this new analysis dictated that the scope had to be bound and choices down-selected for analysis. Light-water nuclear Small Modular Reactors have been modelled for cogeneration of flexible power generation and heat supply for DH energisation on the basis of a shorter average distance for the pipeline connection from a potential plant location to the centre of demand of the various city-scale DH networks. Gen IV advanced reactors were modelled for cogeneration of power and hydrogen production. This was based on their potential for lower costs and higher operating temperatures associated with Gen IV nuclear heat supply systems. This higher temperature is an important element in enabling more efficient hydrogen production processes. The technology dataset for this configuration has been based on technical papers from the Japanese Atomic Energy Authority's development programme for High Temperature Gas Reactors. Their High Temperature Test Reactor has been in operation since 1999 and JAEA has also demonstrated regular periods of sustained hydrogen production using the high temperature sulphur-iodine thermo-chemical process. Whilst there is an HTGR already capable of demonstrating hydrogen production through a high temperature thermo-chemical process, more work is required to determine the optimum combination of nuclear heat supply system with the optimum hydrogen production technology which could be deployed in a timeframe to support Net Zero. The new analysis in this report identifies that advanced nuclear plants coupled with higher temperature more efficient hydrogen production plants can be a cost-effective source of additional hydrogen with low carbon footprint and relatively low land-take.

Conclusion 7 - nuclear can have an expanded role in power generation as well as supplying heat for DH energisation and hydrogen supply into a future network for multiple applications. A number of recent studies have characterised choices regarding nuclear deployment as being limited to risky, expensive baseload electricity plants. This report identifies that the deployment of new nuclear plants does not need to be risky or expensive. Large Gen III+ reactors could be a cost-effective option involving many new plants by 2050 if deployed in the right way and consistent with the findings of the ETI Nuclear Cost Drivers project. The report also identifies the potential to expand into heat supply through cogeneration of heat and power, and the potential for additional sources of cost-effective hydrogen with low carbon footprint from cogeneration nuclear plants producing electricity and hydrogen.

Conclusion 8 – market, policy and regulation analysis within this report indicates the importance of developing and consulting on policy frameworks for domestic heat decarbonisation, industrial heat decarbonisation, and the timing and characteristics of the future UK hydrogen supply market. Choices regarding integrated solutions for decarbonising heat and transport are best identified and made locally. But there is a UK Government role in identifying policy options and guidance at a national level for decision making at a local level. The same applies to the decarbonisation of the industrial use of heat. Hydrogen is expected to be a key vector in the achievement of Net Zero with many potential applications with distribution enabled by a national transmission system. Hydrogen is also required to produce ammonia as the decarbonisation fuel of choice for maritime use. Supplying the hydrogen economy will require diverse sources providing high volumes of low-cost hydrogen with a low carbon footprint. Stimulating the market to produce such sources of supply will require a policy framework indicating the timing and characteristics of the future UK hydrogen supply market.

Conclusion 9 – the potential policy approach for nuclear suggested by this new analysis is to initially launch around 10 GWe of additional new Gen III+ reactor capacity and in parallel to support stage gated development programmes for UK deployment of LWSMR and Gen IV. Optimum levels of further nuclear capacity additions would be better informed by 2030. The decision for large Gen III+ reactors is not when to start, but when to stop. An initial optimised programme of around 10 GWe of new Gen III+ capacity beyond HPC is a decision of low or no regret provided construction duration and costs continue to reduce as predicted by the findings of the ETI Nuclear Cost Drivers project. The ETI project indicated the importance of a handful of relatively simple concepts in enabling nuclear cost reduction including commitment to a programme of capacity rather than individual unconnected projects, and the benefits from deployment of multiple units in an uninterrupted construction sequence on the same site. This additional capacity can be expected to potentially commence operations between 2028 and 2035 if suitable projects are committed at the right time. Over the next 5 years, staged gated reviews of LWSMR and Gen IV development programmes would provide a clearer indication of the likelihood of realising the anticipated benefits from these two technologies. This additional understanding, accompanied by progress in the development of other low carbon energy technology programmes, would support further periodic policy reviews and decisions in the period 2025 to 2035 regarding policies for deployment of LWSMR, Gen IV, and the continued deployment of Gen III+ with reducing costs.

Conclusion 10 – change is required if the UK is to get on track for Net Zero by 2050. If nuclear is to fulfil its potential role in decarbonising the energy system, then the policy framework must change and both UK Government and the nuclear sector (represented by the Nuclear Industries Association) have a role to play in leading and enabling such a change. The UK is not currently on a trajectory that will achieve Net Zero by 2050. The UK is not on track to meet the fourth budget (2023 to 2027) and in September 2020 the Committee on Climate Change is expected to publish its recommendations on the level of the Sixth Carbon Budget. If new nuclear is to play a significant role, this report identifies some potential market, policy and regulation issues requiring development, and the importance of some ongoing issues requiring continued management by industry and Government. Overall, more urgency is required to deliver a managed transition to Net Zero. The implication of not being on track to achieve the 2050 net zero target is that the UK is contributing to the cumulative emissions which will result in exceedance of the 2 degrees scenario. From 2007, it will have taken 18 years to deliver HPC. If that rate of delivery for new nuclear is maintained, then there will be less than 8 GWe of new capacity by 2050. For nuclear to play a significant role in the transition to Net Zero, then the overall policy regarding new nuclear may stay the same, but the enabling policy framework must change. Both Government and NIA have a role in this.

Acronyms

ABWR	Advanced Boiling Water Reactor
AGR	Advanced Gas-cooled Reactor
AMR	Advanced Modular Reactor
ANT	Alternative Nuclear technologies (Project)
AP1000	Gen III+ reactor design from Westinghouse
BECCS	Bio-energy with Carbon Capture and Storage
BEIS	(Department of) Business, Energy and Industrial Strategy
BERR	(Department of) Business, Enterprise and Regulatory Reform (predecessor to BEIS)
BOB100	ESME Decarbonisation Scenario that is the Best of Both of TECH100 and SOC100
CAPEX	CAPital EXPenditure
CCC	Committee on Climate Change
CCGT	Complex Cycle gas Turbine
CCS	Carbon Capture and Storage
CEA	Alternative Energies and Atomic Energies Commission (in France)
CHP	Combined heat and Power
Cogen	Cogeneration
CORWM	Committee on Radioactive Waste Management
DACC	Direct Air Capture of CO_2
DCF	Design Capacity Factor
DECC	Department for Energy and Climate Change (predecessor to BEIS)
DH	District Heat (System)
EEDB	Energy Economics Database Programme
EPC	Engineer, procure and Construct
EPR	Reactor design developed by the organisation now known as Framatome
ESBWR	Economically Simplified Boiling Water Reactor
ESC	Energy Systems Catapult
ESME	Energy System Modelling Environment (a whole energy system model)
EUR	European Utilities Requirement for Light-Water Reactors
ETI	Energy Technologies Institute

FID	Final Investment Decision
FOAK	First of a Kind
GDA	Generic Design Assessment
Gen III+	Generation III+ nuclear reactor
Gen IV	Generation IV nuclear reactor
GFR	Gas cooled Fast Reactor
GHG	Green House Gas
GIF	Generation IV International Forum
GWe	Giga-Watt electric
HPC	Hinkley Point C (Project)
HTGR	High Temperature gas Reactor
IAEA	International Atomic Energy Authority
IP	Intellectual Property
IUK WP7	Innovate UK Work Package 7 (of the Energy Technologies Benchmarking Project)
JAEA	Japan Atomic Energy Authority
LAEP	Local Area Energy Plan
LFR	Lead cooled Fast Reactor
LTE	Low Temperature Electrolysis
LWSMR	Light-Water (Nuclear) Small Modular Reactor
MPR	Market, Policy and Regulation
MSR	Molten Salt Reactor
NCD	Nuclear Cost Driver (Project)
NDA	Nuclear Decommissioning Authority
NFNZ	Nuclear for Net Zero
NIA	Nuclear Industries Association
NOAK	Nth of a Kind
NuScale	A reactor vendor promoting a design of light-water small modular reactor
NPS	National Policy Statement
NSD	Nuclear Sector Deal
OCC	Overnight Capital Cost
PPSS	Power Plant Siting Study

PV	(Solar) Photo Voltaic
PWR	Pressurised Water Reactor
RAB	Regulated Asset Base (funding mechanism)
SCWR	Supercritical Water-cooled Reactor
SDE	SMR Deployment Enablers (Project)
SFR	Sodium cooled Fast Reactor
SMR	Steam Methane Reformation
SOC100	ESME Scenario for 100% Decarbonisation Using Speculative Behavioural Changes
SSH	Smart Systems and Heat (programme)
SZB	Sizewell B (Nuclear Power Station)
TECH100	ESME Scenario for 100% Decarbonisation Using Speculative Technologies
UKSMR	Consortium acting as vendor for a new design of LWSMR
VHTR	Very High Temperature Reactor
WACC	Weighted Average Cost of Capital

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