Department of Energy & Climate Change

ATKINS

SMR Techno-Economic Assessment

Project 1: Comprehensive Analysis and Assessment

Techno-Economic Assessment Final Report
Volume 1

For The Department of Energy and Climate Change

21 July 2016

Notice

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This document has 121 pages including the cover.

Document history

Job number: 5141619			**Document ref: 5141619-301-011-01**			
Issue	Purpose description	Lead Authors	Checked	Reviewed	Authorised	Date
01	First formal issue	G Rubio A Tricot	K Scully	A McFarlane J Brooking	R Beake	21/07/16

Client signoff

Client	DECC
Project	SMR Techno-Economic Assessment - Project 1 – SMRs: Comprehensive Analysis and Assessment
Document title	SMR TEA Report: Volume 1
Job no.	5141619
Copy no.	
Document reference	5141619-301-011-01

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Executive Summary

The UK Government has set an ambitious target to reduce the UK's carbon emissions by 80% by 2050. Evidence from the Committee on Climate Change (CCC) suggests that meeting this target will require largely decarbonising the energy sector (including heat and transport) by 2030.

The Department of Energy and Climate Change (DECC) expects new nuclear power to play a key role in supporting decarbonisation and maintaining security of supply, with an initial fleet of large nuclear power stations planned for construction by 2035. Small Modular Reactor (SMR) technology could have a potential role in the UK energy sector in supporting deployment of low carbon generation that is quicker to deploy and easier to finance without Government backing, compared with large nuclear.

A Techno-Economic Assessment (TEA) has been performed on Small Modular Reactor (SMR) technology against a set of pre-defined criteria. SMRs are defined as reactor systems that operate below 300 MWe and are designed to take full advantage of modularisation.

The TEA was open to all reactor technologies for which small modular variants exist or are being developed. The following technologies were represented in the TEA: Integral Pressurised Water Reactors (IPWR); Pressurised Water Reactors (PWR); High Temperature Gas Reactors (HTGR); Molten Salt Reactors (MSR); Sodium-Cooled Fast Reactors (SFR) and Lead-Cooled Fast Reactors (LFRs). Countries that have presented at least one design to the TEA include USA, China, South Korea, UK and South Africa and a partnership between countries.

Participation by SMR vendors in the TEA was voluntary; the completeness of the data provided depended on the vendor's ability and willingness to provide extensive data in a relatively short period. The responses therefore represent only a sample of the potential designs that are under development globally. The TEA study was of necessity limited in scope; the main body of assessment work was confined to the data provided by the vendors, a 'self-selected' sample. Where necessary, clarifications were sought from the vendors but no detailed due diligence was performed. There are some countries that are very actively involved in the development of SMR technology that have not participated in the TEA, notably Russia, Japan and Canada. Therefore in order to provide a broader context, reference has been made to internationally recognised studies on Gen IV technologies being used by SMR vendors.

The intent of the study was to inform UK Government as to whether SMRs have the potential to provide the economic, financial, technical and commercial opportunities that have been claimed, whilst identifying the risks to achieving these. In particular, to ascertain whether SMR technology has the potential to contribute to the generation of low carbon electricity at affordable prices, but also what the impact on the economy would be if the UK were to pursue a strategy to become a manufacturer and exporter of SMR technology. The findings presented in this TEA are judged to be sufficiently representative of the status of development of SMR technology in terms of design and certification. The conclusions presented are therefore considered to be valid for the purpose of helping to inform UK policy decisions.

It is apparent from the key findings presented below that SMR design development and licensing is proceeding in a number of countries. It is likely that First Of A Kind (FOAK) SMRs will be deployed in some of these countries in the next decade. Despite this international momentum there remains, as this study has shown in the UK context, a great deal of uncertainty with regards to the economics of both SMRs and the counterfactual[1] technologies.

The following factors would contribute to a technically feasible and economically viable SMR programme in the UK:

- SMR achieving a low construction cost in line with the most cost effective vendor estimates.
- SMR widening the pool of investors willing to finance new nuclear and achieving a lower cost of capital than large nuclear by reducing perceived technology risk for nuclear.

[1] A scenario reflecting what may be expected to happen in absence of Government intervention to support the deployment of SMR technology within the UK.

- The UK Government taking a 'fleet deployment' approach to SMR deployment, planning for modularisation early on and providing investor certainty around the volume of UK SMR deployment of a particular design. Other studies performed in the context of this TEA highlighted this as important for reducing technology costs through learning.
- Advancing the international harmonisation of SMR licensing to enable an efficient export market.
- SMR manufacturing facilities situated in the UK, where a standardised SMR design is developed and an order book develops to maximise benefits of cost reduction and wider economic opportunities.

If Government wishes the UK to have the option to participate in this emerging market and deploy a UK developed SMR for domestic and export markets, it may wish to take action to support this objective and stimulate investment in the technology. Without intervention by Government, SMRs would be unlikely to develop in the UK as they are unlikely to achieve cost parity with large nuclear until 5-8 GWe of deployment of a particular design.

Key Findings:

Technology readiness

The key findings from this study with respect to the above are:

- IPWR technology has the potential to contribute to the low carbon generation of electricity in the UK around 2030. This technology has a high level of technical readiness. Furthermore, some designs have been certified by national regulatory bodies in their country of origin, or are about to start the process.
- All other technologies require a significant investment in R&D before they will be commercially deployable. Some, though, may offer technical advantages and greater cost competitiveness compared with IPWRs, possibly through the development of intrinsically safe designs with less complex systems. With well-funded R&D programmes, HTGR and SFR could be ready for commercial deployment in the period between 2035 and 2050 (noting that different vendors are at various stages of development). Other reactor technologies are less likely to be deployed in this timeframe, given the amount of outstanding technical challenges.
- The IPWR technologies, being further developed, offer less opportunity for UK capability development and generation of IP. The non-IPWR technologies, being less developed, have the potential to offer an improved opportunity for UK innovation and the acquisition of IP rights. This could include nuclear technology design in addition to manufacturing and modularisation.

Integration into the existing UK infrastructure

- The deployment of IPWR technology would require minimal to no changes to the existing nuclear infrastructure; this is not the case with other technologies where fuel manufacturing facilities and facilities for the permanent disposal of waste will need to be modified or built and licensed.
- SMRs present many benefits with respect to connecting to the UK's electricity transmission and distribution networks.
- SMRs have the potential to offer greater operational flexibility than large nuclear and siting opportunities closer to points of demand, supporting more efficient grid operation.
- SMRs have the potential to deliver heat for district heating due to their ability to be located closer to points of heat demand.

SMRs in the UK regulatory system

- Timescales and costs for licensing are unlikely to reduce for SMRs compared to large nuclear. Timescales could be significantly longer for technologies that are highly innovative and in particular for non-IPWR designs.
- The maturity of IPWR technology and current alignment with UK regulatory expectations would allow a Generic Design Assessment (GDA) to commence, with the required level of design and safety case substantiation, within the next five years.
- Although UK regulations are generic, all technologies will present situations that have never been regulated before in the context of large nuclear. All technologies will therefore face challenges during GDA.

- International harmonisation of the licensing process is a challenge for the nuclear industry. For SMRs this challenge has particular significance due to the reliance of the business case on replication of multiple identical units in international markets.

Cost of generation

- The estimated Levelised Cost of Electricity (LCOE) for IPWRs was compared against Nth of a Kind (NOAK) costs for counterfactual technologies (large nuclear, offshore wind and combined cycle gas turbine (CCGT)) deploying in 2031. For designs other than IPWR, cost estimates are currently not sufficiently developed to make valid comparisons. Given that SMRs are a new technology, cost estimates overall are uncertain.
- First Of A Kind (FOAK) LCOE for a generic (IPWR) SMR is expected to be between £86/MWh and £124/MWh, with a central estimate of £101/MWh (excluding GDA costs). This is based on cost estimates from the two most economically viable IPWR vendors, and assumes a 54% increase in cost due to “optimism bias” – i.e. the tendency of project appraisers to be overly optimistic. It also assumes that SMR has an equivalent cost of capital to large nuclear (estimated by DECC to be 8.9%). However it is recognised that SMR is a new technology and there is a substantial risk that these costs will be higher than this if costs accumulate during development or if financing costs are initially higher than they are for large nuclear.
- The estimated SMR FOAK LCOE (excluding GDA costs) is 30% higher than DECC’s estimate for large nuclear, 7% lower than offshore wind and between 16% lower and 3% higher than CCGT (depending on the carbon price). This compares technologies on the basis of power generation costs. SMRs could also be used for generating district heating, which could create an additional revenue stream positively impacting the economics.
- The higher initial cost of SMR relative to large nuclear reflects the premium on FOAK costs and the reduced economies of scale for SMRs. However, SMRs have the potential to see technology costs reduce at a faster rate than large nuclear costs for two reasons: Firstly, SMR deployment involves a higher pace and volume of reactor production. Secondly, stronger learning could be achieved for SMRs with their greater proportion of factory build (45% - 60%) in comparison to large reactors (30-35%), as manufacturing facilities provide a more effective learning environment. Projects 5-7 found that large nuclear has historically achieved learning rates of 1-3%, whereas SMRs could achieve in the central case a learning rate of between 6.5% and 8% (depending on the pace of deployment), and 5-10% in the low and high learning scenarios. The central learning rates estimated for SMRs are more in line with the observed learning rates of industries such as CCGT turbines (10%-22%), wind turbine production (5%-19%), shipbuilding (15%-20%) and aircraft manufacturing (18-20%) where a high proportion of construction is factory-based.
- Given an expected SMR learning rate of between 6.5% and 8%, SMRs could become cost competitive against large nuclear after 5-8 GWe of global deployment of a single design. The degree of SMR cost reduction is sensitive to a number of assumptions, including the rate of UK deployment, the global market for SMRs and the market share that the UK design could achieve.
- This assessment assumes that supply chain constraints initially limit UK SMR deployment to 400 MWe per annum, rising to 800 MWe per annum after ten years, and that the UK could export 500 MWe of the technology each year. At this pace of deployment, SMRs could become competitive against large nuclear within a decade of the first plant commissioning, after 3.5 GWe of UK deployment and a further 4.5GWe of deployment abroad. This is provided that the UK commits to fleet deployment and that there is access to a similar export market with parallel price tolerance.
- International deployment of SMRs may be enhanced through international harmonisation of the licensing process for SMR technology. The potential for the UK to export SMRs and achieve cost reduction will be impacted by the likelihood of the UK exporting an identical design to that deployed in the UK.

Welfare impacts

- A Net Present Value (NPV) has been calculated for SMR deployment to provide an indication of the overall impact of SMR deployment on UK energy costs – with a positive NPV indicating that SMRs would reduce generation costs relative to alternative technologies and a negative NPV indicating that SMRs would increase generation costs. The assessment takes into account the high upfront costs of SMR deployment as well as the ability of SMR to achieve cost reductions over time through learning. The NPV does not consider the wider economic impacts created by an SMR programme (including the impact of SMR on employment, GVA and tax revenues), which are assessed separately.

- The NPV of generation for an initial 2GWe UK SMR programme is expected to be negative relative to large nuclear (-£4.8bn) and CCGT (-£8.4bn), and positive against offshore wind (+£0.4bn) in our central scenario.
- There is a significant degree of uncertainty in estimates of welfare impacts. For instance, the NPV of SMRs relative to large nuclear varies between +£2bn and -£14.2bn with the range driven by three factors:
    1. Uncertainty around FOAK capital costs for SMR, with a range of -19% and +28% to the central estimate;
    2. The learning rate at which capital costs reduce with greater deployment, with a range of 5% and 10%; and
    3. The export market for UK SMRs, with a range of 300 MWe and 750 MWe assumed to be deployed per year. The larger the global market for a particular design, the greater the potential for cost reduction through learning.
- Deploying a larger programme of SMR than 2GWe can improve the overall NPV of the programme, as SMR costs become more competitive with the counterfactual technologies over time. Based on the central estimate of SMR costs, the NPV relative to large nuclear improves to -£3.5bn for an SMR programme out to 2050, including 12GWe of UK deployment and 10GWe of exports. Forecasting costs this far in advance is however inherently uncertain and costs will be clearer following advanced design and initial deployment of an SMR design.
- The SMR NPV is also sensitive to the cost of capital, which is based on the risk investors take. SMR could make it easier to finance new nuclear; both by reducing construction risk and by reducing the amount of finance needed for each project. It is expected that the cost of capital could reduce once the FOAK SMR plant is operational. If SMR were able in the long-run to achieve a 1% reduction in the cost of capital (equivalent to an 11% reduction in financing costs) then an SMR would see an NPV of +£3.0bn against large nuclear after 8GWe of UK deployment. Conversely if SMR initially incurs a higher cost of capital than large nuclear due to it being seen as a less mature technology, then the NPV would fall to -£6.2bn for deployment out to 2050. Cost of capital will, in part, be a function of the policy environment and decisions made by Government, which may influence the eventual costs.
- SMR may also present other qualitative impacts not factored into the NPV. These include improved air quality and reduced dependence on fossil fuel imports relative to CCGT, as well as a more dispatchable form of low carbon generation relative to offshore wind, thereby enabling more efficient system-wide performance. There is also uncertainty around the feasibility and cost of the counterfactual technologies, although this has not been modelled within this assessment.

Wider economic impacts

- SMRs have the potential to create broader economic advantages to the UK economy. If SMRs are manufactured in factories within the UK, a 2 GWe UK deployment programme could create additional benefits greater than an equivalent deployment programme for large nuclear or counterfactual technologies.
- The UK is estimated to provide up to 70% of the supply chain requirements for SMRs deployed in the UK. This is based on the assumption that manufacturing facilities are based in the UK and that the UK makes a number of interventions to upgrade its nuclear supply chain, including the implementation of the Nuclear Supply Chain Action Plan.
- Between 2017 and 2040, with UK manufacturing 70% of supply chain components, the estimated total gross impacts consists of £20 billion of undiscounted Gross Value Added (GVA), with average employment of 9,700 jobs and tax revenues of £7 billion to the Exchequer. Assuming a lower 60% supply chain participation, undiscounted GVA for the same period is estimated at £18 billion, average annual employment of 8,200 jobs and £6 billion of tax revenues.
- Between 2017 and 2040, the estimated net impacts from the SMR programme displacing large nuclear is an estimated £1.7 billion of undiscounted GVA (equivalent to increased GDP of £70m per year), £0.6 billion in taxes and average employment of 800 jobs per annum.

- The wider economic benefit is impacted by four key assumptions:
    1. The differences in the scale of expenditure between SMRs and the counterfactual technologies, with SMRs incurring a greater degree of spend over the modelled period due to the high costs of the initial plants;
    2. The extent of local firms' involvement in the SMR supply chain, particularly if the UK is able to attract manufacturing facilities to be situated in the UK;
    3. The export potential of SMRs if the global market develops for SMRs and if the UK can achieve a 10% market share; and
    4. The existence of spare capacity in the UK economy, such that initial expenditure on the SMR programme does not necessarily displace other activity.

- The assessment has not considered the potential indirect impact on economic activity from initial SMR deployment affecting energy bills.

Summary of economic assessment

The findings of the assessment of a 2GWe programme of UK SMR deployment (including 2.5 GWe of SMR exports) commissioning between 2031 and 2035 are summarised in the table below. This shows discounted NPV, Net Value Added (NVA) and net job increases over the life of the SMR plants built (i.e. out to 2094). Ranges around NPV reflect uncertainty around capital costs and learning rates. Net Value Added reflects the incremental economic impact of the SMR industry relative to a counterfactual such as large nuclear.

Counterfactual:	Direct Welfare Impact of 2 GWe SMR	Wider Economic Impact of 2 GWe SMR	Qualitative Impacts of SMR:
Large Nuclear	-£4.8bn NPV (-£14.2bn to +£2.0bn range)	£1.2 billion NVA; 300 jobs per year	• Potentially easier to finance SMR • Greater potential for long run cost reduction from SMR
Offshore Wind	+£0.4bn NPV (-£9.0bn to +£7.2bn range)	£1.0 billion NVA; 200 jobs per year	• SMR more flexible / dispatchable • Offshore wind subject to greater competitive downward pressure on costs
CCGT	-£8.4bn NPV (-£17.8bn to -£1.6bn range)	£1.3 billion NVA; 300 jobs per year	• SMR reduces fossil fuel imports • SMR health benefits in cleaner air • CCGT potentially inconsistent with decarbonisation targets

The SMR programme is estimated to have an NPV of +£0.4bn to -£8.4 bn. This should be considered in the context of the macroeconomic benefits appraised for the SMR programme which suggests that it could potentially generate NVA of up to £1.3 billion (central scenario) for the UK economy.

Further sensitivities considered the impact of programme of SMR deployment out to 2050, including 12 GWe of SMR plant commissioning in the UK and 10 GWe of exports, are summarised in the table below. These show discounted net impacts of SMRs relative to a counterfactual of large nuclear for the life of the plants deployed. The NPV range reflects sensitivities around the cost of capital.

Counterfactual:	Direct Welfare Impact of 12 GWe SMR	Wider Economic Impact of 12 GWe SMR
Large Nuclear	-£3.5bn NPV (-£6.2bn to +£3.0bn range)	£1.6 billion NVA; 500 jobs per year

An SMR deployment programme might deliver a net benefit to society under a number of circumstances:

- If initial build costs for SMRs are low and do not incur optimism bias (staying in line with vendor estimates).
- If SMRs were able to achieve a high learning rate and is deployed over a sufficiently large volume and if the counterfactual technology does not also benefit from cost reduction through learning.

- If SMRs were able to achieve material reductions to the cost of capital relative to large nuclear.
- If deployment of large nuclear and CCGT were constrained such that SMRs displace more costly offshore wind. This scenario might occur if accelerated decarbonisation and expansion of the electricity sector leads to increased demand for low carbon generation, particularly if financeability challenges around large nuclear deployment persist.
- With greater UK supply chain deployment. There are a number of factors that are potentially critical to a UK SMR supply chain developing, including progress in harmonising licensing arrangements, the UK Government taking a 'fleet deployment' approach to SMR deployment, planning for modularisation early on and providing investor certainty around the volume of UK SMR deployment of a particular design.

Potential SMR deployment strategies for the UK

If Government wishes to open the option for deployment of an UK SMR, there are a number of choices available. The TEA has identified a number of issues to address: technology choice, time to deployment, technology risk, estimated cost of electricity, and capacity in the UK nuclear industry. The key strategic choices are:

- If Government's strategic priority is to support nearest term deployment of SMRs thus achieving the earliest generation of electricity, it could support an IPWR technology. To enable SMR costs to converge with the cost of large nuclear, UK owners would likely need to commit to deploying a minimum volume of a single design that is also licensable abroad with minimal or no changes through the international harmonisation of licensing requirements for SMRs. To attract investment and to overcome UK specific deployment challenges (e.g. the costs of GDA) Government could consider supporting UK specific technology development and licensing, including full participation in international licensing harmonisation. It should however be recognised that there is uncertainty over whether and when SMR IPWR would become cost competitive (per GWe) with large nuclear or whether it would employ a greater UK-based supply chain. This uncertainty will reduce with time, and costs will need to be continually monitored and reconsidered as the technology progresses. The principal market failures that SMR could seek to address are equivalent to those which large nuclear addresses, including the negative externality of carbon (which is not fully addressed by carbon pricing policies). The much lower capital cost per SMR unit could additionally address the market's failure to finance for large nuclear.

- If Government's strategic priority is to stimulate the development of UK's nuclear engineering supply chain and target a potential cost breakthrough in nuclear generation, then there is greater potential in less advanced reactors. Through funding R&D for a more innovative SMR design, the UK will develop a next generation of nuclear scientists and engineers and could re-gain a role in civil nuclear design. R&D could also allow for greater opportunities for UK directed innovation, enabling Government to only choose to support commissioning of plants once a design has demonstrated clear cost savings against large nuclear. However, this would likely delay potential deployment of SMR until beyond the early 2030s, with time to deployment reflecting the choice of non-IPWR technology selected. Government would also be taking on risk in selecting a particular design, given the uncertainties that exist today around the viability of the non-IPWR technologies, including cost, technology risk, licensability, and time to deployment. This risk is also the case for IPWR designs, although there is greater certainty around the viability of particular designs as they are closer to deployment.

These two strategic options are not necessarily mutually exclusive if resources are made available and private sector investment can be stimulated. In both cases near term action and Government intervention would be required if an UK SMR option is to be available for deployment in the 2030s when substantial deployment of low carbon generation is anticipated.

Glossary

AACE	Association for the Advancement of Cost Engineering
AGR	Advanced Gas cooled Reactor
ALARP	As Low As Reasonably Practicable
ANT	Alternative Nuclear Technologies
BAT	Best Available Techniques
BoP	Balance of Plant
C&I	Control and Instrumentation
CAPEX	Capital Expenditure
CCC	Committee on Climate Change
CCGT	Combined Cycle Gas Turbine
CfD	Contracts for Difference
CHP	Combined Heat and Power
CITB	Construction Industry Training Board
CORDEL	Co-operation in Reactor Design & Licensing
CRDM	Control Rod Drive Mechanism
CTE	Critical Technology Element
CVCS	Chemical Volume Control System
DAC	Design Assessment Confirmation
DECC	Department of Energy and Climate Change
DEVEX	Development Expenditure
DH	District Heating
DNO	Distribution Network Operator
DoE	Department of Energy (USA)
EA	Environment Agency
EPRI	Electric Power Research Institute
EPZ	Emergency Planning Zone
ESME	Energy System Modelling Environment
ETI	Energy Technologies Institute

EUR	European Utility Requirements
EW	Economic Workstream
EY	Ernst & Young
F4N	Fit For Nuclear
FDP	Funded Decommissioning Programme
FOAK	First Of A Kind
GDA	Generic Design Assessment
GDF	Geological Disposal Facility
GDP	Gross Domestic Product
GFR	Gas-Cooled Fast Reactor
GIF	Generation IV International Forum
GVA	Gross Value Added
GWe	Gigawatt electric
HLW	High Level Waste
HPC	Hinkley Point C (nuclear power station)
HTGR	High Temperature Gas Cooled Reactor
HVM	High Value Manufacturing
IAEA	International Atomic Energy Agency
IEA	International Energy Agency
ILW	Intermediate Level Waste
INL	Idaho National Laboratory
IP	Intellectual Property
IPWR	Integrated Pressurised Water Reactor
LCOE	Levelised Cost of Electricity
LFR	Lead Cooled Fast Reactor
LLW	Low Level Waste
LLWR	Low Level Waste Repository
LoC	Letter of Compliance
LWR	Light Water Reactor

MSR	Molten Salt Reactor
NAMRC	Nuclear Advanced Manufacturing Research Centre
NDA	Nuclear Decommissioning Authority
NESA	Nuclear Energy Skills Alliance
NGET	National Grid Electricity Transmission
NIA	Nuclear Industry Association
NIRAB	Nuclear Innovation and Research Advisory Board
NNL	National Nuclear Laboratory
NNPP	Naval Nuclear Propulsion Programme
NOAK	Nth Of A Kind
NPS	National Policy Statement
NPV	Net Present Value
NRW	Natural Resources Wales
NSAN	National Skills Academy for Nuclear
NSAN-M	National Skills Academy for Nuclear Manufacturing
NSSG	Nuclear Skills Strategy Group
NVA	Net Value Added
OCC	Overnight Capital Cost
O&M	Operations and Maintenance
ONR	Office for Nuclear Regulation
ONS	Office for National Statistics
OPEX	Operating Expenditure
PCP	Primary Coolant Pump
PSA	Probabilistic Safety Assessment
PV	Present Value
PWR	Pressurised Water Reactor
RAG	Red-Amber-Green
R&D	Research and Development
REPs	Radioactive Substances Regulations Environmental Principles

ROW	Rest Of World
RPV	Reactor Pressure Vessel
RWM	Radioactive Waste Management Ltd
SAP	Safety Assessment Principle
SCAP	Supply Chain Action Plan
SCWR	Super-Critical Water Reactor
SFAIRP	So Far As Is Reasonably Practicable
SFL	Springfields Fuels Ltd
SFR	Sodium-cooled Fast Reactor
SG	Steam Generator
SoDA	Statement of Design Acceptability
SMR	Small Modular Reactor
SSA	Strategic Siting Assessment
SSCs	Structures Systems and Components
SZB	Sizewell B
TEA	Techno-Economic Assessment
TRISO	Tristructural Isotropic
TRL	Technology Readiness Level
TW	Technical Workstream
UUK	URENCO UK
VfM	Value for Money
WACC	Weighted Average Cost of Capital
WNA	World Nuclear Association

1. Introduction

The UK Government has set an ambitious target to reduce the UK's carbon emissions by 80% by 2050. Evidence from the Committee on Climate Change (CCC) suggests that meeting this target will require largely decarbonising the energy sector (including heat and transport) by 2030. The Department of Energy and Climate Change (DECC) expects new nuclear power to play a key role in supporting decarbonisation and maintaining security of supply, with an initial fleet of large nuclear power stations planned for construction by 2035. Small Modular Reactor (SMR)[2] technology could have a potential role in the UK energy sector in supporting deployment of low carbon generation that is quicker to deploy and easier to finance without Government backing, compared with large nuclear.

DECC has commissioned the SMR Techno-Economic Assessment (TEA) programme to understand the potential costs and benefits that SMRs could bring to the UK. The findings of the programme are expected to help inform a future Government policy decision on whether SMRs have a role to play in the UK energy market.

A previous feasibility study conducted by National Nuclear Laboratory (NNL) (Ref. 1) identified that SMRs present an opportunity for the UK to regain technology leadership. The study recommended an additional, more detailed analysis against UK requirements be completed. Following the feasibility study, DECC commissioned the production of a specification (Ref. 2) to define a credible and neutral process that would highlight the potential costs and benefits that could be realised by the deployment of an SMR fleet in the UK. The specification defines a number of technical and economic assessment criteria and the expected supporting evidence needed to perform the SMR TEA.

There are a total of seven projects that make up the TEA Programme of work:

- Project 1 – SMRs: Comprehensive Analysis and Assessment
- Project 2 – SMRs: Systems Optimisation Modelling
- Project 3 – SMRs: Emerging Technologies
- Project 4 – SMRs: UK Regulatory Regime
- Projects 5-7: Can Building Nuclear Power Become More Cost Effective?
  - Project 5 – Advanced Manufacturing
  - Project 6 – Advanced Assembly, Modularisation and Construction
  - Project 7 – Control, Operation and Electric Systems

To perform the TEA, these projects have generated appropriate evidence and have assessed the potential of SMRs against the different assessment criteria (Ref. 2).

Atkins has been commissioned by DECC to carry out the administration of data gathering and to undertake a full and detailed analysis, as part of Project 1 – SMRs: Comprehensive Analysis and Assessment. Atkins has led on the technical assessment (Section 4), while EY has been appointed as a subcontractor to conduct the economic assessment (Section 5) and delivery options assessment (Section 6).

The findings of the Project 1 assessment are presented in this report. It is noted that Volume 2 of the Project 1 assessment report will not be published due to the commercially sensitive content.

This report also provides a summary of some of the key findings from Projects 2 to 7 and provides reference to the relevant reports (Section 7).

[2] For the purposes of the TEA, the term SMR refers to nuclear reactors up to 300 MWe that are designed with modular technology, pursuing economics of series production, factory fabrication and short construction times.

2. Purpose

Within the context of the SMR TEA Programme, Project 1 delivers an evidence base to help inform UK Government's policy decisions on whether and how the UK could support the development and deployment of SMRs. This assessment is based on SMR vendor data collected and subsequently analysed to understand the technical and economic opportunities, barriers and risks.

The objectives of the Comprehensive Analysis and Assessment include:

- Collation of a vendor data set regarding SMRs in the global marketplace;
- Highlighting the potential costs and benefits of an SMR programme;
- Completion of a design-neutral assessment of SMRs against the specified criteria (Ref. 2); and
- Analysis of data against delivery options to determine the potential for Government support of SMR development in the UK.

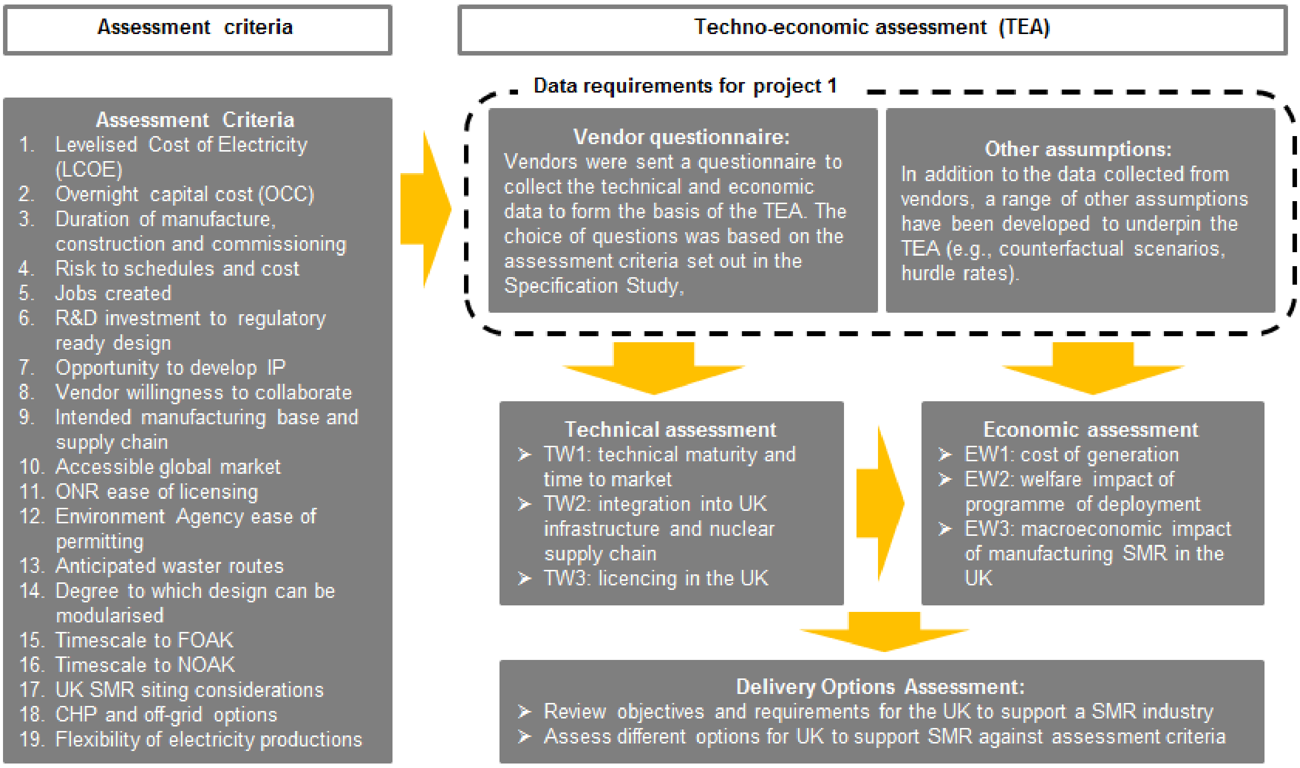
This report provides:

- An outline of the TEA methodology applied, including the vendor engagement approach.
- A summary of data analysis based on the evidence collated from vendors. Note this report will not present any commercially confidential data, such as the raw data responses submitted by each vendor. Any supporting data that is considered commercially confidential is available in Volume 2 of this report (Ref. 3).
- A summary of the key technical findings (technology readiness, infrastructure & licensing) and economic findings (cost of generation, welfare impact & macroeconomic impact).
- An assessment of delivery options in order to help inform a Government policy decision. Note that this is an objective assessment of the opportunities and barriers for each delivery option and does not include a final recommendation on the preferred delivery approach.
- A summary of the key findings from Projects 2 to 7 of the SMR TEA.

3. Developing the Techno-Economic Assessment

The Project 1 TEA is a single, integrated assessment of the technical and economic opportunities of deploying SMRs in the UK. Analysis results have been shared between technical and economic workstreams to provide integrated Project 1 conclusions. Figure 3-1 below presents a high-level overview of how Project 1 has been delivered starting from the assessment criteria provided by DECC (Ref. 2).

Figure 3-1 Overview of Project 1 delivery



To manage the assessment, work has been structured into three Technical Workstreams (TWs) and three Economic Workstreams (EWs). The strategy for delivering the TEA is provided in detail within the TEA Methodology (Ref. 4).

3.1. Project Participants

In order to ensure the TEA represented the views of a wide range of stakeholders, key participants were identified and consulted during the assessment. The stakeholders consulted included:

- SMR vendors;
- Key representatives from academia and industry;
- UK regulatory bodies.

3.1.1. SMR Vendor Participants

The participation in the TEA of vendors was voluntary, with DECC issuing an open invitation to participate in the study. A total of 17 SMR vendors responded indicating their desire to participate. To gather the required information from vendors, an assessment pack was prepared. To ensure consistency, all vendors opting to take part in the TEA were issued the same pack, and each vendor was provided their own secure folder allowing them to upload responses confidentially.

Out of the 17 vendors expressing interest, 14 uploaded responses. Countries that have presented at least one design to the TEA include USA, China, UK, South Korea and South Africa and a partnership between the USA and the EU. Certain countries which are active in the area of SMRs have not submitted any technology to this TEA, notably Canada, Russia and Japan.

Following the submission deadline, there was a period during which clarifications were sought from vendors where needed.

Following discussions within the TEA Programme, it was agreed that submissions with the highest level of technical and economic detail would be assessed within the TEA Project 1. These included some of the vendors that submitted IPWR, HTGR and MSR technologies. Other submissions were considered as emerging technologies and assessed in Project 3.

For technical descriptions of each reactor design, refer to Appendix A of Volume 2 (Ref. 3).

3.1.2. Industry and Academia Consultations

In addition to the engagement with SMR vendors, consideration was given to other stakeholders and interested parties relevant to SMR development. A number of closely engaged stakeholder groups were identified, including industry, academia and Government. The interest of wider stakeholders including NGOs, the public, local councils etc. was recognised but such wide consultation was beyond the scope of this study at this stage.

During the study period informal contact was maintained with many of the stakeholders. It was judged that closer engagement with a select number of the UK's key industry and academia figures would add value to the TEA by aligning the study with key stakeholder views. Three individuals were identified as being lead representatives of the academia and industry stakeholder groups.

In order to inform the TEA and seek alignment with key stakeholder interest, briefings were held with the following individuals:

- Dame Sue Ion OBE, Chair of the Nuclear Innovation and Research Advisory Board (NIRAB);
- Keith Parker, CEO, Nuclear Industry Association (NIA);
- Professor John Loughhead, Chief Scientific Advisor, DECC.

The stakeholders were all fully aware of Government interest in the possible role of SMRs in a low carbon electricity market, as well as the uncertainty around the economic and technical viability of the various international designs. It was understood that these are complex areas with many interconnecting factors, which can only be judged at a future stage by Government. The study team was encouraged to concentrate on a fact based approach in order to present data which would assist Government in determining policy.

The balance of interest between early deployment to the grid and maximum UK engineering and supply input was discussed, as was the desirability of capturing intellectual property (IP) for the UK. The value of developing this IP was recognised. The team was cautioned by a senior industry representative not to over-estimate the value of IP to the detriment of other relevant factors. It was also noted that there can be substantial value to be obtained through IP in the areas of manufacture and assembly, meaning that even the more mature designs (in which design IP opportunity is limited) could offer opportunities for a UK contribution in manufacturing. Desire to own design IP should be balanced against the aim of delivering a cost effective reactor technology, manufacturing jobs and opportunity for export with a large and enduring UK contribution. IP is considered in Section 4.2.5 of this report.

It was also felt there was a clear appetite for the UK to reinvigorate its leadership in nuclear technology development. There was support from industry for this study and for SMR development in the UK, but also some concerns around the subject of district heating. Hence, there was a concern from industry that this assessment should not detract from the understanding of the potential contribution from SMRs without district heating.

The message from industry was also that any policy option development should retain a diverse energy mix, and should continue to recognise the very different value that large nuclear delivers in terms of well-understood, large-scale baseload power, in addition to the flexibility and possibility of financing that may be offered by SMRs.

3.1.3. Regulatory Consultations

To inform the regulatory readiness assessment within the TEA (Section 4.4), meetings with the Office for Nuclear Regulation (ONR) and the Environment Agency (EA) were held. The purpose of these meetings was to discuss key issues that could potentially cause regulatory challenges for the licensing of SMRs within the UK and to consider how the licensing processes could be applied to SMRs.

The findings from these sessions are further detailed within Section 4.4.2.

4. Technical Assessment

The technical assessment is structured by technical workstreams, as identified in Section 3. The overall objectives are to understand the maturity of different SMR technologies and identify the potential challenges and opportunities presented by existing UK infrastructure and the UK regulatory regime. The main findings are summarised in Section 4.1 below, with the supporting information presented in Sections 4.2 to 4.4.

4.1. Summary of Technical Workstreams

Assessment of Technical Maturity

- From the technology maturity assessments, two clear groups have emerged: Integrated Pressurised Water Reactors (IPWRs) and a group of various designs that are not based on light water reactor technology. For ease of reference, this assessment will simply refer to this second group 'non-IPWRs' (see Section 4.2.2 for a description of technology types).

- Several IPWR designs have started, or are about to start, the process of being certified in their own country, although unresolved technical challenges still exist. Some IPWR vendors have well-advanced plans for construction projects.

- From the information submitted to the TEA, IPWRs are the only technology that have design maturity levels that would allow entering a Generic Design Assessment (GDA) within the next five years given that GDA applicants must provide a sufficient level of safety and security documentation to commence the process. This would make IPWRs the only technology realistically deployable around 2030 (see Section 4.2.4).

- Non-IPWR technologies require a significant amount of investment in Research and Development (R&D), which introduces uncertainty about commercial deployment dates. The level of R&D does vary between the actual technology types (see Section 4.2.4).

- IPWR designs although well advanced do present opportunities for the development of IP in the areas of manufacturing and modularisation (see Section 4.2.5).

- Non-IPWR technologies have the potential to offer an improved opportunity for innovation and the acquisition of IP rights. This could include nuclear technology design in addition to manufacturing and modularisation (see Section 4.2.5).

Integration into the Existing UK Nuclear Infrastructure

- Large nuclear power stations are two to four times more space efficient than SMR power stations (except possibly Molten Salt Reactor (MSR) plants) when comparing the ratio of permanent site area to electrical power output (see Section 4.3.1.2).

- SMRs present many benefits with respect to connecting to the UK's electricity transmission and distribution networks. The challenges in UK Grid Code compliance faced by new large nuclear power stations are not expected to apply to the same extent for SMRs (see Section 4.3.2.2).

- For IPWRs, the existing UK fuel production infrastructure could support SMR fuel production with minimal adaptation. This presents an opportunity to maintain continued operation of the UK nuclear fuel supply chain by sustaining the demand for fuel which would otherwise diminish as existing stations are permanently closed down. It is noted that SMRs do have reduced fuel economies (i.e. more tonnes of enriched uranium required per unit electrical power) compared to large nuclear (see Section 4.3.3.2).

- Significant fuel infrastructure upgrades and / or implementation of new facilities would be required to support non-IPWR technologies, especially in the area of enriched fuel pellet manufacturing. This might not present a barrier to deployment for High Temperature Gas-cooled Reactors (HTGRs), with overseas fuel suppliers identified by vendors (see Section 4.3.3.2).

- IPWRs are well aligned with the UK spent fuel and waste management strategy. Significant and complex challenges would be faced by non-IPWR technologies to meet UK requirements for waste management and disposal. However, it is expected that there are fewer challenges for HTGRs (see Section 4.3.4.1).

- Approximately 55% of the overnight capital cost of an SMR power station can realistically be supported by the UK supply chain at present. However, this could increase to around 70% with UK Government intervention (see Section 4.3.6).

- With few exceptions, Combined Heat and Power (CHP) applications have not been considered by vendors within the reference plant designs or in the safety case (see Section 4.3.5).

SMRs in the UK Regulatory System

- The UK Safety Assessment Principles (SAPs) (Ref. 5) and Radioactive Substances Regulations – Environmental Principles (REPs) (Ref. 6) are generic and allow for an evaluation of any technology, once the designs have been sufficiently developed and the safety and environmental claims have been properly substantiated (see Section 4.4.1).

- The maturity of IPWR technology and current alignment with UK regulatory expectations would allow a GDA to commence, with the required level of design and safety case substantiation, within the next five years (see Section 4.4.1).

- Although UK regulations are generic, all SMR technologies will present situations that have never been regulated before in the context of large nuclear. All SMR technologies will therefore face challenges during GDA (see Section 4.4.2.12).

- ONR relies on the availability of operating experience, including experience of related reactor designs, systems and components, during the GDA. The lack of operating experience will require extra scrutiny of codes and methods and more stringent monitoring and inspection arrangements for First Of A Kind (FOAK) plants (see Section 4.4.2.21).

- Timescales and costs for all SMR technologies to complete GDA are unlikely to be less than for large nuclear. For more innovative SMR technologies, timescales could be longer and costs could be higher than for SMR IPWRs (see Section 4.4.2.1).

- The final configuration of the plant has to be considered at the beginning of a site licence application. This might have implications for the staged construction of modules (see Section 4.4.2.3).

- International harmonisation of the licensing process for SMR technology presents a significant challenge that would need to be overcome in order to enhance overseas deployment (see Section 4.4.3).

4.2. Assessment of Technical Maturity

The objectives with respect to technical maturity were identified in the SMR TEA Methodology (Ref. 4), although some of these objectives were modified once vendor data was received and reviewed. The finalised objectives are summarised below:

- Perform a critical review of all individual vendor Technology Readiness Level (TRL) self-assessments and supporting evidence.
- Identify the development requirements for SMR technologies to reach TRL 9, informed by vendor submissions.
- Identify key technical challenges and risks to the schedule and cost of SMR deployment.

- Assign vendors a risk category to inform the level of 'optimism bias' applied to the cost data during the economic assessment.
- Provide guidance on the categorisation between those considered current SMR technologies and those which are considered emerging SMR technologies.

The detailed methodology and results from the TRL assessment are included in Appendices B to D in Vol. 2 (Ref. 3). An overview of the method and the key findings are presented in the sub-sections below.

4.2.1. Summary of TRL Methodology

A well-defined and widely adopted approach utilised across the Defence and Nuclear industries for measuring the maturity of individual technologies is the TRL scale. This readiness scale comprises 9 levels, commencing with paper based studies of the design concept (TRL 1) and finishing with a proven technology (TRL 9), implemented in its intended environment, and operating over the full range of design conditions. For further information regarding the development and common approach to Technology Readiness Assessments refer to the Department of Energy (DoE) Technology Readiness Assessment (Ref. 7).

For the purposes of this TEA, the technology maturity assessment is based on the DoE approach with some refinements, as discussed below. The input requested from the SMR vendors are summarised as follows:

- The technology maturity template and questionnaire received by vendors were designed to interrogate the development maturity of the ten key plant areas and the Critical Technology Elements (CTEs) within them as described in the TEA methodology (Ref. 4).
- The vendor was responsible for identifying CTEs and assigning appropriate TRL scores as per the DoE Technology Readiness Assessment (Ref. 7).
- The vendor was responsible for providing justification of the TRL score through the comments within the template and any supporting information.
- The vendor was responsible for providing a development plan identifying how the current TRL shall reach full development (i.e. TRL 9).

The analysis performed on the submissions as part of the TEA is summarised as follows:

- CTE scores were combined to provide plant area TRL scores. Plant area scores were combined and multiplied (using weightings assigned to each plant area) to provide an SMR TRL.
- Vendor responses were assessed and a scorecard has been compiled against the following attributes: data completeness, data accuracy, data reliability, degree of innovation and unresolved technical challenges. The scorecard has been used in conjunction with supporting information (limited to the submissions provided as part of the TEA) to assign one of four 'confidence levels' against each vendor submission. The confidence levels range from 4 (High) to 1 (Low).
- The confidence levels have been used to revise the plant level TRL scores across the suite of vendor submissions eliminating overly optimistic or pessimistic scores. The purpose of the revised TRL score is only to identify trends in maturity on a consistent basis across the technology groups, acknowledging that the nature of supporting information is variable.
- The vendor plant TRL is revised across the nine point TRL scale by multiplying by the confidence score and dividing by four.
- Finally a risk category can be assigned directly from the revised TRL score as described in the TEA methodology document (Ref. 4):
    - TRL ≤ 3 constitutes risk category 'A';
    - TRL > 3 and ≤ 6 constitutes risk category 'B';
    - TRL > 6 and ≤ 9 constitutes risk category 'C'.

These risk categories directly relate to the technical risk associated with the SMR design at the time of issue and have been incorporated into the 'Cost of SMR Generation' modelling presented in Section 5.2.

4.2.2. SMR Technology Types

The TEA was designed to encourage the participation of a wide range of SMR vendors in order to gain a clear understanding of the potential and current development of SMR technology types globally. On this basis the Invitation to Participate was open to all vendors regardless of technology.

Identification of reactor traits led to the grouping of vendors by reactor technology. Although other distinctive features were considered, this was thought to be the most robust and credible grouping criteria. An overview of these groups is provided below. Additional information on the individual reactor technologies, as provided by the participating vendors, is presented in Appendix A of Vol. 2 (Ref. 3).

4.2.2.1. Integrated Pressurised Water Reactor

Integrated Pressurised Water Reactors (IPWRs) offer a step change in the plant design approach from the conventional large nuclear Pressurised Water Reactors (PWRs), whilst heat generation and core cooling methods (uranium dioxide fuel and light water moderator / coolant) remain fundamentally the same. The IPWR incorporates the entire primary circuit into the Reactor Pressure Vessel (RPV). This offers the opportunity to remove the requirement for the large bore primary pipework and significantly reduces the risk of loss of coolant accidents. The Steam Generators (SGs), Pressuriser and Primary Coolant Pumps (PCPs) are all housed within the RPV offering considerable space savings when designing the primary containment building.

4.2.2.2. High Temperature Gas Cooled Reactor

High Temperature Gas Cooled Reactors (HTGRs) are a type of thermal reactor, in which nitrogen or helium is typically used as the reactor coolant, with a graphite moderator. They operate at high temperatures, usually between 700-950°C, but can be in excess of 1000°C. High temperature operation is permitted by containing fuel in Tristructural-Isotropic (TRISO) particles with fissile material surrounded by three ceramic layers of pyro-carbon and silicon carbide. TRISO particles are embedded into a graphite matrix and formed into either graphite pebbles or graphite blocks with the graphite providing part of or all of the neutron moderation required. Key advantages of HTGRs include the ability to provide process heat to a greater range of industrial applications due to the high process heat temperatures (relative to other nuclear technologies). The use of TRISO fuel introduces an additional barrier to the release of radioactive materials to the environment.

4.2.2.3. Lead Cooled Fast Reactor

Lead Cooled Fast Reactors (LFRs) are a type of unmoderated nuclear fission reactor in which the primary coolant is molten lead or lead-bismuth eutectic. LFRs can operate at atmospheric pressure and high temperature, up to 600°C. The high boiling point of lead gives LFRs a large margin to coolant boiling. As lead is a very dense material it provides a useful radiation shield, providing gamma protection to plant equipment and operators. LFRs benefit from atmospheric operation and the benign interaction of the lead coolant with air and water. As of today, several challenges remain unsolved with LFR designs, among those, the amount of structural support required due to the sheer volume of very dense lead or lead-bismuth and the associated expense of bismuth.

4.2.2.4. Molten Salt Reactor

Molten Salt Reactors (MSRs) are a type of nuclear fission reactor in which the primary coolant and the fuel itself, is a molten salt mixture. The nuclear fuel is dissolved in the molten fluoride or chloride salt. In thermal spectrum designs, the fuel salt would reach criticality by flowing into a graphite core which would serve as the moderator slowing down neutrons to sustain criticality. In the fast neutron reactor designs, the fuels are further enriched but the neutrons do not need to be slowed down to maintain criticality and a moderator is therefore not required. MSRs have the ability to operate at atmospheric pressure and the associated negative temperature coefficients of fluoride salts increases the plant’s inherent safety. The use of molten salts, however, does introduce novel chemistry control challenges.

4.2.2.5. Sodium Cooled Fast Reactor

Sodium Cooled Fast Reactors (SFRs) are a type of unmoderated nuclear fission reactor in which the primary coolant is molten sodium. SFRs operate near atmospheric pressure and at high temperatures of approximately 550°C. Sodium’s high boiling point gives SFRs a large margin to coolant boiling. SFRs can be configured with either a pool or looped primary coolant arrangement. Advantages of SFRs include long refuelling intervals, with 20 years between refuelling achievable. Sodium’s high chemical reactivity does introduce challenges. Sodium is explosive when in contact with water and burns in air so additional containment requirements are necessary.

4.2.3. Technology Readiness Levels and Risk Categorisation

The technology maturity assessment and risk categorisation is carried out in accordance with Appendix B of Vol. 2 of this report (Ref. 3). TRL results and risk categories are grouped by technology type as described in this section.

The analysis of TRLs is based purely on the vendor submissions, as supplied to the TEA. Other vendors around the world are developing reactor technologies that currently stand at different levels of maturity. Only those that have chosen to participate in the TEA are taken into account in this assessment. This approach was considered to be the most appropriate to ensure the use of accurate and up to date information as supplied by each vendor. It does however mean that the assessed readiness levels of the different technologies relied on the level of appropriate detail and completeness of the vendor's own submission. The limited time available for vendors to complete the assessment could have impacted the detail of the TRL submissions provided. This is an important consideration which should be borne in mind when interpreting the results of the assessment as presented.

A TRL analysis provides an indication or trend in technology development maturity. Table 4-1 presents the vendor provided TRL scores (from data extracted directly from the vendor templates) and the revised TRL scores (from data extracted from the vendor templates and confidence levels applied) as a TRL range within each technology group. It is stressed that revised TRL scores are necessary to allow trends to be identified on a consistent basis across technology groups, based on a limited data set. The method to revise TRL scores has not been developed to allow accurate comparison between individual vendor designs, therefore when reviewing the results emphasis should not be given to the exact scoring. Results are also indicative and based on a limited sample size.

The detailed assessment results, including individual vendor scorecards, confidence levels, TRL assessments and risk categories are available in Appendices B, C and D (in Vol. 2, Ref. 3).

Table 4-1 Technology maturity assessment – grouped by technology type (all vendors)

	Vendor TRL	Revised TRL
IPWR	6 – 8	2 – 8
HTGR	3 – 8	2 – 6
LFR	7	2
MSR	6 – 7	2
SFR	7	2

With only one exception, TRL scores provided by the different vendors were narrowly grouped between 6 and 8. These high TRL levels imply that all technologies have a prototypic plant, operationally tested in a simulated laboratory environment. In view of this, the supporting evidence provided by the vendors was examined and a scorecard assessment was performed. As a result of this, it was concluded that some vendors did not provide substantiating evidence that would support the claimed TRL according to the DoE methodology (Ref. 7). This could be due to the application of a certain amount of optimism bias by the vendors, but also due to the misinterpretation of the TRL scale and the required levels of substantiating evidence. It is noted that vendors may have had further substantiating evidence but chose not to submit it for various reasons. However, this assessment was based solely on the justifications and evidence provided. The revised TRLs should therefore be understood as what can be underpinned by substantiating evidence provided to the TEA and does not present a judgement on the validity of the TRLs reported by vendors. A complete validation of the TRLs provided by vendors would require due diligence work and a level of engagement beyond the objectives of this TEA.

The review of the supporting evidence assigned higher confidence levels to the submissions from IPWR and HTGR vendors, who generally provided evidence of design justification through physical testing.

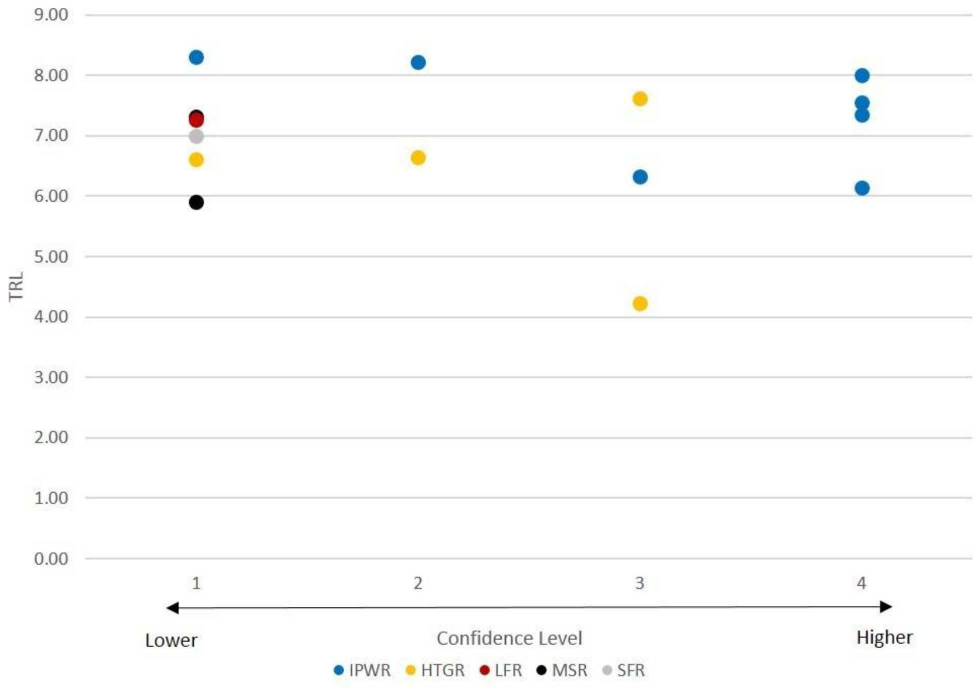
Within the TEA, IPWR technology was found to represent the lowest technical risk for implementation at the time of assessment. Although HTGRs require additional technical development to achieve similar maturity levels to the IPWRs, it is noted that they offer a viable alternative solution that could be commercially available 5 to 10 years after IPWR deployment. To facilitate this, an appropriate level of investment and technical resource capability needs to be made available to HTGR development programmes. The revised TRLs associated with MSRs, LFRs and SFRs suggest that these technology types are still at the concept design stages and should be considered emerging technologies at this point in time.

When interpreting the TRL scores presented in this section, it is important to avoid some of the common misconceptions regarding TRLs, some of which have been highlighted in previous studies (Ref. 8). The key points have been provided below.

- TRLs are time specific; they explain what risk there might be if the technology element is introduced into an operating plant at the time of assessment.
- TRLs can reduce as well as increase. For example, if an in-service component (TRL 8 – 9) failed through high cycle thermal fatigue due to the component's environment and operating conditions, the component may require redesign which could result in the TRL score reducing to 5 – 6.
- TRLs are context specific. A technology element that is mature in one operating plant, or within a certain operating environment cannot be assumed to be as mature in a different system or environment. Even those that appear the same might have significantly different environmental or operational conditions. For example, a pump being used in one reactor plant cannot be assumed to function satisfactorily in an alternative plant without a full re-justification. Water chemistry and transient temperatures may be different, inspection requirements may not be viable under alternative arrangements, fire protection and segregation requirements may be different. Flow characteristics may also be different depending on the pipework configuration.
- The TRL scale is an ordinal scale. The ratings are in order but the distinction between neighbouring points on the scale is not necessarily always the same.
- A TRL score is a useful measure of current technical development, but it is the development plan that drives technical risk reduction.

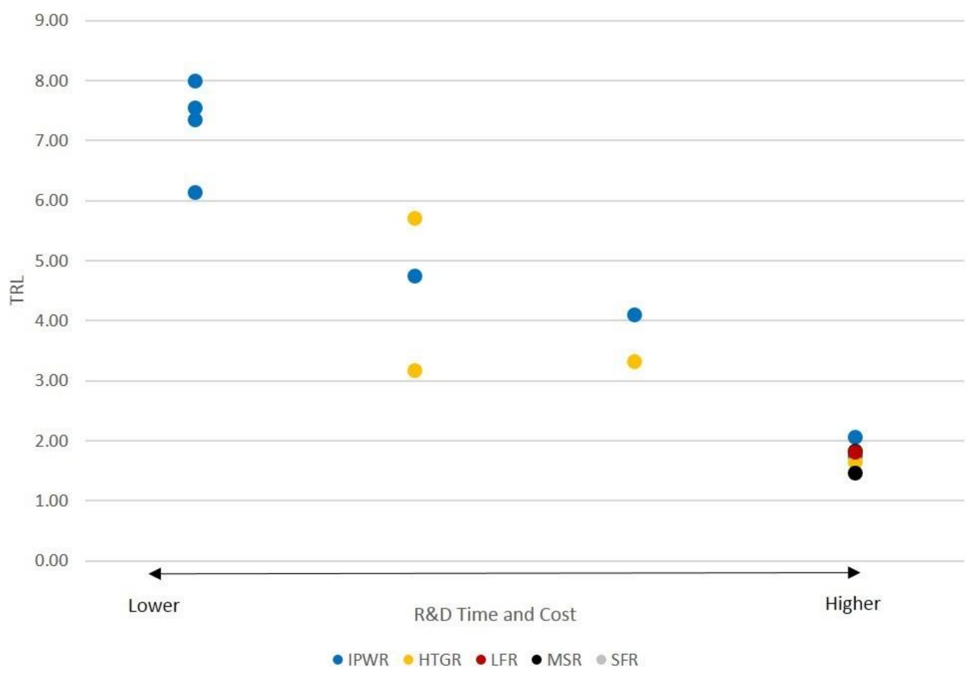
Figure 4-1 shows the vendor supplied TRL scores plotted against the assigned submission confidence level. This provides a visual representation of the relative confidence levels shown by some of the IPWR and HTGR submissions compared to MSR, SFR and LFR submissions.

Figure 4-1 Confidence level vs vendor supplied TRL



Revising the TRLs, based on the confidence level in vendor responses, enables additional conclusions to be inferred regarding outstanding R&D requirements. A graphical representation has been provided in Figure 4-2 of the revised TRL results against a relative outstanding R&D scale. The figure indicates that IPWRs are generally grouped with higher TRL scores and lower development time and cost requirements than the other technologies. HTGRs are shown in the middle sections of the graph following IPWRs. MSRs, LFRs and SFRs are grouped at the right hand side of the graph indicating the greater level of R&D likely to be required before commercial deployment is achievable.

Figure 4-2 R&D estimates vs revised TRLs



4.2.3.1. Status of technologies outside the context of the TEA

Many of the designs presented by vendors for this TEA are based on Generation IV concepts. Some of these concepts have been operated at prototype level or even at commercial level (e.g. the Sodium-Cooled fast breeder reactor Superphénix that was operated in France between 1986 and 1997, or the 250 MWe Prototype Fast Reactor at Dounreay, UK (Ref. 9)). The purpose of this section is to summarise milestones that have been achieved globally by reactor types similar to the non-IPWR technologies represented in the TEA.

Today, the main international body defining and planning collaborative R&D support for the development of Generation IV concepts is the Generation IV International Forum (GIF). Where research efforts are shared across collaborative programmes by SMR organisations and vendors, it offers the potential for designs to reach their development milestones quicker. This could facilitate an earlier commercial deployment for SMRs based on more revolutionary concepts.

The latest GIF Technology Roadmap, issued January 2014 (Ref. 10), assesses the status of six reactor technologies. The roadmap does not assign TRLs to the technologies, but it does outline the accomplishments to date and provides the main R&D objectives along with the milestones anticipated in the next decade. The timelines and research needs are developed for each technology and categorised in three successive phases:

- **Viability phase**, when basic concepts are tested under relevant conditions and all potential technical show-stoppers are identified and resolved,
- **Performance phase**, when engineering-scale processes, phenomena and materials capabilities are verified and optimised under prototypical conditions,
- **Demonstration phase**, when detailed design is completed and licensing, construction and operation of the system are carried out, with the aim of bringing it to the commercial deployment stage.

According to the latest update of the GIF roadmap (Ref. 10), all technologies have started (and some have completed) the Viability phase. The dates when they will reach (or have reached) the Performance and Demonstration phases are shown in Table 4-2.

Table 4-2 GIF Technology Roadmap – Development Milestones

Technology	Performance Phase	Demonstration Phase
Sodium Cooled Fast Reactor (SFR)	2012	2022
High Temperature Gas Reactor (HTGR)[3]	2010	2025
Molten Salt Reactor (MSR)	2025	After 2030
Lead Cooled Fast Reactor (LFR)	2013	2021
Gas Cooled Fast Reactor (GFR)	2022	After 2030
Supercritical Water Cooled Reactor (SCWR)	2015	2025

Generation IV International Forum (Ref. 10)

Of these Generation IV technologies, HTGR, SFR, MSR and LFR technologies have been represented in the TEA. If it assumed that the start of the Performance and Demonstration phases are broadly equivalent to TRLs 5 and 8 respectively, it could be concluded that HTGR, SFR and LFR technologies are currently considered to be at TRL 5. MSRs are currently at a lower level and would only reach the same TRL in 2025. Furthermore, SFR and LFR technologies could be ready for demonstration purposes (i.e. TRL 8) in 2021 and 2022 respectively, with HTGR following in 2025. MSR technology will not be ready before 2030.

It is important to note that achieving the objectives of GIF relies on the commitment of the forum members. A number of participant countries have invested significant resources in the development of the SFR and HTGR technologies due to the historical effort that they have made in advancing these technologies. More limited resources have been used to advance the other technologies (Ref. 10).

[3] The GIF uses the term ‘Very High Temperature Reactor’, which is often used interchangeably with ‘HTGR’

Independent to the GIF, in October 2015 Idaho National Laboratory (INL) published an Assessment of the Technical Maturity of Generation IV Concepts for Test or Demonstration Reactor Applications (Ref. 11). As part of the study, an assessment of the technical maturity of individual concepts was undertaken to see which, if any, have sufficient maturity for either test or demonstration reactor missions. The six concepts investigated are the same as those considered by the GIF (see Table 4-2).

The methodology used in the INL study is very similar to the TRL method used in this TEA and consisted of the following steps:

- Choose the reference advanced reactor design (or design family) for each concept to be evaluated;
- Adopt a technology readiness scale appropriate to nuclear reactor systems (the scale is consistent with the DoE methodology (Ref. 7) used in the TEA);
- Identify the major systems and subsystems to which TRLs are to be assigned;
- Review the technical background for each reference design and assign TRLs to each subsystem based on this information;
- "Roll up" the subsystem scores into an overall TRL for each major plant system and into an overall TRL for the design. Consistent with this TEA, the systems were weighted differently because of the varying importance of the system and the effort and resources needed to develop them to a deployable state.

It is important to note that the INL study is focussed on the efforts made by US DoE to develop each of the six technologies. For this reason, the TRL assessment undertaken by INL may differ from the inferred TRL levels derived from the development phases identified by GIF.

The INL study concludes that the graphite-moderated HTGR and the SFR are deemed to allow for preliminary design and licensing activities for a demonstration reactor within the next 10 years, assuming funding levels appropriate for those activities. With appropriate research efforts for either a MSR (fluoride-cooled graphite-moderated high-temperature reactor) or a supercritical water reactor, preliminary design and licensing for these technologies could be achieved in the next 10 to 20 years. Significant research and development (>20 years) is needed for LFR and GFR technology before these concepts are ready for preliminary design.

These timescales correspond to the following TRLs assigned by the INL reviewers for the reference concepts (Ref. 11).

Table 4-3 Technology Readiness Levels of the overall design

Gas Cooled Fast Reactor (GFR)	Lead Fast Reactor (LFR)	Sodium Fast Reactor (SFR)	High Temperature Gas Reactor (HTGR)	Supercritical Water Cooled Reactor (SCWR)	Molten Salt Reactor (MSR)
2	3	3 – 5	5	3	3

Idaho National Laboratory (Ref. 11)

Beyond the development of SMRs, a number of efforts are being made internationally to develop novel reactor concepts. Some of these concepts benefit from a number of reactor-years of operational experience, as they have already been built and operated as prototypes and demonstrator plants. This evidence has the potential to support the development of SMR concepts to higher levels of maturity within shorter timescales. However, these efforts cannot be accounted for when assessing specific vendor designs within this TEA. Regardless of the level of maturity of the global technology, a new design using novel concepts in a different operational environment needs to undertake a number of development phases, with a number of requirements that need to be met before the design can advance to the next phase.

4.2.4. Current Development and Deployment Needs

The TRL assessment results shown in Appendix C of Vol. 2 of this report (Ref. 3) provide scores against each submission. Vendor responses identified the plant areas and CTEs that require further development in order to progress to the required level before entering into service (i.e. TRL 8). Those technologies scoring low TRLs suggest a need for additional development which is likely to lengthen deployment timescales. Associated to this there is likely to be an increased requirement for investment alongside human and technical resources. As a general trend across all of the technology types, the analysis has highlighted four plant areas consistently requiring additional development (i.e. scoring lower TRLs relative to the other plant areas). These are as follows: reactor plant equipment, fuel and core design, instrumentation and control and safety systems.

The IPWR vendor submissions to the TEA suggested this technology type to be the furthest developed, which implies that an earlier deployment than the other four technology groups could be potentially achieved. The IPWR vendors who indicated the furthest stage of development stated that designs are finalised and that they would be ready to commence GDA. These vendors identified the importance of commencing GDA as soon as possible as well as beginning the procurement process of long-lead components along with agreeing any UK Government guarantees prior to 2020, if the deployment by 2030 is to be achieved.

Testing and development programmes that were identified by the IPWR vendors that are not currently ready to commence GDA included:

- Integrated reactor pumps;
- Fuel assemblies;
- Steam Generator equipment and supporting systems;
- Emergency pressure valve materials;
- Control Rod Drive Mechanisms (CRDMs);
- In service inspection and maintenance procedures.

The HTGR submissions suggested that these development programmes would require additional time compared to the IPWRs. HTGR vendors stated that concept design and pre-licensing had been completed. It is apparent that considerable design effort across the reactor plant is still required before a GDA submission is likely to become possible. Current design calculations are indicative only at this stage and design development and optimisation in most cases has not commenced. There are some areas of risk associated with HTGR technology that have not been tested fully in the nuclear environment, an example being the development of compact heat exchanger technology applicable to a nuclear plant operating in excess of 700°C. Such a testing programme is likely to require significant resources and funds in the order of hundreds of millions of pounds (see Section 4.2.4.1 below). Supplier engagement needs to take place on these higher risk areas to provide a level of mitigation and increased confidence, not only in the ongoing design development, but also in the manufacturability of critical components.

Testing and development programmes that were identified by HTGR vendors include:

- Primary and secondary systems to be taken through the detailed design stages;
- Compact gas – gas heat exchanger;
- Reactor instrumentation and control systems;
- Testing of major primary components at elevated temperatures;
- On-site fuel handling and storage equipment.

MSRs, LFRs and SFRs scored revised TRLs close to level 2. The lower TRLs highlight the requirement for significant technology development before a commercially viable SMR design can be completed. The revolutionary coolant mechanisms give rise to challenging through-life material science and safety justifications. The lack of operating experience is likely to force these design elements through an additional level of scrutiny before entering service, causing further delay. It is most likely that these reactor types will not be commercially available until a later date than IPWRs (but before 2050), however the operational and safety benefits claimed by the vendors (see technology descriptions, Appendix A of Vol. 2, Ref. 3) could justify the longer timescales and associated investments in R&D.

Testing and development programmes that were identified for MSR, LFR and SFR vendors include:

- Salt / sodium / lead coolant pumps;
- Development of thermal hydraulic codes;
- Salt heat exchangers;
- Fuel design and assembly;

- Fuel handling;
- Decay heat removal;
- Challenges associated with coolant (explosive properties of sodium / high density of lead / corrosive properties of fluorides);
- Through life environmental material properties;
- Environmental fatigue development;
- Waste management.

From the TRL assessment it is evident that several of the target deployment dates provided by all vendors appear challenging. The amount of design work that remains for some submissions is significant, even before testing programmes can be identified and facilities can be designed and built. The conclusion for these technologies is that, based on the information submitted to this TEA, it is difficult to foresee how these technologies could be commercially operational prior to 2030.

4.2.4.1. Research and Development cost estimates

Although it is fairly straightforward to identify many of the areas where further R&D is needed, making an attempt to quantify the resources that are needed to successfully resolve those open challenges is far more complicated.

Vendors were asked to provide a technical maturity plan providing details of what is still needed to develop their design to the point where it would be ready for commercial deployment. This enquiry had a very low rate of response from vendors. In this context, estimate of R&D costs are highly uncertain. From the responses provided by vendors developing IPWR designs it can be inferred that, depending on the country of origin, the cost of progressing an IPWR design to regulatory ready status ranges from $150 million to $500 million (£100 million to £325 million).

Responses from vendors of non-IPWR designs show that their expenditure up to date has been in the order of tens of millions of US dollars or less, rather than hundreds of millions. From this, and taking into account that developers of non-IPWR technology will face not only more technical unknowns but also a shortage of design computer codes qualified to perform design activities and safety justifications, it can be concluded that R&D costs for developers of non-IPWR technologies are in the order of hundreds of millions of US dollars.

4.2.5. Opportunities for Intellectual Property

Intellectual property is a complex issue with important legal ramifications. Opportunities for IP are normally linked to the development of innovative concepts. However, the quantification of the value of that IP is difficult and it is linked not only to the value of the innovation, but also to the potential volume of deployment of the technology containing the owned IP.

The ownership of IP allows the owner to control where, how and by whom a particular invention is implemented. This provides a competitive advantage and could be a mechanism that would secure greater UK economic advantage from SMR deployment, either through ensuring the location of manufacturing activities in UK or through the generation of license fees for use elsewhere.

There has been limited evidence from vendors responding to the TEA in respect of IP or the value of IP in their reactor designs that can be independently assessed at this early stage. Three vendors have stated that they own patents on some design areas or broad perspectives of their proposals, or that they own IP. Most claim that there is IP in their designs, but without detail or quantification of the value of it. Overall the value of the IP opportunity is not defined by vendors and would be a complex, lengthy and continuous process to assess and monitor it, so that a proper assessment could be made of the potential return on any investment in the technology.

The opportunities for IP in the early stages of SMR development relate to the novel design solutions that are created when developing the plant. Due to the design complexity related to a nuclear facility, IP is unlikely to be granted at a plant level. There may be more opportunities to develop IP for specific components, the materials used, the manufacturing and inspection techniques, its modular construction methods or decommissioning and waste disposal techniques.

As SMR technology develops, the opportunities for innovation are likely to change. A design that is currently exhibiting a revised TRL of 1 to 4, indicating the design is at the concept stages, will offer increased opportunities for innovation over those that are relatively well developed. The TRL assessment results (Figure 4-2) show how the TRL scores relate to each technology type. The lower TRLs broadly suggest increased innovation opportunities.

Vendors have indicated that design based IP opportunities are likely to be limited with IPWRs, although opportunities in the supply chain might still exist. However, these opportunities are difficult to quantify, as vendors have mostly been focusing on performance aspects of their designs giving less thought to inspection, testing, manufacturing and fabrication. As an example, an IPWR designer with one of the highest TRL scores is currently undertaking an engineering programme that will conclude in 2019 and help them to understand how they will manufacture, fabricate, test and inspect FOAK components associated with their technology. Other vendors have demonstrated little or no consideration of these areas so far. It is reasonable to assume that they will need to go through similar engineering programmes where a substantial amount of issues will be identified regarding the manufacturing of the modules. Resolution of those issues will provide the opportunity for IP.

Related to manufacturing is the inspection of nuclear reactor vessels and components. To reap the production benefits associated with SMRs the manufacturing methods and philosophies will need to be adapted from current nuclear build facilities. This will be needed to allow for compliance with regulatory requirements in terms of inspection, testing and monitoring. This will generate further opportunities for the acquisition of IP.

The opportunities related to the alternative reactor types are substantially increased at the system design level, as these technologies are yet to progress through the detailed design stages (based on information provided to the TEA). There are substantial risks associated with these reactor types due to the uncertainty and the increased timescales for return on investment. The scale of capital investment that would be required for the implementation of R&D programmes for these technologies is estimated to be in the order of hundreds of millions of USD (see discussion in Section 4.2.4.1).

Through the responses provided by vendors, it is possible to identify a number of areas where opportunities for design and manufacturing IP might exist if the UK would develop a commercial partnership with an SMR designer. Any commercial partnership would not necessarily have to be with a UK based designer. The opportunities and potential value of IP would depend on the current maturity of the design as outlined above. These opportunities are closely related to the areas for further development listed in Section 4.2.4. Specific examples identified by vendors include (but are not limited to): fuel assemblies, CRDMs and the associated positioning and indicating equipment, Main Isolation Valve, Reactor Pressure Vessels, Steam Generators, Primary Coolant Pumps, specialist manufacturing techniques and safety system hardware and software.

As a summary, the assessment of the IP opportunity requires an in depth understanding of the market and the maturity of each design. It also requires a decision on how the acquired IP will be deployed, which is not an element within the scope of this study. The vendor submissions may address some of these elements based on the level of maturity and investment made in the development of their designs, but do not provide specifics on the implications for any future investors or shareholders.

4.2.6. Technical Maturity Conclusions

The analysis results indicate that IPWR technology provides the lowest technical project risk for deployment at the time of assessment. The IPWR submissions have scored a revised TRL range of 2 to 8, but with the majority scoring within TRL 6 to 8.

The IPWR submissions support this conclusion. The submissions have been comprehensive in nature providing design information and some justification on most of the requested topics as defined in the TRL template. The CTEs are generally well understood in isolation, the components are well described and are not revolutionary in function. The reactor plant has been considered in its entirety. Further work is required to justify the component functionality as a system or assembly through further prototypic full scale testing.

The analysis results indicate that HTGR technology provides the second lowest technical project risk for deployment into the SMR market at the time of issue. The HTGR group of submissions have scored a revised TRL range of 2 to 6.

The HTGR submissions support this conclusion. The submissions have been wide ranging, with good design detail provided by some vendors. CTEs are not as well defined as for the IPWRs and the justification of scores is not as in depth and, in some cases, it is difficult to understand how they support the TRL score submitted.

There was little in the way of development plans provided and there seem to be some sizeable technical challenges to be addressed. The high temperature of operation and the likely transient issues this may produce has not been discussed. Therefore, it is not known whether the challenges this will cause to vessel and component design have been fully considered. Plant life claims are largely unsubstantiated and there seems to be little in the way of computational analysis or physical testing. This programme of work will need to be carried out in order to progress through TRL 4 and 5.

The analysis indicates that MSR, LFR and SFR technologies seem to be at a lower level of maturity. These grouped submissions have scored a revised TRL of 2.

These technology submissions are at the concept stages focusing on some initial core and fuel designs. Design of the reactor plant functioning as an integrated system has not been provided. Considerable challenges remain, with further work still required to identify and justify the primary steam supply systems before the supporting plant systems are considered. TRL justifications have been provided through scientific papers carried out by third parties on the technology type, as opposed to testing their own design. In some cases the material selection has not yet been carried out and plant life claims have not been justified.

Across the suite of vendor submissions, construction and manufacturing has not been well described yet plays a vital role in the development programme. A good example is the limited documentation presented on the benefits associated with modular construction techniques.

Manufacturing capability, with respect to technology / machines and operators needs to be developed in conjunction with the design to prevent programme delay. Lead times on bespoke specialist machinery and facilities can be equivalent to that of long-lead material orders and will provide major delays if they are not identified at the design stage (i.e. pre-licensing). Some confidence can be found as the route to production shall follow something similar to that of in-service reactor types, i.e. materials, inspection techniques, manufacture and operator skills sets, test rigs and facilities. Manufacturing readiness will however require a high level of focus if SMRs are to meet the demanding deployment time scales stated by the vendors.

To further minimise the risk of construction delays, the supply chain needs to be developed concurrently with the design. Supplier quality needs to be approved with qualification of the manufacturing process and components necessary. Physical shipping routes, jigs and fixtures are to be designed and approved for individual components or assemblies.

4.3. Integration into the Existing UK Nuclear Infrastructure

The deployment of SMR technology could present significant opportunities to develop the UK's nuclear infrastructure. Conversely, the UK's nuclear infrastructure could present a potential barrier to the deployment of SMR technology if development requirements are not identified and addressed. This section identifies the potential benefits and challenges for SMR deployment with a focus on the following five key infrastructure topics:

1. Siting;
2. Electricity transmission and distribution;
3. UK nuclear fuel production;
4. Decommissioning and waste management;
5. Wider benefits (focussed on CHP applications).

In Sections 4.3.1 to 4.3.5 a description of the existing UK infrastructure is provided for these five areas. The relevant findings from SMR vendor responses are presented and any potential challenges or opportunities for UK infrastructure identified. Where relevant, a comparison between large nuclear and SMR technologies is used to highlight the extent of these challenges and opportunities.

Section 4.3.6 reviews the capability of the UK supply chain to support the deployment of SMRs. This section derives an important economic assessment input that estimates the potential proportion of total SMR construction and manufacturing cost that could be spent within the UK supply chain.

4.3.1. Siting

For a site to be considered suitable for the construction and operation of a nuclear power station a wide range of requirements and constraints must be satisfied. This section identifies the relevant selection criteria applied for siting large nuclear power stations in the UK and compares these against the siting requirements for SMR technologies.

Some SMR technologies may require supporting off-site facilities that entail specific siting considerations. For example, a new fuel manufacturing facility may be required, which itself would require nuclear site licensing and would be subject to its own siting assessment. Due to the limited information that the participating SMR vendors can provide about necessary support facilities at this stage of design development, this assessment focuses solely on power station siting.

4.3.1.1. Siting criteria for large nuclear and SMR power stations

The National Policy Statements (NPS) for energy and nuclear power generation (NPS EN-1 and EN-6, Ref's 12 and 13) sets out the policy basis for the siting of nuclear power plants in England and Wales under the national infrastructure planning system. Eight potentially suitable sites are listed in NPS EN-6 (Ref. 13) for large nuclear power stations deployable by the end of 2025. The sites identified in NPS EN-6 were selected on the basis of a Strategic Siting Assessment (SSA) (Ref. 14) and Alternative Sites Study (Ref. 15). Six of the eight sites currently have owners who plan to construct and operate large nuclear power stations. An independent siting study is being undertaken to identify further potentially suitable sites in England and Wales for large nuclear reactors and SMRs including those which may be deployable over longer timeframes (Ref. 16).

From reviewing the siting criteria from the SSA (Ref. 14) the following themes have been selected for assessing the distinguishing siting characteristics between SMR and large nuclear power stations in Section 4.3.1.2.

- Site area (SSA siting criterion 4.1);
- Cooling demand and availability (SSA siting criterion 4.2);
- External hazards (SSA siting criteria 1.1, 1.3 and 1.7);
- Radiological discharges (linked to SSA siting criterion 1.10);
- Emergency Planning Zone (EPZ) (SSA siting criterion 1.11);
- Site supporting infrastructure (SSA siting criterion 3.2).

It should be noted that the very low power HTGR design (< 5 MWe) has been developed to target the industrial power unit market and for off-grid applications. There are clear benefits presented by this technology with respect to the above siting criteria, such as: very small site footprint (< 0.01 km^2); the option for air cooling removing the need for cooling water supply; reduced radiological discharges; and reduced construction phase land and site access requirements. However, the identification of suitable sites is more dependent on identifying locations where a specific need for embedded power exists (e.g. remote communities, large industrial sites). For this reason a direct comparison of siting with large nuclear or other SMR technologies with respect to the above criteria is not appropriate.

4.3.1.2. Review of siting characteristics for SMR and large nuclear power stations

Site area

The SMR vendors have provided estimates of the permanent site area, which for the purpose of this TEA is defined as the area within the secure perimeter of a UK licensed site. This includes buildings / plant associated with direct cooling from a local source or indirect cooling by forced mechanical draft. The space taken up by permanent facilities outside the secure licensed site area (e.g. car parks, training centres) is not included. Some vendors have also provided estimates of the temporary construction site areas required, but with a higher level of uncertainty due to the site specific nature of this area. Details of the site area information are listed in Appendix H of Vol. 2 (Ref. 3).

To support the comparison of permanent site areas for different SMR and large nuclear stations, the vendor information has been reviewed and a 'standardised' site area has been estimated on a consistent basis for each SMR technology. For more information on the standardised areas and more detailed interpretation of the results please see Appendix H of Vol. 2 (Ref. 3). The main points from the assessment of permanent site areas are summarised below:

- For the IPWRs, there is reasonable consistency in the range of permanent site areas and the ratios of area to electrical power output. For IPWR reference plants having gross electrical power outputs of 200 to 600 MWe, the permanent site areas range from 0.1 to 0.23 km^2. The average ratio of permanent site area to gross electrical power output is 440 m^2/MWe. The most space efficient IPWR reference plant has a ratio of 300 m^2/MWe.
- In comparison, the ratio of large nuclear permanent site area to gross electrical power output ranges from about 110 to 150 m^2/MWe depending on the reactor type. The permanent site areas quoted here for large nuclear plants have been estimated on a consistent basis with the standardised areas estimated for SMR plants.
- The information provided on MSR indicates a much smaller permanent site area for this plant than for the IPWRs. Although there is some uncertainty over the MSR site area (the site layout and the sizing of the Balance of Plant (BoP) buildings appear to be at early stage of development), this case indicates the potential that MSR plants could fit within a relatively small site area of 0.05 to 0.1 km^2.
- One IPWR vendor provided information on how the permanent site area would increase for a plant configuration with more reactor modules than in the basic reference configuration. In this case, it was estimated that doubling the number of modules and electrical power output (from a single to twin unit plant) would increase the permanent site area by a factor of 1.8.

There is less reliable information and more variability with respect to construction site areas as they are more sensitive to particular site characteristics and construction plan priorities. The main findings are:

- A construction site area less than 0.1 km^2 may be sufficient for the very compact MSR plant (although detailed vendor information is not available to support this).
- According to vendor information, the majority of the featured IPWR plants have an estimated construction site area (including the permanent site area) in the range of 0.3 km^2 to 0.8 km^2 (see Appendix H in Vol. 2, Ref. 3). As would be expected, the SMR construction site areas are smaller than those for large nuclear stations (e.g. 1.6 km^2 for a 2 x 1,630 MWe plant).
- This suggests representative ratios of construction site area to gross electrical power output in the order of 1300 m^2/MWe for SMR (IPWR only) plants and 520 m^2/MWe for large nuclear plants.

Recognising the limited number of suitable sites for new nuclear power stations in England and Wales, it follows that SMR plants are most suited to small sites (less than about 0.2 km^2 permanent site area) which would be too small to accommodate a large nuclear plant. Some larger sites may be considered for SMR deployment where specific siting factors (e.g. cooling water availability, visual impact) would not be compatible with a large nuclear plant. The potential scale of SMR deployment in the UK could therefore be linked to the number of sites which fall into this category in comparison to the number of sites that are suitable for large nuclear plants.

Cooling water demand and availability (for direct or indirect systems)

The amount of waste heat to be removed by condenser cooling is a function of the electrical power output and thermal efficiency of the power plant. The thermal efficiency of SMR plants is similar to that of large nuclear plants. Small IPWRs have essentially the same thermal efficiency as large PWRs (typically 32% to 35% stated by vendors). HTGRs have a higher thermal efficiency than IPWRs due to the higher temperature steam produced. In general comparative terms, the cooling demand for SMR plants and large reactor plants can be considered to be proportional to electrical power output. It follows that water abstraction rates for both SMR plants and large reactor plants are proportional to electrical power output for a given cooling technology. This is confirmed by simple review and comparison of the vendor information (see Appendix H of Vol. 2, Ref. 3) with that from large nuclear plants.

Direct cooling has been adopted for most large nuclear reactors in the UK due to the availability of coastal sites and the relative scarcity of sites on large rivers which can reliably support year-round abstraction rates for indirect cooling systems. The lower electrical power output (and cooling demand) of SMR stations means that a greater number of sites are likely to be suitable on the grounds of cooling water availability compared to large reactor sites. For example with SMR stations, direct cooling may become viable on additional estuary sites and indirect cooling may become viable on additional river sites. For sites where indirect cooling is favoured, the reduced size of the cooling towers for SMR plants (compared to large reactors) would reduce the scale of the visual impact and other environmental impacts.

External Hazards

The SMR vendors have not identified any external hazards that are specific to SMR technology. However, in most of the vendors' SMR designs, the RPVs and other important Structures Systems and Components (SSCs) are located below-grade (i.e. below local ground level). One of the designs has the nuclear island base mat situated 30 m below ground level. This will change the safety case arguments of some external hazards in comparison to large nuclear power plants, and could impact siting criteria.

Locating the reactor building below ground level provides advantages for the seismic hazard protection. It is also likely to strengthen the safety case arguments with respect to some man-made hazards and meteorological hazards. However, by setting SMR reactor buildings into the ground over most of their height, the stability of the buildings may be affected by significant uplift pressures and potential buoyancy under high groundwater conditions. In the UK, this scenario must be addressed in the design basis in line with other natural hazards at 10^{-4} p.a. return frequency. For some SMR designs, it is possible that a sensitivity to high groundwater conditions could affect the feasibility of implementation at certain sites where groundwater levels are high and cannot easily be controlled.

Planned Radioactive Discharges

Very limited information on radioactive discharges was provided by the SMR vendors with the majority unable to provide quantified data. The data that was submitted is included in Appendix H of Vol. 2 (Ref. 3) with the main findings summarised as follows:

- Annual radioactive aqueous discharges for IPWRs are estimated to be less than large nuclear (with respect to total activity discharged). When normalised against power output, IPWR aqueous discharges are estimated to present very similar levels of activity per year.
- Annual radioactive gaseous discharges for IPWRs are estimated to be significantly higher than large nuclear. When normalised against power output the estimates of activity released per year were an order of magnitude higher, with noble gas isotopes providing a disproportional contribution to the total activity.

The release of significant quantities of radioactive noble gases is usually indicative of fuel clad failure events. However, the disproportional gaseous discharge data presented for IPWRs is not attributed to higher frequencies of clad failure as this would also result in a correspondingly high aqueous discharge fission product activity. The fuel design similarities between IPWR and large PWRs provides additional confidence that this is not the contributing factor.

It is possible that the relatively high noble gas discharge activity is instead attributed to the performance of the gaseous radioactive waste abatement systems in the design. Limited information on the current abatement system designs was provided in vendor submissions, but some IPWR vendors confirmed the use of activated charcoal beds to delay the discharge gas allowing short lived isotopes to decay. No details of these systems were presented. It is expected that through engagement with the Environment Agency and application of Best Available Techniques (BAT), the abatement systems would be appropriate sized and designed to sufficiently delay gaseous waste streams to allow noble gas activity to decay to levels considered acceptable by UK Regulators before release to the atmosphere.

It is considered feasible that SMRs could be operated within lower radiological aqueous and gaseous discharge limits than large PWRs. The reduction in actual planned radioactive discharges could be proportional to the reduction in power output, based on the aqueous discharge data.

Emergency Planning Zone (EPZ)

The method for setting an EPZ varies between countries. In the UK, the EPZ is defined based on the position of the point where the unmitigated dose to a person in the 12 month period following the worst case reference accident would not exceed 5 mSv (Ref. 17). Where it is demonstrated that there would be no off-site exceedance of the 5 mSv limit, no EPZ is required. However, this is not a prescriptive criteria and, in some cases, ONR might decide to extend the EPZ due to practical and strategic considerations judged necessary in the interests of confidence in securing public safety. For example, Torness Power Station has an EPZ of 3 km even though 5 mSv over 12 months is not exceeded beyond 800 m from site (Ref. 18).

International methods for setting an EPZ can be more prescriptive. For example, in the US emergency planning areas are set as 10 miles from the source of release. SMR technology is viewed as an opportunity in countries that employ prescriptive methods such as these for defining a new approach to setting EPZs and subsequently improve the siting flexibility. However, these potential developments are not applicable to the UK and SMR vendors would be expected to justify an EPZ that reduces risk to the public so far as is reasonably practicable.

Although the approach for agreeing an EPZ in the UK will not be different than for large nuclear, it is used in the TEA as an indicator on whether the siting policy of SMRs with respect to proximity to local populations should be evaluated differently to large nuclear.

A basic approximation of the EPZ from vendor submissions of the 5 mSv exceedance point has indicated that the EPZ could be 'less than 1 mile'. This could be interpreted as being comparable to the existing UK nuclear power stations with an EPZ of 1 km. Where SMR vendors have stated the EPZ would be "at the site boundary", this has not been estimated in accordance with UK methodologies and no supporting evidence has been provided. These claims cannot be validated at this stage.

On this basis, there is currently no evidence based on EPZ sizing to suggest the siting policy of SMRs with respect to proximity to local populations should be evaluated differently to large nuclear. However, the information available from vendors on this topic is very limited at this stage. Further consideration should be given once more fault analysis and off-site radiological dose assessment findings are available.

Site supporting infrastructure

The information provided by the SMR vendors indicates that the range of infrastructure requirements (e.g. grid connections, potable water, road, rail) throughout the lifetime of the power plant would generally be similar to those for large nuclear power plants. It is noted that the use of increased modular construction techniques could result in reduced supporting infrastructure requirements with respect to bulk material import. However, there may be an increase in the number of large single plant items delivered to site. The exact nature of any differences with large nuclear during construction are unknown and would be highly dependent on site specific characteristics. At present, there are no clear factors identified suggesting that the site supporting infrastructure requirements would necessitate different siting considerations for SMRs than for large nuclear.

4.3.2. Electricity Transmission and Distribution

All generators connected to the UK transmission or distribution networks are required to meet various connection requirements, including compliance with relevant codes to ensure the plant synchronises with the network and operates safely. Furthermore, the ability to provide additional balancing services (defined and discussed below) to support the network will become of greater importance as the amount of renewable generation increases. This section assesses the alignment of SMR technologies with UK requirements and discusses the ability to provide additional balancing services.

This section does not assess the technical or economic benefits and of having SMR technology as part of the UK electricity market; these topics are considered within Project 2 and Projects 5-7.

4.3.2.1. UK Electricity Transmission System Requirements

There are a number of requirements that need to be considered when connecting a generator to the UK transmission or distribution networks. The transmission network transmits high-voltage electricity from generating sites across the country. The transmission network is managed by National Grid Electricity Transmission plc (NGET) as the Transmission System Operator for the UK (with the exception of Northern Ireland). The distribution networks transmit electricity from the high voltage transmission network to the various domestic and commercial users. The distribution networks are managed by the various regionalised Distribution Network Operators (DNOs).

The requirements for a generating plant to be connected to the transmission network are explained in a number of documents, including the UK Grid Code (Ref. 19), which is published by NGET. The Grid Code defines the technical requirements for connecting, and operating, both generation and demand to the UK transmission network. The Distribution Code (Ref. 20) sets out the requirements for connection to the distribution network, which are similar to the Grid Code but not as onerous.

Direct connection to a local distribution network is only possible for smaller generating technologies. Commercial UK nuclear power plants have therefore been connected to the transmission network to date, however, the SMR plants that have an electrical power output of <50 MWe could be connected to the distribution network. Managing power flows at the distribution level is more efficient, meaning that SMRs could provide an additional benefit helping NGET perform balancing services.

The Grid Code (Ref. 19) places numerous technical requirements on generators connected to the transmission network. The extent of these requirements vary with the electrical power output. In general the requirements are more onerous the larger the size of generation. The SMRs reviewed cover a wide range of sizes, as defined by NGET in England and Wales:

- Small (< 50 MWe);
- Medium (50 to 99 MWe);
- Large (≥ 100 MWe).

The exact requirements will therefore vary from between technologies and site configurations.

NGET also procures ‘balancing services’ in order to ensure the security and quality of electricity supply and to balance demand and supply across the transmission network. The Balancing Code portion of the Grid Code (Ref. 19) defines mandatory ‘System Ancillary Services’ (Part 1) that must be provided, and discretionary System Ancillary Requirements (Part 2) that generators may agree with NGET to provide[4]. The mandatory requirements include reactive power and frequency control services; the latter requires power plants to monitor the transmission grid frequency and adapt the level of generation accordingly.

Additionally, reductions or increases in power output over a 24 hour period could be agreed in advance with NGET based on forecasted demand. The provision of balancing services through a daily load cycle and / or the ramp up and down of delivered power in response to demand is termed ‘load following’. This is achieved in nuclear power plants by the control of power generated in the core or bypassing the steam turbine.

In addition to the requirements of the NGET, the European Utility Requirements (EUR) (Ref. 21) places requirements on load following. Key requirements include:

- Capable of daily load cycling operation between 50% and 100% of its rated power;
- A ramp rate (i.e. change in electrical power as a percentage of rated power per minute) of ±3%.

Network balancing is an important ability for any transmission operator and has traditionally been done by large thermal plants that can provide quick response to changes in demand. Nuclear power plants have typically provided base load power in the UK. With fossil fuel plants gradually being replaced by non-fossil fuel technology, the requirement to balance the network will fall to other generators and initiatives such as demand side response. Load following capabilities would enable SMRs to enter into more flexible balancing and settlement agreements for trading electricity.

4.3.2.2. SMR Compliance with Codes

Vendors provided a mixed depth of information with respect to the Grid Code (Ref. 19), with most confirming the expectation that their design would be compliant. It is acknowledged that achieving compliance derives from the choice of generator and the majority of vendors have not selected this yet. It should be noted that vendors have generally indicated that they anticipate the use of the UK supply chain to select and procure the generator technology.

In recent years, new nuclear plants have had difficulty fully meeting existing Grid Code requirements. This has resulted in modifications to both the plant design and the Grid Code. However, the issues facing large nuclear were due to the large size of the plant, hence by their nature SMRs are unlikely to face these issues.

The Grid Code (Ref. 19) is a document that is continually being developed as technologies and generation types change. The requirements in place when SMRs will sign connection contracts will be likely to differ from what current documentation states, however the fundamental principles are expected to remain.

Whilst the majority of vendors have not considered compliance with EUR (Ref. 21), most have developed their design with consideration of the Electric Power Research Institute (EPRI) Utility Requirements document (Ref. 22). SMR vendors have confirmed that they can offer load following services compliant with both Grid Code and EUR requirements:

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[4] See Section CC.8.1 of the Grid Code (Ref. 19)

- Typically ramp rates of up to 5% rated power per minute are achievable, with rates as high as 10% per minute claimed by some vendors.
- A daily cycle between 100% and 20% is generally claimed by vendors, although some vendors suggest smaller cycles between 100% and 40%.
- Reactive power capability through voltage control has been confirmed by a limited number of SMR vendors.

4.3.2.3. Summary of SMRs Compliance with the UK Power Network

The potential benefits offered by the deployment of SMRs with respect to compliance with UK electricity network requirements are summarised as follows:

- Compliance with the Grid Code is not expected to incur the same level of challenges experienced by large nuclear in recent years. To ensure any required changes are identified in good time to allow modifications to either the Grid Code or SMR plant design, it is recommended continual liaison between NGET and SMR vendors is undertaken during the development of the technology.
- SMRs can provide network balancing services, with positive indications from vendors that the designs would be compliant with the Grid Code and EUR requirements. The ability to locate low power SMRs (< 50 MWe) at the distribution level, provides additional balancing opportunities.

There are additional benefits and technical challenges with respect to SMRs operating in load following.

4.3.3. UK Nuclear Fuel Production

This section provides information on the current UK fuel enrichment and fabrication capability, with estimations of the current and possible future demand from large nuclear power stations. Based on the information provided by vendors, it postulates the possible demand resulting from the deployment of an SMR fleet within the UK. From this assessment, potential opportunities for the UK nuclear fuel supply chain and possible barriers to SMR deployment are identified.

4.3.3.1. Existing UK Nuclear Fuel Infrastructure

The UK currently has full fuel cycle facilities including major reprocessing plants. The UK is predominantly self-sufficient throughout its nuclear programme, with the exception of natural uranium supply.

UK fuel production

The front end fuel cycle services are provided at two UK sites:

- **URENCO UK (UUK)** provide the necessary enrichment services using the centrifuge facility at Capenhurst site to enrich uranium, in uranium hexafluoride (UF_6) form, up to ~5% U-235. At the end of December 2014, UUK had increased the operating capacity to 4,900 tSWU/yr (Ref. 23)[5]. Based on the current operating capacity, the maximum annual enrichment output of 5% U-235 is approximately 593 t according to the UUK website (Ref. 24)[6]. If 4% U-235 is required than the maximum annual output increases to approximately 800 t.
- **Westinghouse Springfields Fuels Limited (SFL)** manufacture the oxide fuels in the form of ceramic pellets with a maximum annual pellet production capacity equivalent to 600 t of uranium fuel, according to the World Nuclear Association (WNA) website (Ref. 25). SFL manufacture the fuel assemblies with a maximum annual capacity equivalent to 800 t of uranium fuel (Ref. 25). SFL currently manufactures the fuel pellets and assemblies for all operating UK nuclear power stations. It also has the capability to convert uranium dioxide (UO_2) to UF_6, however this facility has not been operational since 2014.

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[5] The capacity of enrichment plants is measured using the Separative Work unit (SWU), which relates to the effort necessary to separate U-235 and U-238.
[6] Note the UF_6 feed requirements are calculated using the 'Calculate Feed and EUP from SWU Quantity' tool. SWU is taken from the URENCO website (Ref. 23). Product assays are changed for each enrichment level. Tails and feed assays are left as default values.

UK existing nuclear fuel demand

The UK currently has 15 reactors generating about 18% of its electricity. It is conservatively assumed that the total Advanced Gas-Cooled Reactor (AGR) fleet will, on average, require 268 tU/yr based on the fuel data presented in the Description of the Advanced Gas Cooled Type of Reactor (Ref. 26). For Sizewell B (SZB), the UK's only operating PWR, the demand for enriched uranium is assumed to be an average of 25 tU/yr, based on EDF Energy (Ref. 27) and International Atomic Energy Agency (IAEA) PRIS data (Ref. 28)

UK new nuclear fuel demand

The latest electricity generating projections by DECC (Ref. 29) estimate a total of 14 GWe of new large nuclear power stations will be brought online over the next 20 years to replace the aging AGR fleet and support decarbonisation of the UK energy sector. The demand these new power stations will place on the UK nuclear fuel supply chain is highly uncertain. This assessment will conservatively consider scenarios where the demand from new large nuclear power stations on the UK fuel supply chain ranges from 3.6 GWe to 9.0 GWe.

The annual fuel requirement for new large power stations is assumed to be 25 tU/GWe. This is a conservative value estimated using data available for planned large nuclear plants (Ref's 30, 31 and 32), with initial fuel loadings conservatively factored in. This value is close to that suggested by WNA (27 tU/GWe) for modern nuclear plants (Ref. 33).

4.3.3.2. Impact of a UK SMR Fleet

Descriptions of the fuel characteristics and fuel cycles for each SMR vendor are provided in the technology descriptions, Appendix A of Vol. 2 (Ref. 3). The key fuel parameters are summarised in Appendix I of Vol. 2 (Ref. 3). The data in Appendix I has been used to derive the main findings in this section.

The capability of the existing UK nuclear infrastructure to supply SMR fuels is summarised below. Where the capability exists to support fuel production, the likely available capacity is estimated.

- IPWRs use similar fuel design to large PWRs and could potentially make immediate use of the UK supply chain. The enrichment to <5% U-235, fabrication of UO_2 fuel pellets, and manufacturing of required fuel assemblies are all within the capabilities of the UK fuel infrastructure. Upgrades to existing infrastructure are expected to be minimal and would not present a barrier to supporting small IPWRs.
- Modifications to UUK facilities would be needed to provide the necessary level of enrichment for HTGRs, which use 19.5% U-235. Relicensing of the site might also be necessary. The unique geometries of the fuel elements mean that it could not be fabricated within the UK without considerable changes being made to the existing fabrication capability. Overseas commercial suppliers have been identified by vendors as being able to supply fuel for an initial fleet.
- MSR technology requires an entirely different fuel supply chain infrastructure. The ability to produce this type of fuel is not currently available within the UK and a suitable overseas supplier has not been identified. Chlorination of PuO_2 is not an established process for the nuclear industry, with no existing UK capability to undertake this. The production of MSR fuel pellets is likely to require long-term investment in underpinning R&D and significant development of UK infrastructure.

Estimated SMR fuel demands

The annual fuel demand of the individual IPWRs is presented in Appendix I of Vol. 2 (Ref. 3). On review of the supporting information provided by IPWR vendors an annual fuel demand of 32 tU/GWe.yr is considered to be representative. If the initial fuel load is averaged over the plant lifetime then the upper estimate of annual fuel demand increases to 34 tU/GWe.yr. For HTGR technology the annual fuel requirement is estimated to be 11 tU/GWe.yr. MSR technology is estimated to need 9 t of $PuCl_3$ per GWe.yr.

Estimated UK capacity to support IPWRs

As previously discussed, IPWRs are the only technology that can be supported to a reasonable extent by the existing UK fuel production infrastructure. The deployment of non-IPWR technologies would need to be supported by significant infrastructure upgrades and, possibly, new fuel facilities. For this reason only IPWRs are considered when estimating the UK capacity. Two scenarios are considered: Scenario 1 represents the lower estimate of possible fuel demand from IPWRs and large nuclear on the existing UK fuel supply chain. This scenario assumes SMRs are deployed at a rate of 400 MWe/yr from 2030 to 2040 reflecting the construction constraints identified by the System Requirements for Alternative Nuclear Technologies study (Ref. 34) and supported by some vendor responses. Scenario 2 assumes double the deployment of SMRs and that the UK supports a much higher portion of new large nuclear power stations. These scenarios are presented in Table 4-4. Both scenarios assume that SZB is the only existing nuclear power station still operating.

Table 4-4 UK generating capacity scenarios

	Scenario 1 (Lower)	Scenario 2 (Upper)
New SMR (IPWR) Fleet	4.0 GWe at 34 tU/GWe.yr	8.0 GWe at 34 tU/GWe.yr
New Large Nuclear	3.6 GWe at 25 tU/GWe.yr	9.0 GWe at 25 tU/GWe.yr
Existing Large Nuclear (SZB)	25 tU/yr	25 tU/yr

Note: the fuel demands for new large nuclear and SMRs include initial fuel loads.

Figure 4-3 presents a simplified comparison between possible fuel demand for new nuclear and UK infrastructure capacity for both scenarios.

Figure 4-3 2040 fuel capacity and demand comparison

It is apparent that the low estimate (Scenario 1) is well within the UK capacity and new nuclear (including both large power stations and SMRs) would replace the majority of lost fuel demand through the closing of AGR stations. Even the high estimate (Scenario 2) is within the total capacity of the UK fuel production capacity. The actual available capacity will be dependent on the extent to which UUK and SFL export services overseas.

4.3.3.3. Summary of UK nuclear fuel infrastructure

The main findings from the assessment of existing UK fuel infrastructure capability are:

- The deployment of IPWR technology presents a significant opportunity for the UK nuclear fuel supply chain to maintain the level of output currently utilised by existing UK nuclear power stations.

- The ability to produce fuel and fabricate fuel assemblies for HTGRs currently exists overseas, but the UK does not currently have this capability. Therefore, fuel supply is not a significant barrier for initial HTGR deployment, however the UK would not see the economic benefit.
- UUK has the potential, but is currently unable to enrich uranium to 19.5% U-235 as required for HTGRs. Modifications would be required to existing plants or a new purpose built facility required. Amended safety cases and re-licensing of the site might be required for the production, storage, transportation of fuel enriched to 19.5% U-235.
- For MSR technology no fuel manufacturing capabilities are currently available in the UK or overseas. With the intention to utilise existing UK plutonium stockpiles whilst minimising nuclear safety and proliferation risks, Sellafield would be an ideal candidate site for such a technology.

4.3.4. Decommissioning and Waste Management

Any potential SMR vendor within England and Wales must demonstrate that they have considered how the spent fuel and radioactive waste from nuclear operations will be managed throughout the plant life. Ultimately the spent fuel and higher activity radioactive waste[7] will be transferred from sites for disposal, at which point the liability will be transferred. Vendors must be able to demonstrate that the spent fuel and radioactive wastes generated can be safely disposed and that the plant is safe to decommission. The safety of the reactor design is assessed by ONR and the Environment Agency through the GDA and site licensing processes.

This section compares the SMR technologies against the UK expectations for the following topics:

- Spent fuel;
- Waste management;
- Decommissioning.

4.3.4.1. Spent Fuel

This section discusses the spent fuels generated for the different technology types and assesses the likely compatibility with UK disposal infrastructure. The current UK Government strategy for managing spent fuel is to store it securely to allow heat decay to meet disposal limits. When these limits are met, the spent fuel will be repackaged for disposal in a Geological Disposal Facility (GDF), which has not yet been built. Radioactive Waste Management Ltd (RWM) are responsible for delivering the GDF and ensuring the long-term safe disposal of spent fuel and higher activity radioactive waste (Ref. 35).

All spent fuel reprocessing is scheduled to end in the UK by 2018. The January 2008 White Paper on Nuclear Power (Ref. 36) confirmed the UK Government’s intention that new nuclear power stations built in the UK should proceed on the basis that spent fuel will not be reprocessed and that waste management plans should proceed on this basis. The assessment of IPWR technology therefore assumes the direct disposal of spent fuel (i.e. no reprocessing).

The UK Government’s Nuclear Industrial Strategy (Ref. 37) does confirm that “if Generation IV systems become commercially adopted by utilities then reprocessing is likely to be needed in future decades”. On this basis, for the non-IPWR technologies considered in this assessment, the possibilities for reprocessing are presented.

IPWRs

The uranium dioxide fuel for IPWRs is readily comparable to fuel for PWRs currently operating (i.e. SZB) and planned for construction and operation in the UK. Substantial work has been undertaken looking at the technical aspects of Light Water Reactor (LWR) spent fuel disposability. This includes the duration of storage that would be required to allow the fuel to cool sufficiently prior to disposal in the GDF. Assessments to date have indicated a need to store spent fuel for between 70 and 100 years prior to disposal in the GDF. Fuel canisters for IPWR spent fuel could readily be manufactured allowing for both storage and disposal within the existing GDF design.

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[7] Higher activity radioactive waste refers to High Level Waste (HLW), Intermediate Level Waste (ILW) and certain Low Level Wastes (LLW) that cannot be disposed of in the Low Level Waste Repository.

A disadvantage of the IPWR over large nuclear is the greater volume of spent fuel produced per GWe. Based on the planned refuelling strategies and fuel assembly dimensions provided by IPWR vendors, it is estimated that the spent fuel volume per GWe could be greater than large nuclear by a factor of 2 (compared against the UK EPR spent fuel, Ref. 38), as shown in Figure 4-4.

For the use of MOX fuel or thorium based fuel, there is technical confidence in the ability to use existing storage and disposal casks. An area that would benefit from further assessment is the cooling time needed prior to disposal in the GDF, as this period is expected to be longer for MOX fuels than for uranium dioxide fuel.

HTGRs

For HTGRs using TRISO fuel, there has been significantly less UK development work on disposability to date. There are no commercial plans for using this fuel type in the current fleet of new build technologies being considered in the UK, therefore disposability has yet to be formally assessed by RWM.

The ceramic nature of the fuel gives confidence that similar safety arguments can be presented for TRISO fuel disposal as for LWR uranium dioxide fuel. This is due to the shared principle of having a ceramic low leachable fuel providing a first barrier to activity release. It is noteworthy that TRISO pebble bed reactors (thorium fuel and helium cooled) have operated in Germany. Further research should therefore be available to substantiate the fuel disposal solution.

Reprocessing TRISO type fuel is inherently difficult (Ref. 39), with HTGR vendors assuming direct disposal of spent fuel. HTGR vendors have indicated that existing spent fuel transport casks (including a UK licensed design) would be suitable for use. The interim storage arrangements required are still at the concept design phase. To increase the confidence that HTGR spent fuel can be safely managed, future work should focus on demonstrating compatibility and disposal arrangements for the GDF.

An additional challenge facing HTGR fuel is the volume of spent fuel produced per GWe due to the comparatively lower power density. Using vendor fuel usage and fuel element dimensions data it is estimated that the spent fuel volume per GWe could be between 7 and 12 times higher for HTGR fuel than for IPWR fuel.

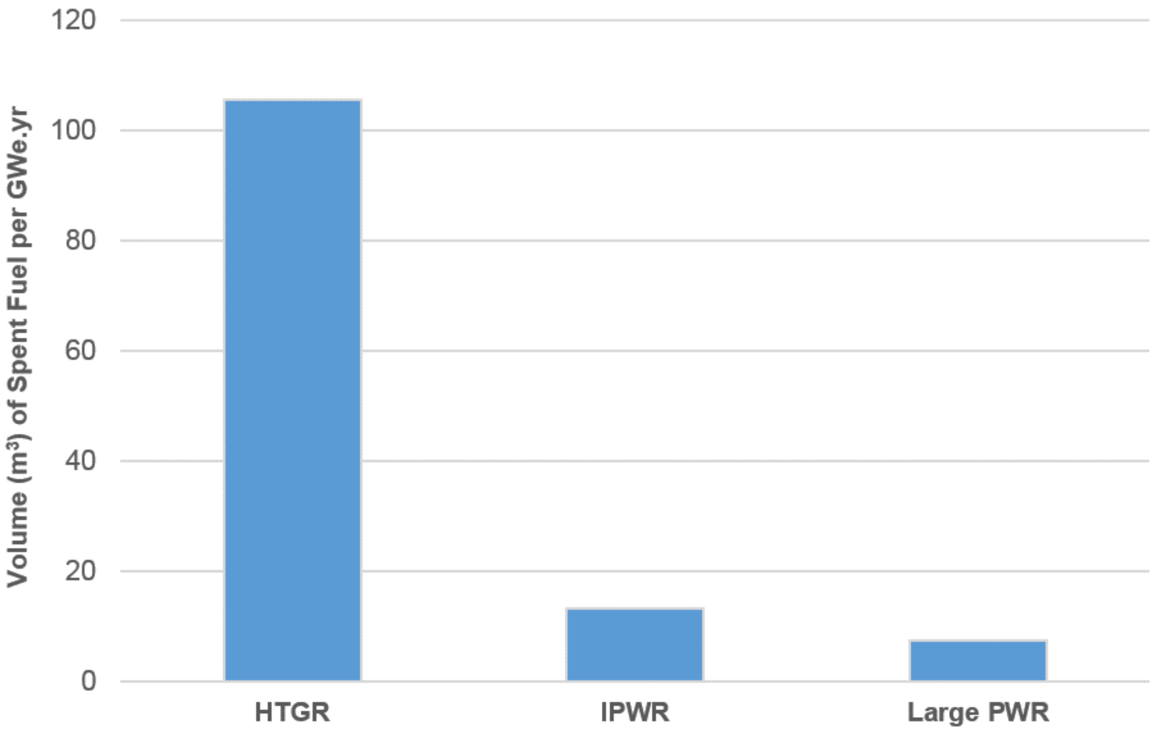


Figure 4-4 Estimated spent fuel volumes

Whilst this is a significant increase, it should be noted that the greater volume per unit heat energy generated means that the average rate of heat dissipation per canister would be lower. This offers the advantage of potentially allowing spent HTGR fuel disposal canisters to be positioned in a more compact arrangement within the GDF. It could also mean that HTGR storage canisters reach the lower levels of heat generation required for disposal sooner than IPWR packages.

Spacing of waste packages within the GDF will depend upon the heat output per unit area the disposal facility can safely accommodate. Using spent fuel data provided by vendors and waste package specification data developed by Nirex (Ref. 40) it is possible to calculate an illustrative GDF space requirement for the different technology types. It is estimated that the area to accommodate spent fuel waste packages, per GWe of deployment, is lower for HTGRs than IPWRs.

For TRISO fuel using fuels other than uranium, such as thorium, there is greater uncertainty. The disposal and long-term stability of thorium oxide fuel is expected to be similar to uranium oxide fuels, however the work to substantiate this has not been undertaken.

MSR

Management of MSR spent fuel presents a greater level of uncertainty than IPWR and HTGR technologies. In fuel disposal safety cases it is the low leachability of oxides that provides the primary barrier to activity migration. Chlorides are soluble and mobile so disposal within a similar disposal cask would have one fewer barrier. This would present a significant challenge to the disposal safety case.

It is noted that if reprocessing of the fuel is undertaken, the mobility of activity from fission products can be managed. However, this leaves an activated chloride waste form requiring disposal as ILW. The choice of chloride as a salt form is therefore challenging from a disposal view, regardless of whether the fuel is reprocessed. It is noted that no commercial reprocessing facilities are currently available. Investment in this infrastructure would be necessary should any disposal case for MSR spent fuel necessitate the reprocessing option.

If MSR spent fuel is not reprocessed then the solubility and mobility of chlorides will challenge the GDF for a number of reasons. The GDF is being developed assuming most waste will be in stainless steel containers.

The storage of bulk chloride increases the risk of corrosion, which could drive a need for alternative storage solutions. More importantly, chlorine (made up of Cl-35 and Cl-37) will activate, with the Cl-35 producing the particularly problematic radionuclide Cl-36. With a 301,000 year half-life, Cl-36 is one of the most significant nuclides for disposal. It is noted that the use of fluoride fuel, which is adopted for alternative MSR concept designs, would improve this position.

If chloride fuel is pursued, the risks associated with Cl-36 can be reduced by constructing a chlorine isotopic segregation facility as part of the supporting fuel infrastructure. This facility would provide pure Cl-37 to minimise the creation of Cl-36.

4.3.4.2. Waste Management

The UK Government's current waste management strategy for England and Wales for higher activity radioactive waste is to store it until a disposal slot is available in the GDF (Ref. 35). It is assumed that operational ILW would be stored and accumulated within secure interim storage facilities over the operational lifetime. The demonstration that operational and decommissioning higher activity wastes are compatible with the GDF is managed by RWM through the Letter of Compliance (LoC) process.

Low Level Waste (LLW) compatibility can be readily assessed using the Waste Acceptance Criteria (Ref. 41) for the Low Level Waste Repository (LLWR). It should be noted that the LLWR is planned for closure before a first SMR plant would be expected to be decommissioned. New infrastructure for LLW disposal would therefore be needed, but this is true for new large nuclear as well. For this reason, the management of LLW is not discussed further within this section.

As SMR designs are developed for implementation in England and Wales, the SMR vendors would need to demonstrate that materials are selected to minimise the quantity of radioactive waste. In particular, UK Regulators expect the creation of particularly problematic radionuclides to be limited over the lifetime of the plant. The assessment undertaken here has concentrated upon the fundamental parts of the design that are unlikely to change. These include:

- Activity abatement systems;
- Moderator;
- Coolant;
- Non-fuel core components.

It is noted that operational and decommissioning waste types and quantities were not provided by vendors in sufficient detail to allow a thorough assessment. However, the following high-level observations are informed by the SMR vendor submissions.

IPWRs

Where Chemical Volume Control System (CVCS) ion exchange resins that are similar to existing wastes are used, then this operational waste is likely to be compatible with disposal in the GDF. There are, however, novel filtration materials and techniques available. One vendor suggests the use of antimony selective ion exchange resin, which would constitute a novel waste. To provide greater confidence that novel resin wastes would not present significant disposal challenges, more details on the proposed resin, its volumes, activities and proposed disposal packaging would need to be considered by RWM or LLWR.

The moderator / coolant and non-fuel core components are not expected to present novel wastes.

HTGRs

The HTGRs use graphite moderators and beryllium oxide reflectors. These waste types are not novel but it is likely that additional substantiation for safe disposal will need to be demonstrated. Historically, graphite impurities have been problematic to RWM, particularly the presence of chlorides leading to Cl-36. The waste types from decommissioning are similar to existing waste types from Magnox reactors and the Winfrith Dragon reactor, so it is unlikely there will be problematic wastes.

MSRs

Waste from the MSR core presents a significant disposal challenge as the presence of bulk fluorides in the GDF will challenge the disposal safety case with respect to package corrosion. Activation of fluorine is low and active fluorine isotopes have very short half-lives, hence it may be possible to convert the fluoride salt into an oxide for disposal, releasing or recovering the fluorine. To reduce the risk of significant issues arising later in the design development, it is recommended that the plan for fluorine disposal and its associated challenges are addressed prior to taking the design forward.

4.3.4.3. Decommissioning

UK Regulators expect design features to be incorporated that will simplify decommissioning and reduce operator doses during this phase. Consideration has been given to the complexity of site decommissioning at the end of operation for each technology.

IPWRs

In general, detailed decommissioning plans have not been provided by the vendors. From the information submitted, it is likely that the decommissioning of the small IPWRs will be similar to decommissioning larger PWRs. The internal heat exchangers could add to the complexity of core internals removal but is considered credible with existing tooling within the UK civil nuclear industry. The materials from the core and primary circuits are acceptable in existing waste types and no orphan wastes are envisaged. Additional relevant operating experience is available from the decommissioning of Naval Nuclear Propulsion Programme (NNPP) reactors.

HTGRs

For HTGRs, similar reactor technologies have been decommissioned worldwide so it is expected to be technically feasible to decommission. However, HTGRs vendors have acknowledged that their designs are not at the stage where any detailed consideration of decommissioning has been given.

MSRs

The key principles expected by UK Regulators and a high level overview of the decommissioning process is recognised within the MSR vendor’s decommissioning plan. However, there is insufficient detail to perform a meaningful assessment on the decommissioning for MSR technology. The coolant removal presents a challenging aspect for the decommissioning of MSR technologies, with heating necessary to maintain fluidity until it is removed and packaged. As noted in Section 4.3.4.2, the disposal of the coolant should be discussed at the earliest opportunity with RWM to understand the compatibility with the GDF. Providing the coolant and fuel can be removed, there is nothing within the design as presented that would be problematic for decommissioning.

4.3.4.4. Impact to UK Waste Management Infrastructure

The impacts to UK infrastructure are summarised by reactor type below:

- IPWRs present the most compatible SMR design with the UK waste management strategy and UK infrastructure. It is unlikely that changes to existing and planned UK waste management infrastructure would be required to support this technology.
- HTGRs using uranium based TRISO fuel do not currently align with the existing waste strategy and infrastructure. However with further development of the fuel disposability case, this could be shown to be compliant with UK regulatory expectations.
- MSRs are likely to require the largest development of UK infrastructure and present the greatest challenge with respect to regulatory compliance. RWM could raise concerns on the quantities of fluoride from the coolant and chloride from the fuel, as these will challenge the disposal safety case.
- The use of thorium based fuel in any of the SMRs would require infrastructure change for spent fuel reprocessing or direct disposal options.

The findings are summarised in Table 4-5:

Table 4-5 Summary of UK waste and decommissioning infrastructure findings

	IPWR	HTGR	MSR

Spent Fuel	Spent fuel well understood from both technical and regulatory aspects due to similarities with SZB.	Long-term disposal of spent fuel requires further research; likely to be compliant but high in volume per MWh by comparison to IPWRs.	The use of chloride fuel salts could present a significant challenge for long-term disposal.
Waste Management	The waste types are well understood and unlikely to present a significant challenge, although the quantities produced are unknown.	UK has experience of managing similar waste types but further work is required to substantiate the long-term disposal.	Managing and storing corrosive waste products could present a complex disposal challenge.
Decommissioning	Decommissioning is not expected to present significant challenges for any of these reactor technologies (provided the waste management challenges are addressed).		

4.3.5. Wider Benefits

Under the Climate Change Act 2008 (Ref. 42) the UK has a commitment to reduce emissions of greenhouse gases, including a reduction in CO_2 emissions. SMRs are capable of decarbonising both electricity and heat production, compared to traditional fossil fuel plants, by offering Combined Heat and Power (CHP). This section aims to understand the wider benefits from SMR deployment beyond electricity generation that have been considered by vendors. It does not attempt to present an economic case for the utilisation of any off-grid applications identified, but simply presents the technical feasibility.

4.3.5.1. Examples of Wider Benefits

Heat generated from SMR plants has the potential to support a number of industrial applications that are dependent on the supply of process heat, including:

- District Heating (DH);
- Desalination;
- Chemical industry applications.

DH refers to the deployment of process heat to provide space heating in urbanised areas. International examples of nuclear power plants being used for DH include the Beznau power station in Switzerland. This is a medium sized twin unit plant capable of producing 1,130 MWth per reactor (Ref. 28) (larger than SMRs), and providing approximately 80 MWth to a local DH network (Ref. 43). The UK already has 1,765 DH networks of varying sizes, as detailed in the Summary Evidence on District Heating Networks in the UK (Ref. 44). These networks utilise heat from a range of sources, however none use heat from nuclear power plants. The System Requirements for Alternative Nuclear Technologies report (Ref. 34) considers SMRs viable for DH deployment provided the distance between heat source and DH network is 30 km or less. On this basis, the System Requirements report confirmed that three quarters of the sites identified as being potentially suitable for SMR deployment were suitable for provision of heat, as they were within 20 km of potential DH networks (Ref. 34).

Desalination refers to the production of potable water from saline water sources. A common method for desalination is distillation, which separates salts and minerals from water through evaporation, by applying heat. Potential markets exist for deploying SMRs for desalination, particularly in arid parts of the world such as parts of Africa, Middle East and Asia where the use of desalination technology is common. Nuclear power plants have been used for desalination, for example the Aktau plant in Kazakhstan. This small 750 MWth plant, provided potable water over 27 years of operation (Ref. 45).

Depending on the temperature of the process heat available, a wide range of chemical industry processes can be supported. These include oil refining, biomass gasification and hydrogen production. No examples of UK nuclear power plants supporting chemical processes are available. Examples of other heat generation technologies supporting chemical process in the UK are available however, for example VPI Immingham (gasfired power station located in Lincolnshire) is one of the largest CHP plants in Europe. The company website (Ref. 46) claims to be capable of supplying 930 tonnes of steam per hour to nearby oil refineries.

4.3.5.2. SMR Off-Grid Applications

Most IPWR vendors do not include process heat design features as part of their reference design configuration or safety case, although they are incorporated into one of the IPWR and HTGR reference designs. In these particular cases, the immediate customer has requested that process heat applications be included in their plant, but in general there are no particular technical or economic reasons why process heat applications would be included in the reference design. The inclusion of these additional applications would be at the request of the end customer, although vendors without CHP designs have stated that the plant could be adapted to include such features, if required. Design adaptions would include alterations to plant control systems and BoP.

For HTGR vendors, CHP design features are generally considered within the reference designs. HTGRs are particularly well suited to CHP applications due to high coolant operating temperatures, facilitating a higher process heat temperature. The same principle applies to MSRs, which operate at similar temperatures.

Most vendors confirmed that 100% of steam could be diverted away from the steam turbine, supplying all thermal power as process heat. This would result in the following process heat temperatures:

- 268°C to 300°C for IPWRs;
- 540°C to 550°C for HTGRs (using gas-steam cooling);
- Approximately 800°C for HTGRs (using gas-gas cooling);
- Approximately 570°C for MSRs (using molten salt-steam cooling).

SMR vendors have also considered a range of CHP applications, with varying reductions in electrical power output in order to draw off steam at different tempeatures between turbine stages for process heat. However, a pro-rata balance between heat and power was broadly assumed using the original (i.e. full electrical power) plant efficiency.

Where mature SMR designs have incorporated CHP applications, the considerations with respect to nuclear safety were limited to preventing radioactivity within the process heat system and little attention has been given to how this application may affect safety classified secondary cooling systems. Radiation monitoring within the process heat system and "insulation blocking" between the secondary cooling loop and the heating loop were identified as protective measures. A more comprehensive assessment and substantiation of the required protective measures against the Regulators' expectations would be needed before commercial deployment.

Vendors that do not currently have CHP applications within their standard design, have not fully considered the nuclear safety case implications. The majority of these vendors have stated that they expect that the impact of the required modifications would be small, or even that they would present no impact at all on the safety case. This assumption will need to be carfully reviewed when applying for a site license application including CHP.

The only other nuclear safety impact identified was the need to consider additional external hazards introduced by locating SMR site close to hazardous facilities (e.g. chemical processing facilities) to utilise process heat. However, these hazards would be considered and addressed via the site-specific external hazards safety assessments.

4.3.5.3. UK SMR Off-Grid Opportunities and Challenges

All vendors confirmed that SMR technology is suitable for the range of wider benefits identified in Section 4.3.5.1, although most have not included these design features within their reference design. The inclusion of process heat applications within a reduced number of SMR reference designs has largely been driven by the requirements of the FOAK customer. However, the extent of consideration of CHP in the potential nuclear safety case is of concern.

Although vendors are confident that the modifications to both the design and the safety case are feasible, a full explanation has not been provided by any vendor as to how this modification will affect the delivery of fundamental safety functions. In some cases, vendors have said that no safety functions are delivered from the conventional side of their plants and therefore, no safety function will be affected by the introduction of process heat. In the UK, it is common that some SSCs of the conventional island are safety classified; failure of those SSCs to perform their functions might affect the control of reactivity fundamental safety function. SMR vendors will need to justify that this is not the case for their designs before ONR will accept that no safety functions will be delivered from the conventional side of the plant. Without this justification, significant complications might arise when adapting the plant for process heat applications. The inclusion of design features that support process heat applications in an initial SMR GDA design submission would promote valuable early engagement with the regulator.

Aside from the challenge to substantiate the CHP applications within the safety case, the greatest technological barrier to utilising CHP is likely to be implementing DH networks. Ultimately, deployment of SMRs for CHP purposes would have to be considered on a site by site basis with the decision to be made by the operating utility based on the site specific business case.

4.3.6. Analysis of UK Supply Chain Readiness

4.3.6.1. Overview

An analysis of the UK supply chain readiness has been performed to support SMR technology based on in-depth knowledge of the nuclear industry and data provided by SMR vendors. Engagement directly with equipment manufacturers has not been sought as the type of equipment required is SMR technology specific.

The deployment of an SMR fleet in the UK has the potential to create economic growth supported by a diverse supply chain encompassing R&D, engineering, construction, manufacturing and other support industries including training and education.

The economic analysis detailed in Section 5.4 of this report indicates that successful deployment of SMRs, supported by a robust UK supply chain could contribute a Gross Value Added (GVA) of £20bn (over 2017 to 2040), with average employment of 9,700 jobs and tax revenues of £7 billion to the Exchequer.

There are a number of barriers to be overcome if the potential for the UK supply chain is to be realised including:

- Confidence in long-term commitment to nuclear power;
- Visibility of future volume of work in the nuclear sector;
- Development of international partnerships with overseas suppliers;
- Cost of equipment qualification for use in nuclear;
- Export control constraints;
- Export financing.

In order to maximise realisation of the opportunities presented for the UK supply chain, it is essential that the supply chain is correctly positioned with the right capability and capacity to service SMR deployment. This will require investment in a number of areas including:

- **R&D:** Depending on the SMR technology, and stage of development, there could be significant R&D opportunities. IPWR technology is based on proven technology and is much closer to market and therefore R&D is limited compared to less well developed technologies. To maximise opportunities to become involved in emerging technologies, investment will be needed in R&D facilities and development of the necessary knowledge and skills required through research institutions and academia. The Nuclear Advanced Manufacturing Research Centre (NAMRC) has been established to support nuclear R&D and further investment is likely to be needed in R&D for emerging technologies.
- **Engineering design**: Whilst the UK has considerable expertise in nuclear engineering design, further resources may be needed to support a large deployment programme. Depending on the rate of deployment, skill gaps may emerge in specialist nuclear engineering disciplines.
- **SMR manufacturing facilities**: Manufacturing facilities exist in UK for submarine nuclear reactors which could potentially manufacture SMRs. Alternatively, new facilities will need to be developed. A

significant order book will be needed to make the investment in existing or new facilities economically viable. This is discussed further in Section 4.3.6.3.

- **Nuclear qualification of equipment:** This is a barrier for market entry and significant investment is required to achieve qualification. Suppliers will need a significant worldwide market opportunity to make the investment viable. The Fit for Nuclear (F4N) initiative by NAMRC, in conjunction with Areva and EDF Energy, is supporting UK companies to achieve the necessary standards for nuclear qualification.
- **IP:** Development of IP either independently or in collaboration with SMR vendors. It should be noted that IP opportunities in design and manufacturing relating to those technologies closest to deployment are less than those technologies that are not so well developed (see Section 4.2.5).
- **Advanced manufacturing:** The High Value Manufacturing Catapult (HVM Catapult), which includes NAMRC and is backed by government, is supporting UK manufacturers to develop manufacturing innovation and capability to support the nuclear industry. Advanced manufacturing includes welding, machining, metrology and inspection and can be applied to many components including the SMR reactor vessel.
- **Fuel:** Fuel manufacturing facilities exist in UK for servicing the existing nuclear fleet and it is likely they can manufacture fuel assemblies for IPWRs. However, additional facilities will be required for new and innovative fuels for non-IPWR technologies such as HTGR and MSR.
- **Partnerships:** Exploring potential partnerships with overseas manufacturers to invest in UK may require government intervention and incentives such as grants or government to government agreements.

4.3.6.2. Vendor Assessment of UK Supply Chain Opportunities

In order to assess the potential opportunities for the UK supply chain to support the development and deployment of SMR technology, vendors were invited to provide details of the proportion of Overnight Capital Cost (OCC) and operating and maintenance costs that could be provided by the UK supply chain. This was requested for SMRs deployed in the UK, and the corresponding proportion for SMRs deployed overseas. The vendors' responses are generic and do not relate to a particular country of overseas deployment. Export control restrictions will prevent deployment of nuclear technology in certain countries and as such it has to be assumed that any export potential is to countries where export control constraints will not be a barrier to deployment.

The vendor responses were variable and reflected the individual vendor's manufacturing base and country of origin. For example, some vendors have extensive manufacturing facilities in their home countries and indicated that a relatively small proportion of the reactor would be manufactured in the UK, but they also highlighted the potential for the UK supply chain to grow that proportion over time. Some of the vendors were overly optimistic and in some instances not credible. For example, vendors indicated that the fuel could be 100% provided by the UK supply chain, but the UK does not mine uranium therefore 100% of the fuel cycle cannot be provided by the UK. An informed view of the vendors' responses, based on existing knowledge of the nuclear industry, has been taken to arrive at the potential opportunity for the UK supply chain to support SMRs.

Vendor responses indicate that between 68% and 89% of the cost associated with UK deployment of IPWR technology could be supported by the UK supply chain. Taking into account vendor optimism regarding cost elements such as fuel, steel and large switchgear, it was calculated that around 55% can realistically be supported by the UK supply chain at present. However, this could increase to around 70% with Government supported initiatives such as HVM Catapult, Cogent, Nuclear Skills Strategy Group (NSSG), the National Skills Academy for Nuclear (NSAN), the National Skills Academy for Nuclear Manufacturing (NSAN-M) and implementation of the Nuclear Supply Chain Action Plan (SCAP) (Ref. 47).

This compares to the Atkins-Oxford Economics report (Ref. 48) which assessed that the UK supply chain could support between 44% and 63% for large nuclear, with the higher percentage only being achievable through a number of interventions, including the SCAP. The greater potential for UK supply chain to support SMR deployment is largely due to the size of components being more aligned with UK capability. For example, the size of heavy forgings required can be produced in UK, unlike the heavy forgings for large nuclear, and the size of the turbines required.

Assessment of the potential for UK supply chain involvement in emerging technologies such as HTGRs and MSRs is extremely difficult as there is not enough information to form an opinion. For example, it is known that MSRs will operate at a much lower pressure than LWRs, and that it is feasible that reactor vessels could be manufactured in the UK. However, the infrastructure requirements for MSR fuel manufacturing and waste disposal are not well defined at this time (discussed in Sections 4.3.3 and 4.3.4).

4.3.6.3. UK Supply Chain Capability and Capacity

The Nuclear SCAP developed by the Government (Ref. 47), in partnership with industry, sets out the strategy for delivering the Government's vision of the UK nuclear industry becoming a global leader. Whilst the Nuclear SCAP focused on large nuclear, the successful deployment of an SMR fleet in the UK has the potential to deliver the strategy in terms of economic growth, job creation, and to leverage UK expertise to create export opportunities.

The report included 30 actions required to position the UK nuclear supply chain to maximise its potential and deliver the Government's vision of the UK becoming a world leader in nuclear.

The SCAP identified that setbacks in delivery of the nuclear new build programme has damaged confidence in the viability of investing in developing capability to support the nuclear industry. The capability and capacity of the UK supply chain needs to be built up to support nuclear new build, including SMRs, and position itself to maximise export potential. This will only be achieved through creating the right environment for the supply chain to invest.

The key elements of the supply chain are explored in further detail below.

Research and Development

The report 'A Review of the Civil Nuclear R&D Landscape in the UK' published by Government (Ref. 49) concluded that whilst the UK R&D community is engaged internationally, the institutional and funding landscape for nuclear R&D is lagging behind changes in nuclear policy and needs to be reshaped as part of evolving nuclear policy. The report also concluded that R&D capability is smaller than in the past and attention needs to be focused on areas where gaps exist, such as advanced fuel cycles and future reactor systems. SMRs clearly fall into the area of future reactor systems. However, IPWRs are based on well proven technology and the opportunities for R&D and nuclear engineering input are limited compared to less well developed SMR technologies. The opportunities for R&D will also be dependent on the vendor's stage of design development.

Engineering Design

The majority of the engineering design activities required to develop the design for GDA readiness will be completed by the vendor, and in the case of those designs closest to market, much of this work has already been done. Opportunities exist for UK engineering organisations to support the vendor design teams to develop their designs to be ready for UK GDA including:

- Conversion of US vendors design from 60 Hz to 50 Hz;
- Potential need for a revised instrumentation and control design based on previous GDA experience;
- Software and smart instruments considerations;
- Civils design (site specific);
- Seismic assessments;
- Grid Code compliance (discussed in Section 4.3.2).

GDA and Site Licensing Support

The majority of vendors who responded have no experience of the UK regulatory process. There is a major opportunity for UK nuclear engineering companies to support a vendor during the GDA process and site licensing process.

Civil Works and Buildings

The UK construction supply chain is well established, skills gaps are however emerging in some trades. The Construction Industry Training Board (CITB) has identified skills gaps across the entire construction industry, and in particular carpenters, steel fixers, steel erectors, pipefitters, welders and scaffolders. Skills shortages impact on schedule and cost, and a recent study by Build UK highlighted that around 50% of construction companies are operating at 90% capacity due to skills shortages. Large infrastructure projects currently under way and in the pipeline (for example Crossrail, HS2, and large nuclear new build) will drive an increase in construction skills. This expectation is supported by the National Infrastructure Plan for Skills (Ref. 50) which estimates that an additional 100,000 resources need to be trained by 2020, and 250,000 workers will need to retrain / upskill over the next decade.

Reactor Plant and Equipment

One of the key benefits of SMRs compared with large nuclear is the ability to manufacture units in a factory environment and ship them to site for module assembly. This eliminates the need for high quality fabrication in the field which reduces site construction time, cost and risk. The HVM Catapult and the NSAN-M are working with the UK supply chain to develop advanced manufacturing skills that will be needed to support SMR manufacturing. NAMRC has also recently announced that it is working with an SMR vendor to identify the most cost effective way of manufacturing the SMR reactor pressure vessel. Further information provided by NAMRC on the role of advanced manufacturing techniques with respect to SMR deployment, is presented in the Projects 5-7 report.

The existing UK submarine reactor manufacturing facility could possibly be utilised to manufacture SMRs, or alternatively a new factory would be required to be built. Both the existing and new facilities would require a significant order book to make investment by the manufacturer viable. The size of order book required will depend on whether the manufacturer has existing facilities or requires new facilities. For example, the existing submarine reactor manufacturing facilities currently have spare capacity and would require less investment.

An IPWR has a number of components such as heavy forgings, steam generator, control rod drive mechanisms and primary cooling pumps that can be manufactured in other facilities and shipped to the reactor manufacturing plant for assembly as part of the reactor. The UK supply chain, with the support of HVM Catapult and NSAN-M, is well positioned to manufacture SMR components but would need investment to achieve nuclear qualification.

Turbine Generator Plant and Equipment

It is generally recognised that the current UK supply chain is largely unable to support large nuclear in this area. It is envisaged that SMRs will need smaller turbines and that this may open up the market for UK suppliers. UK suppliers have not been approached at this stage as sufficient detail regarding the size of turbines required is not available, but it is believed that there might be suppliers in the UK that would have the capability to manufacture turbines of the size that would be needed for an SMR. The main barrier is qualification of equipment for nuclear applications and vendors would need a significant order book to make supplier investment in qualification viable.

Electrical Equipment

The market for large electrical equipment such as high voltage switchgear and transformers is dominated by overseas manufacturers. However, this accounts for less than 10% of the total cost of an SMR. The UK demand for large switchgear and transformers is unlikely to be large enough to encourage a supplier to manufacture these in the UK. Smaller electrical equipment can be supplied by the UK supply chain but again nuclear qualification is a barrier.

Cooling Water and Heat Rejection

The cooling water and heat rejection plant and systems can be supplied by the UK supply chain although, again, qualification will be required if the systems are classified as nuclear.

BoP and Other Systems

BoP includes all other equipment and systems needed for a functional power station. The vendors believe that up to 90% can be provided by the UK supply chain.

Special Materials

This element of the supply chain includes coolants, lubricants, and moderator and is vendor and technology specific. The vendors' responses indicate that as much as 90% of this could be supplied by the UK supply chain, although this is less certain in the case of non-IPWR technologies.

Project Management and Construction Supervision

The UK has a strong track record in project managing and delivering major projects. Skills currently being deployed to support large nuclear are transferrable to SMR but capacity needs to be increased to accommodate growth in nuclear deployment. The Cogent Renaissance Nuclear Skills report (Ref. 51) highlights that Project Management skills are most at risk. The increase required will depend on rate of deployment and any overlap with large nuclear plants currently planned for deployment.

Fuel

The ability of the UK supply chain to support the fuel cycle is dependent on the vendor, technology and type of fuel. As discussed in Section 4.3.3, the UK is well positioned to support fuel enrichment and manufacture for IPWR fuel. However, investment in new facilities will be required to accommodate fuels requiring higher enrichment and innovative fuel designs.

Operations and Maintenance

The UK's experience in nuclear Operations and Maintenance (O&M) is focused on the existing civil nuclear fleet operated by EDF Energy, and the defence nuclear facilities at Faslane and Devonport. The existing supply chains at the existing sites are mature and highly experienced in nuclear work.

As the existing civil nuclear plants come to the end of their operational life, experienced resources will become available. However, many of the existing operators are nearing retirement. The Cogent Renaissance Nuclear Skills Series report estimates that 1,000 operators will be required per year to cope with replacement demand and new demand. Investment in training and attracting staff into the nuclear industry will be needed to develop nuclear skills to bridge the gap. The Cogent Renaissance Nuclear Skills Series report sets out recommendations for training and development of the required skills with the help of the Nuclear Energy Skills Alliance (NESA).

Waste Management and Decommissioning

The UK has considerable experience in nuclear waste management and decommissioning. As discussed in Section 4.3.4, the existing waste management infrastructure should be capable of handling waste from IPWRs. It is less certain what level of investment in infrastructure may be needed for management of other used fuels and waste.

4.4. SMRs in the UK Regulatory System

This section describes the challenges that SMRs could potentially face within the context of the UK regulatory system. An assessment of the alignment with the UK regulator's expectations is performed for the technology groups. Following this assessment, the report presents potential challenges during GDA and site licensing, due to new regulatory situations and SMR specific design features. Finally, there is a description of the international efforts being made to harmonise the international licensing of SMRs.

4.4.1. Alignment with UK Regulators' Expectations

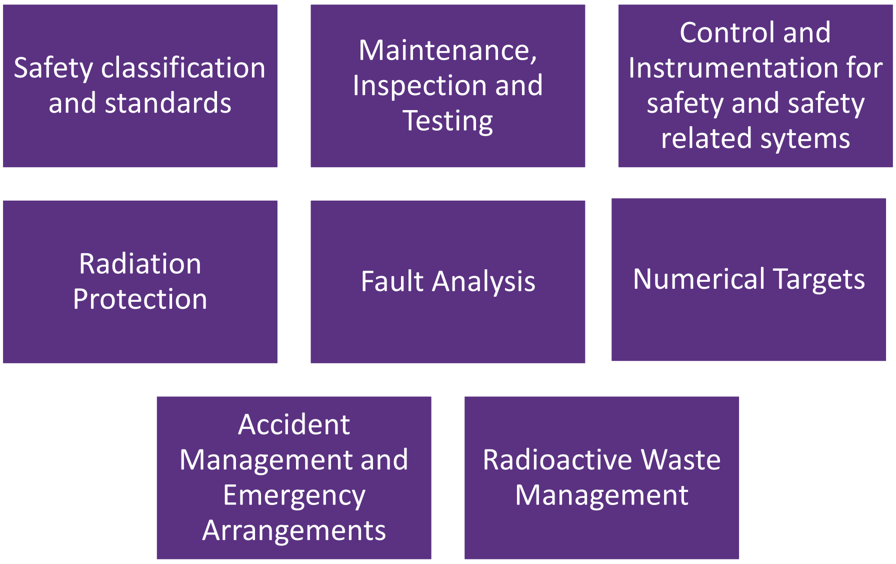
This section discusses the extent to which the design development of different SMR technologies is taking into account the expectations of ONR and the Environment Agency / Natural Resources Wales (NRW). Experience in the UK shows that considering all aspects that affect safety and environmental impact early in the design has a clear and tangible impact on the ease of licensing and permitting. Trying to retro-fit such considerations later in the development cycle, or in response to UK regulator assessment, is likely to result in costly and time consuming design changes.

The purpose of this section is not to conduct a 'pre-GDA', but to assess where the different technologies are currently positioned in terms of understanding and meeting UK regulatory expectations. This has been done for a selection of technical topics covered in the UK SAPs and REPs (Ref's 5 and 6) as explained in Section 4.4.1.1 below. The assessment is based on the responses provided by the vendors regarding the design, operation and maintenance of their reactors.

4.4.1.1. Methodology

This project has assessed design alignment with UK regulatory expectations using information obtained from the vendors in the following selected assessment areas.

Figure 4-5 UK ONR SAP and Environment Agency REPs topics covered in assessment



The vendor data was assessed through production of UK regulatory context scorecards (see Appendix F of Vol. 2, Ref. 3). Once compiled, the individual vendor scorecards were grouped by reactor type and a single SMR scorecard was produced for IPWR, HTGR and MSR technologies.

This group scorecard provides an indication of the current status of UK regulatory alignment for the three reactor groups based on vendor information that is common across the grouped vendors. However, any significant examples of potential non-compliance or compliance for individual vendors has also been included. The group assessment is more beneficial for comparing current and innovative technologies and has been used as the basis for analysis in this report.

The scorecards produced assessed the eight selected assessment areas (Figure 4-5) against five assessment categories as follows:

1. Data completeness;
2. Data accuracy;
3. Data reliability;
4. Alignment with ONR's SAPs (Ref. 5);
5. Alignment with the REPs (Ref. 6).

It is noted that the SAPs and REPs provide guidance to Regulators to facilitate consistent assessment and are not strictly guidance for licence applicants or permit holders, nor regulatory requirements against which compliance must be demonstrated. However, they can be used in the context of this assessment to give an indication of alignment with UK regulations.

The scorecard assessment system assigned a Red-Amber-Green (RAG) status to each of the criteria described above (see Appendix F of Vol. 2, Ref. 3). Justification statements have been provided for each RAG assigned in these scorecards. The criteria for assigning a RAG status for each category are given in Table 4-6 below. It is apparent from the definitions that the scorecard is not seeking to assess or compare how "safe" the different technologies are.

Table 4-6 RAG scorecard definition

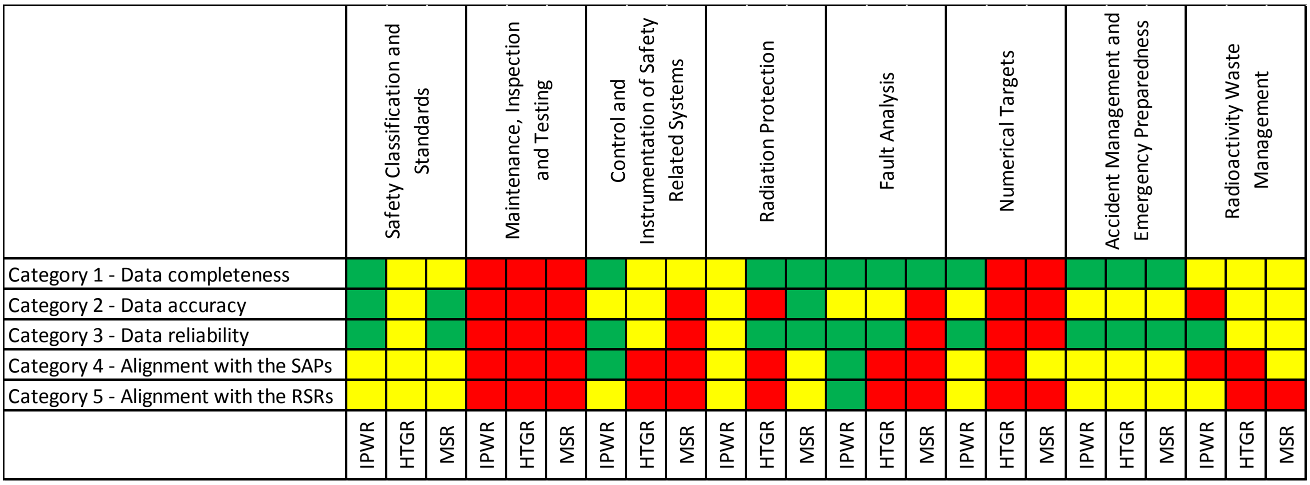
	RED	AMBER	GREEN
Category 1 – Data completeness	Vendor has not answered the questions in this technical area.	Vendor has answered the questions in this technical area to some extent but not completely.	Vendor has answered the questions in this technical area.
Category 2 – Data accuracy	Vendor does not address the questions in its responses for this technical area.	Vendor does address the questions in its responses to some extent but not completely.	Vendor addresses the questions in its responses.
Category 3 – Data reliability	The data provided is believed to have a significant level of uncertainty associated with it.	The data provided has a level of uncertainty associated with it.	The data provided is considered to be appropriately supported by suitable sources.
Category 4 – Alignment with the SAPs	There are examples of misalignments with the SAPs in the design details provided.	There are some examples of potential misalignments with the SAPs.	The design details provided imply that the design is mostly aligned with the SAPs.
Category 5 – Alignment with REPs	There are examples of misalignments with the REPs in the design details provided.	There are some examples of potential misalignments with the REPs.	The design details provided imply that the design is mostly aligned with the REPs.

The information has been assessed by focusing on SMR and UK specific potential risks, challenges, benefits and opportunities.

4.4.1.2. Licensing and permitting assessment

The grouped licensing scorecard described in Section 4.4.1.1 is shown in Figure 4-6. For a more detailed explanation of the assessment performed and how the RAG statuses have been assigned, see Appendix G of Vol. 2 (Ref. 3). It is important to understand that Red or Amber statuses do not imply that the design is unsafe or would not gain regulatory approval. A scorecard of Green's would not be expected in advance of starting a GDA process. At this stage in the design development the RAG statuses are indicative only of the level of effort required to overcome licensing challenges and substantiate the design.

Figure 4-6 Licensing scorecard



Based on the scorecard, the following conclusions can be drawn:

- IPWR technology is better aligned with the expectations of UK Regulators than the other technologies. This is because IPWR technology is based on well understood principles and proven concepts. There is also significant operating experience on the regulation of LWR technology in the UK that is available to designers.
- Whereas some areas of UK regulations are well understood by non-IPWR vendors, the lack of design maturity in many technical areas makes it difficult to understand how UK regulatory expectations would be met.
- The lack of maturity of technologies other than IPWRs (see Section 4.2.3) exerts strong influence in the assessment of likely time to reach a 'GDA–ready' design.
- It is a UK regulatory expectation that requirements for maintenance, inspection and in-service testing (including the procedures and frequencies) must be identified in the nuclear safety and environmental case. SMR vendors as a whole have demonstrated limited consideration of these activities within their designs so far. This might create problems in the UK given the novelty of all designs (including IPWRs) with respect to this criterion.
- It is not clear how integral concepts will allow for testing, maintaining, monitoring and inspecting integral components in service or at intervals throughout their life, commensurate with the reliability of each item.
- With the exception of some IPWR vendors, little consideration has been given to the design of Control and Instrumentation (C&I) systems.
- Some IPWR vendors have performed a Probabilistic Safety Assessment (PSA) in line with UK expectations. Therefore, there is an estimate of the risk profile of these plants that could be assessed against the numerical targets in the UK SAPs. The risk profile of other technologies is mostly unknown.
- Limited engineering substantiation has been provided to demonstrate how passive systems will deliver safety functions. Operational principles based on passive concepts (e.g. natural circulation of the primary circuit coolant) are expected to be the subject of deep scrutiny by the UK regulator.
- Fuel materials and designs not previously used in the UK will generate novel wastes that will need to be disposed of. Waste routes need to be in place at the time of GDA submission. There is no evidence of disposability assessments having been performed for many reactors.
- Vendors outside the UK might not be familiar with the interpretation that the UK applies to the As Low As Reasonably Practicable (ALARP) and Best Available Techniques (BAT) principles. They have focused their design in meeting local regulatory targets which might create difficulties during the GDA (similar to the challenges already experienced by international large nuclear reactor vendors in the UK).

At the time that ONR and the Environment Agency are formally asked to perform a GDA of the proposed nuclear power station design, the applicant is expected to provide sufficient safety and security documentation to enable ONR to undertake at least a Step 2 assessment (Ref. 52). This documentation should include:

- A statement of the design philosophy and a description of the conceptual design sufficient to allow identification of the main nuclear safety claims. This includes identification of hazards, control measures and protection systems.
- A description of the process being adopted to demonstrate compliance with the legal duty in the UK to ensure risks to workers and the public are ALARP.
- Details of the safety principles and criteria applied by the requesting party and how they are likely to be achieved by the design.
- An overview of the approach, scope, criteria and output of the probabilistic and deterministic safety analyses.
- References to standards and design codes used with justification of their applicability.
- Details of the safety case development process.
- Sufficient detail for ONR to satisfy itself that the SAPs (Ref. 5) are likely to be satisfied.

During the GDA, the Environment Agency will consider the quantity and dose implications of discharges (both radioactive and non-radioactive), radioactive wastes arising and the disposability of such wastes, the strength of the BAT case as well as conventional environmental impacts such as water use. At the time of applying for a GDA slot, the applicant is expected to provide reassurance that adequate consideration has been given to the characterisation and disposability of any radioactive wastes that will be produced by the power station.

Taking the GDA Step 2 requirements above and the findings in the licensing scorecard (Figure 4-6) into account, when considering the likelihood of achieving a GDA-ready design in the next five years, SMRs can be divided into two groups.

- **Group 1: SMRs based on proven concepts.** This group includes those SMRs based on LWR technology (i.e. IPWRs). With the current state of these reactors, efforts are mostly dedicated to testing and licensing / certification with little R&D still to be completed. However, there is still significant work to be done to demonstrate how some of the novel concepts introduced in the design would meet the expectations in the UK regulatory system. Examples of this are thermo-hydraulics of natural circulation, the interaction between natural circulation and reactivity control and the integral design concept.
- **Group 2: SMRs based on emerging concepts.** This group includes SMRs that require a significant amount of fundamental R&D in order to understand many of the identified and unresolved challenges. Areas where extensive R&D is still needed include materials selection, disposability studies for novel fuels, ageing of concrete in below-grade concepts or passive systems.

For reactors in Group 1, it is credible that they will be able to produce the documentation for the UK Regulators to undertake a GDA within the next five years.

It is unlikely that SMR designs where a significant amount of R&D is still required (i.e. Group 2), will be able to put together the safety and security documentation expected by ONR and the Environment Agency to apply for GDA in the next five years. For reactors in Group 2 that benefit from significant operating experience (e.g. HTGRs), the expectation is that it will take between 10 and 15 years to produce the safety and security documentation that would allow them to progress beyond GDA Step 2 (i.e. describe the claims being made as part of the safety and environmental case). For reactors with little or no operational experience (e.g. fast spectrum MSRs), putting in place a preliminary safety report that will include sufficient information for GDA Step 2 assessment is likely to take more than 20 years.

It is important to note that SMR plants will also need to be compliant with the requirements for security at nuclear premises. These are laid down in the Nuclear Industries Security Regulations 2003, as amended. At the moment, it is unclear what the volume of deployment in the UK could be. Furthermore, the operational regimes of a utility running several SMR plants in the country are also unknown. However, it is important to note that the economic impact of security on a dispersed number of small plants has the potential to be considerably greater than the impact of a small number of large plants.

4.4.2. SMRs in the UK Licensing Process

In the UK, the licensing of nuclear power plants is a two-phase process. The first phase, GDA, involves the assessment of potential new nuclear reactor designs on a generic (i.e. non-site specific) basis. The second phase involves seeking a nuclear site licence and environmental permit to construct and operate a reactor, based on the GDA design, but at a specific site. The specific characteristics of the site may require small changes to the generic design assessed in the GDA.

During GDA, ONR will conduct a security assessment alongside the safety assessment, with a focus on understanding the areas of the installation that require protection and the measures and security infrastructure that would be implemented should the facility be built. If the generic reactor design is accepted by Regulators, ONR would require all the security arrangements to be incorporated into the licensee's site specific security plan. This plan will need to be approved before construction commences.

It is important to note that while the site licence applicant is the UK licensee (i.e. the prospective site operator), the requesting party for GDA is normally the technology vendor or an operator / vendor partnership. Early identification of the operator, which could be a private company or public sector body, is essential to ensure that potential licensing issues identified in this section would be addressed.

The discussions in Sections 4.4.2.1 to 4.4.2.3 are based on the evidence presented by vendors, as well as the consultations held with both ONR and the Environment Agency during the course of this project. The purpose of these regulator consultations was to discuss specific features of the SMR designs, and the level of substantiation and justification that would be required to accept these in the context of the UK regulatory framework.

4.4.2.1. Generic Design Assessment

The GDA is a joint assessment undertaken by ONR and the Environment Agency (which can act on behalf of NRW). ONR will perform a detailed safety and security assessment of a design, based on a submission made by the requesting party. The Environment Agency assesses radiological discharges and disposal. At the end of each of the four GDA Steps, the Regulators will issue summary reports documenting their findings along with a number of supporting technical assessment reports. If the design is judged to be acceptable, ONR will issue a Design Assessment Confirmation (DAC) and the Environment Agency will issue a Statement of Design Acceptability (SoDA). It is important to note that, although significant advantages have been identified in going through GDA for any reactor intended to be built in the UK, the GDA is not mandatory.

When a design is given a DAC by ONR it means that, based on the submitted information, the generic design is capable of being built and operated in the UK, on a site bounded by the generic site envelope in a way that is safe and secure. GDA does not replace the licensing process but will make a significant contribution to ONR's assessment of the licence applicant's safety case. A DAC does not guarantee that a site licence will be granted.

The SoDA is guidance to the requesting party that the Environment Agency gives strong indication that a site-specific proposal based on the design will receive the necessary environmental permits in the future, however it does not guarantee it.

The time and cost necessary to complete a GDA depends on two main factors:

1. The ability of the applicant to gather sufficient evidence, from R&D work, to demonstrate that all aspects of the design that affect safety and security will meet regulatory requirements.
2. The Regulators' in-house knowledge of the design and resource availability. Should this not be adequate, specialist contractors will need to be used. This might not be easy for some disciplines and it will introduce increased overheads for the Regulators to comply with their obligations.

Before evaluating timescales and costs in a quantitative way, it is important to note that ONR has made clear its expectations regarding SMRs in a note to the Energy and Climate Change Committee on small nuclear (Ref. 53). The following important observations were provided by ONR:

- Anyone wishing to build and operate a nuclear reactor of any scale in the UK would be subject to the same safety standards. The law requires risks to be reduced So Far As Is Reasonably Practicable (SFAIRP), whether from a small or a large reactor;
- A safety case for a small reactor will not necessarily be simpler than for a large reactor. ONR would anticipate that taking a small reactor of novel design through a GDA process would take a similar time to that taken to assess an evolutionary design of a large reactor;

- Whilst expertise in this field is scarcer, it is assumed to be possible to adequately assess a new design within six years from the point of first request.

GDA costs

Vendors have indicated that costs incurred to generate a design that is ready for regulatory review by their local regulators range from $150 million to $500 million (see Section 4.2.4.1). This range is based on data from the vendors that are close to, or have reached this stage in development and corresponds to IPWR technology only. Expenditure by developers of non-IPWR technology is significantly less than this to date. Given the novelty of non-IPWR designs when compared to LWR technology, it is reasonable to assume that progressing those designs to the point where they will be ready for regulatory assessment, is likely to be higher than for IPWRs.

The Leigh Fischer report (Ref. 59) estimates that, for large nuclear, GDA has a central cost estimate of £362 million. The ONR has stated that the cost of the GDA for the regulator has been in the region of £35 million (Ref. 54), and that this cost has been charged back to the requesting parties in full. The cost estimate made by Leigh Fisher is broader than just the regulator fees, with the additional costs falling into the following three main categories:

- Preparation of GDA safety and security documentation by the requesting party;
- Requesting party personnel and administration costs incurred by interacting and responding to regulatory queries during the GDA;
- Design modifications made to the plant by the requesting party as a result of the regulatory review.

A limited amount of vendors have provided an estimate of their provisions for GDA, without providing a full breakdown of how those funds will be spent. Based on the information available, it can be inferred that vendors have made the following provisions for GDA:

- $10 million to $23 million (£7 million to £15 million) to adapt the existing body of the work developed for the local regulator to be ready for a GDA submission, or to prepare a new submission from scratch for the UK;
- $93 million to $200 million (£60 million to £130 million) to go through GDA. It is assumed that this will cover the regulator’s fees and also personnel and administration costs incurred by interacting and responding to regulatory queries during the GDA.

In addition to the expenditures above, it is anticipated that vendors will need to set funds aside to address design modifications as a result of the regulatory review of the design. Based on the experience of the design companies that either have gone, or are currently going through GDA, these costs can be estimated to be in the vicinity of $250 million (£160 million). However, at the moment this figure is highly speculative.

GDA timescales

EDF-Areva’s 1.6 GWe UK EPR is the only third-generation reactor to have completed the GDA process. The process took five years and was closed with more than 700 Assessment Findings that will need to be resolved by any licensee who adopts the design for construction. Whereas some aspects of the UK EPR design with respect to safety are innovative (e.g. the core catcher), the reactor is generally based on LWR technology that is well understood by the UK regulator. There is also significant operating experience available for this technology in terms of operations and waste production and management.

In the case of UK ABWR, the GDA was launched in January 2013. The expectation is that design acceptance will be granted in December 2017, subject to timely and quality submissions by Hitachi-GE.

It is assumed in this TEA that, at the time of first request, an SMR design will be sufficiently developed such that the documentation needed to complete a GDA Step two assessment will be available, regardless of technology type. With this in mind, it is estimated that completing the GDA for an SMR will take no less time than for large reactors. For revolutionary designs it could take considerably longer. The basis for this estimate is:

- SMRs would be expected to meet the same safety standards as current designs with larger MWe capacity.
- There is limited world-wide operational experience with small reactors.

- In order to make up for the lack of operating experience, it is likely that the regulator will request additional analytical and experimental work to demonstrate the safety and security of novel designs.
- Limited operational experience means that there is likely to be only a limited amount of international expertise available to be called upon.
- Regulatory resources are finite meaning that SMR GDA applicants would need to compete for regulatory resources. In 2016 there are two GDAs for large nuclear in progress, although both could be completed in 2017.

4.4.2.2. Potential GDA challenges

The SAPs (Ref. 5) are not reactor or technology-specific. Instead they are flexible to allow assessment of SMR or any other technology. ONR has confirmed that, at present, there is no intention to change the SAPs or the site licence conditions to accommodate a particular technology in any way. Similarly, the environmental permitting regime was overhauled in 2010 with a new regulatory framework, and amended further since, so there is no expectation of change to the Environment Agency's expectations for permit holders in the near future. However, SMRs will present UK Regulators with certain regulatory scenarios that have never been contemplated before, regardless of the type of technology. The following potential challenges to SMR progression through GDA are identified:

Challenge 1 – Single module vs multiple modules GDA

Some vendors offer a standard plant consisting of multiple modules. This introduces a new situation for GDA where a plant contains several reactor modules within a single reactor building. This is different from the concept for planned large nuclear new build of a multi-unit site, where two or more large reactors are housed in separate reactor buildings, but are co-located on the same site. For example, the GDA submission for UK EPR was for a single unit, with the Hinkley Point C site licensing process then substantiating the co-location of two units on a single site. Where vendors present multiple reactor units in a single building, with the possibility of varying the number of reactor modules and deploying them incrementally, this poses a challenge on what scope should be assessed in the GDA process.

The advantages and disadvantages of submitting either a multi-module plant or a single module for GDA need to be considered. This is expected to have implications not only during the GDA itself, but also for a future licensee applying for a site licence and permit based on an SMR technology with a DAC and SoDA for a specific scope. Depending on what the DAC applies to (the single module or a multi-module plant), the difficulties to obtain the site licence and permit could be more or less onerous.

Vendors mostly report that individual modules do not share safety-related systems. This will need to be assessed by the regulator during GDA. Regardless of this, in some cases, multiple modules are expected to be installed within common civil structures, share non-safety related systems, and be operated from the same control room. This has implications in terms of operational modes, exposure to combined hazards, accident management, human factors and more.

As stated earlier, the SoDA that is granted at the end of GDA states that the Environment Agency believes the site permit applicant is likely to obtain the environmental permits necessary to build and operate the plant for that design. A SoDA granted for an individual module might not provide the same indication that environmental permits can be obtained for a plant consisting of multiple individual modules.

Challenge 2 – Lack of operating experience

The lack of operating experience makes it likely that SMR FOAK will receive more regulatory attention than for new large nuclear. There will be high regulatory expectations in terms of additional monitoring (both for worker safety and of discharges), instrumentation and design for accessibility, especially where off-prototype testing is not used. This will be more critical in some areas such as, for example, source terms for designs with novel fuels and coolants.

Apart from system qualification, it is likely that ONR will require each component to be individually qualified. This might pose challenges for the testing and certification of passive systems. Assumptions and claims of maintainability and reliability, especially for high integrity components in integral concepts, will need to be properly substantiated. In the area of fault studies, SMRs are likely to heavily rely on extensive theoretical and experimental validation. Computer codes will need to be validated and qualified for their application to the analysis of SMR technology. ONR is likely to scrutinise what is claimed for every application of computer code and how those claims are substantiated. In addition, ONR is likely to carry out their own independent assessment. For the Environment Agency, the lack of operating experience may also mean that additional work will need to be done in order to understand the characterisation and disposability of radioactive waste and discharges produced by the plant.

Challenge 3 – Specific design aspects
During the previous feasibility study (Ref. 1), a number of generic design challenges were identified for SMRs. These still apply and a vendor submitting an SMR for GDA within the next 5 years should expect to be thoroughly scrutinised by the Regulators in the following areas (noting that not all apply to all SMR designs):

- Integral concept. This includes mechanical design requirements, layout, safety classification, cable routing and qualification of components in a harsh environment;
- Maintenance and in-service inspection;
- Substantiation of passive safety systems;
- Demonstration and validation of natural circulation thermal hydraulics;
- Interaction between natural circulation and reactivity control;
- Development of advanced neutronic and thermal hydraulic coupling models for non-conventional fuels;
- Source term management for long refuelling cycles (noting that for some designs the same fuel load stays in the reactor for the entire life of the plant);
- Identification of initiating events. Whereas some vendors claim that some initiating events are eliminated by design (e.g. control rod ejection in designs with internal CRDMs), new concepts and plant configurations with multiple smaller reactors might introduce new ones.
- Refuelling methods and fuel route;
- Long-term interaction between concrete and soil for below-grade concepts;
- ALARP demonstration of a plant configuration with multiple smaller reactors;
- BAT case for a plant configuration with multiple smaller reactors.

Challenge 4 – Operations and licensed site boundary
A number of novel operational modes have been suggested for SMR plants. These do not only differ from the way large nuclear reactors are operated, but raise questions over the concept of the site boundary. In particular, operational regimes might be proposed where a control room in a central remote location could control several SMR units in different geographical locations. This is likely to raise significant security concerns, as the nuclear reactors would be operated from a facility that is located beyond the site boundary. The location for this facility for remote operation would be a nuclear licensed site itself as well, which has further implications. At the moment, it is not possible to anticipate how and if ONR would contemplate nuclear facilities being operated remotely.

If several modules are planned to be operated from the same control room, the applicant would be expected to justify (amongst other things):

- Number of operators for each unit;
- Adequate control of the plant in all operating conditions;
- Numbers of maintenance staff, health physicists and other site staff;
- Size of control room;
- Prioritisation of activities in the control room both during normal operations and in accident conditions.

Challenge 5 – Waste disposability
As part of the GDA process, consideration needs to be given to the disposability of all radioactive wastes as well as spent fuel that would be generated through operation and decommissioning. Regulators have indicated that requesting parties should obtain a view from the Nuclear Decommissioning Authority (NDA) on the

disposability in a GDF of any higher activity wastes and spent fuel. The assessment is normally done by the RWM and covers the following:

- Nature of the higher activity wastes and spent fuel;
- Proposals for packaging;
- Radionuclide inventory of ILW and spent fuel;
- Assessment of proposed ILW packages;
- Assessment of spent fuel packages.

On the basis of this assessment, RWM is expected to certify whether ILW and spent fuel from operation and decommissioning are compatible with existing arrangements and plans for transport and disposal in the UK. The challenges faced by different SMR technologies with respect to waste management and decommissioning are discussed in Section 4.3.4.

There might be as well security aspects raised by the fact that some designs use fuels with higher levels of enrichment.

4.4.2.3. Site-specific licensing and permitting

During the process of applying for a site-specific licence and permit for an SMR, it will be important to understand some basic elements that differentiate SMRs from large nuclear plants (Ref. 55) including:

- Modularity of fabrication shifts construction activities from sites to factories.
- Lower power is likely to lead to a reduction of the source term as well as a smaller radioactive inventory in a reactor, although this will have to be properly substantiated.
- Many of the designs are below-grade providing more protection from natural or man-made hazards but, at the same time, higher potential for accidental environmental ground contamination.
- The modular design opens the possibility to have multiple reactor units in the same plant.
- Reduced demand for cooling water.
- Ability to remove a reactor module at the end of the lifetime.

It is unlikely that any of these features will contribute to simplifying the process of obtaining a site licence or permit compared to large nuclear, as these claims will need to be equally substantiated. Some specific examples are discussed below. In specific terms, the multi-module concept could be problematic when moving from a GDA SoDA and DAC for a single module into a site permit application for a multi-module plant.

Environmental permits cover ‘normal operations’ only, and account for the normal fluctuations and events that the operator would expect to happen during the life of a facility. What constitutes “normal operation” and the associated discharges will vary with reactor type. Normal operation includes infrequent but necessary aspects of operation, consistent with the use of BAT, for example, occasional fuel pin failures in a reactor. In this example of pin failure, a SoDA might have been given for an SMR unit that has justified a certain frequency of occurrence for the event. If the site permit application is for an SMR plant of several modules, additional justification might need to be provided, above and beyond what would be expected for a reactor that has successfully gone through GDA to understand what the cumulative effect could be.

Guidance is provided by the Environment Agency on the ‘Criteria For Setting Limits On The Discharge Of Radioactive Waste From Nuclear Sites' (Ref. 56). This guidance is generic and could be applied to a nuclear power plant of any size. The approach in the UK is that discharges and their impact are minimised such that doses are ALARP and they are minimised through the use of BAT. The ‘rule of thumb’ is that discharges have to be no greater than those from similar power stations around the world with no gross disproportionality applied to SMR when compared with large nuclear. The fact that, for SMRs, limited operating experience exists means that greater conservatism in modelling and calculations is to be expected which could lead to higher initial discharge limits until relevant operating experience is accumulated. Similarly, extra monitoring arrangements should be expected for FOAK first operating cycles.

In terms of risk, the expectation in the UK is to perform an evaluation of off-site risks and consequences using a Level 3 PSA. The PSA model should take into consideration the characteristics of the site. It should provide insights into the relative importance of accident prevention and mitigation measures, expressed in terms of the adverse consequences for the health of the public, the contamination of land, air, water and food. Numerical targets are not expected to be relaxed for SMRs and, although these might be easier to achieve for these designs, they will still need to be compliant with the ALARP principle. Although a full Level 3 PSA does not need to be developed during the GDA, an estimate of the risk profile of the plant does need to be provided. This raises the issue again of a single unit successfully completing GDA followed by a site licence application for multiple units. Consideration will need to be given to the scalability of accident consequences with the number of modules.

It has been suggested that one of the advantages of SMRs is that they can be deployed progressively at the same site. The idea behind this is that a number of units can be built and commissioned and, once they are in operation, fund the construction and commissioning of extra units. Although building new reactors on or very near a site with existing operating units is common practice in large nuclear plants, there are significant differences between such an approach and the staged approach suggested for SMRs:

- A DAC and a SoDA are valid for 10 years, subject to no significant new information arising during this period to undermine the Regulators' confidence in the safety and security of the design. Even within the 10 year period, if new techniques and methods have been developed that impact on safety or environmental protection, the expectation would be for these new advances to be considered in the new modules.
- It is unclear whether installing new modules as part of an existing SMR plant will require the re-licensing of either the plant or the extra modules. Should this be the case, the economic benefits of a staged deployment of SMRs might be affected. In the case of the permit, the permitted discharge and waste disposal levels would need revising.
- Some of the proposed designs consist of a single civil structure shared by several modules. At the moment, the licence conditions do not contemplate a situation where a new reactor is installed in a plant where other reactors are being operated. This situation may require a modification of the existing licence conditions.

The multi-module philosophy and the staged construction of modules will also need to be taken into consideration in the development of a Funded Decommissioning Programme (FDP) which is an important step in obtaining a site licence. A UK nuclear operator is responsible for managing any waste produced, sourcing an appropriate disposal route and ensuring that the site is decommissioned according to legal and licensing requirements. This obligation places a duty on the operator to submit an FDP to the Secretary of State for approval. Within the FDP the operator is expected to make provision for:

- The full cost of decommissioning the installation;
- The operator's full share of the costs of safely and securely managing and disposing of the waste.

The FDP should minimise the risk of recourse to public funds in the future and should be submitted at the time of licence application. The Energy Act 2008 and FDP cost recovery scheme guidance (Ref's 57 and 58) make provisions for the modification of an FDP either by the Secretary of State or the operator. An FDP may contain mechanisms relating to certain types of modifications that fall above any threshold set out in the regulations (Ref. 57). For example, the operator might be able to predict in advance that a modification might be required as a matter of course and set out appropriate mechanisms in the FDP. In such a situation, the Secretary of State would expect to approve any such modifications compliant with the mechanisms set out in the FDP.

In summary, an FDP that envisages staged construction could be developed, provided that the operator can foresee the final number of SMR modules at the point of submission. Provision would have to be made in the FDP so that modifications to the plan can be approved as the number of modules in the plant increase.

4.4.3. International Regulatory Harmonisation

At present, a number of international working groups are active in the area of international regulatory harmonisation for SMRs. The purpose of these groups is to develop global regulatory frameworks and licensing support for export of concepts developed in accordance with the specific experience and regulatory framework of one country. The reasoning for achieving greater harmonisation is that, if the design needs to be changed substantially every time it is to be approved under a different regulatory regime, many of the potential benefits of SMR deployment would be difficult to achieve:

- If a foreign design completes the GDA process with an outcome that requires significant design modifications for it to be licensed by the UK Regulators, investors might find supporting UK deployment less attractive than if the SMR could be built "as designed".
- If the UK wants to manufacture and export SMRs to the world, a significant order book would need to be in place before an investor decides to fund an SMR factory. The business case of such a factory will be heavily reliant on being able to deploy SMRs with minor to no modifications after leaving the factory.

The two main working groups in international regulatory harmonisation of SMRs are the International Atomic Energy Agency (IAEA) Regulators Forum and the WNA Co-operation in Reactor Design & Licensing (CORDEL) SMR Task Force.

IAEA Regulators Forum

The purpose of the IAEA Regulators Forum is to identify, understand and address key regulatory challenges that may emerge in future SMR regulatory discussions.

Membership of the Forum is made up of the regulators of Canada, China, Finland, France, Korea, Russia and United States. It is made of a steering committee and three working groups with the following specific objectives:

- **EPZ working group:** to establish an understanding of each member's regulatory views on EPZ size of scaling preparedness for SMRs to capture good practices and methods.
- **Graded approach working group**: to establish an understanding of each member's policies and application of the so-called 'Graded Approach', with a focus on how it might be applied to address novel approaches and technologies being proposed for SMRs.
- **Defence-in-Depth working group**: to identify key regulatory challenges with respect to Defence-in-Depth (i.e. the provision of diverse and separate systems that provide critical functions to the plant). Other aims are to enhance safety and efficiency in licensing and enable regulators to inform changes, if necessary, to regulatory requirements and practices.

The main outcomes of the forum are:

1. Position statements on regulatory issues;
2. Suggestions for revisions to IAEA documents;
3. Enhanced regulatory frameworks;
4. Description of regulatory challenges;
5. Considerations for international codes and standards organisations.

WNA CORDEL SMR task force

The WNA CORDEL group has an SMR Task Force. The mission of the task force is to promote the standardisation of the reactor designs.

The task force claims that harmonisation of licensing for SMRs will attract investment as it will increase the "predictability of regulatory activities". This is equivalent to a reduction in licensing risks for any potential investor, developer or operator. The task force comprises utilities, plant and equipment vendors, and engineering and research organisations representing the global SMR community.

The group aims to justify a new approach to licensing, given the design characteristics of an SMR (Ref. 55). This approach is based on the issuing of an international design certification that will be accepted by several countries. A case study is being set up on module certification.

The UK's role

Participating in these forums would strengthen the position of the UK in the SMR market in the following ways:

- It would contribute towards removing the single most important technical barrier for global deployment of SMRs – that of regulatory risk and the requirement to change the 'standard factory design';

- The UK Regulators would be better positioned to make sure that the particularities of a non-prescriptive regulatory framework are taken into account in any international harmonised regime;
- It would boost investor confidence as the UK would be seen as committed to SMR development and aligned with the international community's aims;
- It would facilitate the creation of a business case to invest in an SMR factory in the UK. An investment case based solely on the local deployment of locally-manufactured SMRs is unlikely to attract investors in the UK.

The challenge of harmonisation is not small and it is likely to require the acceptance of exceptions for SMRs in some aspects of the regulatory regime in several countries, not only in the UK. This will potentially be time-consuming if the countries required to agree are well-established, mature nuclear nations.

4.4.4. Licensing and Permitting Conclusions

The ease of licensing and permitting of SMRs in the UK has been assessed. The assessment has covered alignment with UK regulatory expectations at both the GDA stage and site licensing.

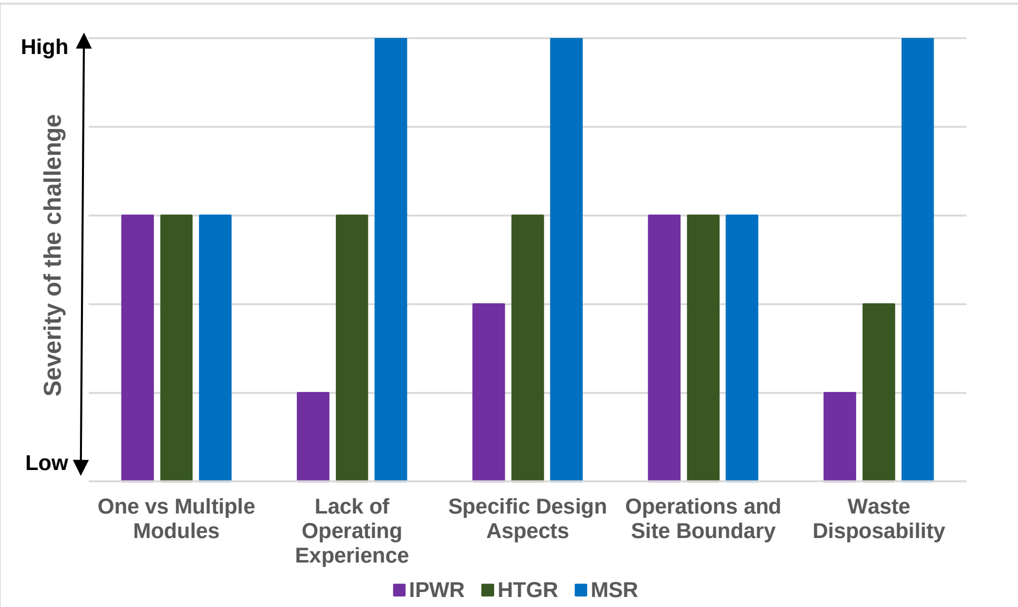
The readiness of SMR technology to undergo GDA has been assessed by evaluating the level of alignment of the different designs against a sample of topics within the SAPs and REPs (Ref's 5 and 6). Consultations were held with ONR and the Environment Agency, the conclusions of which have also been taken into account during the assessment.

The assessment is well-aligned with the findings of the technical maturity assessment (Section 4.1). SMR designs that are based on LWR technology are the ones that are more aligned with the expectations of the UK Regulators. They are also the only ones that are likely to be able to compile the security and safety documentation required at the time of applying for a GDA slot in the next five years. Technologies other than LWR-type need a substantial amount of R&D in order to overcome technical challenges, so that they can produce the level of evidence and justification that will allow them to progress beyond the GDA Step 2.

GDA costs and timescales are estimated to be no less than for large nuclear plants for SMR designs based on IPWR technology. Other technologies may take longer depending on the level of maturity of the safety and environmental case at the time the GDA starts, and on the availability of regulatory expertise to evaluate the submission.

Several challenges have been identified for SMRs going through the GDA. Figure 4-7 is a graphical representation of the severity of the challenges discussed above for three type of technologies.

Figure 4-7 SMR licensing challenges



In the areas of Operations and Site Boundary, and Multiple Modules, all three technology types are expected to face similar challenges. Differences are identified in the areas of Operating Experience, Specific Design

Aspects and Waste Disposability. The trend observed in those is that, at the present status of development, the technology that will be the easiest to license is IPWR, whereas the most challenging one will be MSR. This is understandable since accumulated knowledge exists from large reactors (water and gas cooled) that can be applied to IPWRs and HTGRs. For MSRs, there are a number of areas where no operating experience exists and a significant amount of R&D is needed.

Obtaining a site licence and permit for an SMR plant might be more challenging than for a large nuclear plant, depending on the differences between the configuration that has gone through GDA and the configuration planned for construction. The reduced size compared to large nuclear would not present a clear advantage to permit SMRs, as disproportionate discharges will not be accepted. The principle of proportionality applies and both the quantity and dose impact of discharges will be expected to be minimised using BAT to ALARP levels. Likewise, natural resources will need to be used in a rational and proportional way.

Consideration will need to be given to the number of modules when estimating the risk profile of the plant through PSA techniques. Scalability of accident consequences with the number of modules has to be properly understood and justified.

Finally, if staged construction is foreseen, a number of issues need to be considered. Any DAC or SoDA is valid for a period of 10 years and, after that, would need to be renewed in a process similar to the Periodic Safety Review. The FDP needs to make provisions for the final configuration of the plant, not just the initial plans. Modifications to the licence and permit conditions might be needed should further construction of additional modules be undertaken.

5. Economic Assessment

5.1. Summary of Economic Assessment

A review of the economic feasibility of SMRs within the UK has been conducted with the findings summarised below for each of the three work streams. All economic values that have been estimated in this report are presented in 2015 prices.

Cost of SMR Generation

Vendor cost estimates have been reviewed and critically assessed to inform estimates of the FOAK plant costs for the five vendors that provided cost data. Cost estimates have been assessed on the basis of the plant configuration provided by the vendor, with plants ranging between 95 MWe and 570 MWe and comprised of between one and 12 reactors per plant. FOAK overnight capital costs for vendors are estimated to be in a range of £5,000 and £12,000/kWe in 2015 prices in the central case, equating to a levelised cost of £100-210/MWh. This excludes the further costs of bringing a given SMR technology to market (expected to be around £325 million by IPWR vendors) and through the GDA process (estimated to be an additional £362 million per technology).

Vendors 1 and 2 have been assumed to be representative of a generic SMR as they represent the vendors that provided the highest quality of economic data and are more technologically mature. The estimated FOAK cost for a generic SMR is estimated to be between £86/MWh and £124/MWh, with a central cost estimate of £101/MWh. This excludes GDA costs and the range reflects uncertainty around capital costs. The FOAK levelised cost is significantly higher than the equivalent NOAK cost of a large nuclear counterfactual (£79/MWh), but potentially lower than that of offshore wind (£97/MWh) and Combined Cycle Gas Turbine (£121/MWh if carbon prices are escalated in line with DECC's stated trajectory).

SMRs should be able to achieve greater cost reductions over time through greater experience (i.e. learning by doing) than has traditionally been observed in the nuclear industry. SMR has the potential to align learning conditions more closely with other industries where significant cost reductions have been achieved through a higher turnover of production units and a greater share of production occurring in a factory setting. Based on analysis of potential learning rates, generic SMRs should see levelised costs for new build become competitive against large nuclear after 5 to 8 GWe of global deployment of SMR of that same design and via a single supply chain.

For the other vendors assessed, costs are either unlikely to become cost effective against large nuclear or have highly uncertain costs and are unlikely to be deployable in the 2030s.

Direct Impacts of an SMR programme

The welfare impact to society of a programme of SMR deployment has been assessed by estimating the cost of generation from the SMR fleet relative to the cost of generation from counterfactual technologies. The deployment programme assumes 2 GWe of UK deployment over a five year period and 2.5 GWe deployed abroad (over which cost reduction through learning is also achieved). The welfare impacts do not account for societal costs in developing a technology to the point of starting GDA, nor the potential benefits of SMR beyond the 2 GWe UK deployment. The impacts also do not account for wider system impacts on dispatch and on network costs.

A 2 GWe programme of SMR deployment in the UK is estimated to have a Net Present Value (NPV) to society of between +£2.0bn and -£14.2bn (with a central estimate of -£4.8 billion) if it is displacing deployment of large nuclear – with the range in NPVs reflecting uncertainty around SMR capital costs and learning rate. SMR is expected in the central case to have a positive impact of +£0.4bn relative to offshore wind and -£8.4bn relative to CCGT.

The central expectation of a negative NPV relative to large nuclear is due to SMR costs remaining higher than those of large nuclear for the first 3.5 GWe of UK deployment (and a further 4.5 GWe of deployment of the same design elsewhere). The NPV for a UK SMR programme relative to large nuclear is expected to remain negative out to 2050, as the long-term benefits of SMR after it reaches cost parity do not outweigh the higher initial costs. However if SMR were to achieve a reduction in the cost of capital once the first plant has been successfully deployed, the NPV could reach a break-even point sooner – for instance after 8 GWe of UK deployment if SMR achieves a 1% cost of capital reduction.

This assessment of NPV aims to reflect the costs and benefits of SMR generation relative to counterfactual technologies. However a number of factors are not included in the assessment. The wider economic impacts are assessed separately (see next heading below). It is also noted that there are a number of qualitative benefits to SMR generation relative to the counterfactuals: SMR should have security of supply benefits relative to large nuclear by reducing reliance on Government to provide debt-finance, reducing reliance on fossil fuel imports relative to CCGT and reducing power intermittency relative to offshore wind.

The impact to consumers of the 2 GWe UK deployment programme of SMR over the 60 year operational lifetime of the plants would be equivalent to +£2 on domestic household bills per year relative to large nuclear, -£1.10 per household bill per year relative to offshore wind, or +£1.10 per household bill per year relative to CCGT.

Wider economic impacts of an SMR programme

SMRs have the potential to create broader economic advantages to the UK economy. Between 2017 and 2040, under the 70% supply chain scenario, the estimated total gross impacts (accounting for direct, supply chain and consumer spending) consists of £20 billion of undiscounted GVA, with average employment of 9,700 jobs and a tax contribution of £7 billion to the Exchequer. Assuming a lower 60% supply chain participation, undiscounted GVA for the same period is estimated at £18 billion, average annual employment of 8,200 jobs and £6 billion of tax revenues. Between 2017 and 2040, relative to large nuclear, the estimated net impacts from the SMR programme under the 70% supply chain assumption is an estimated £1.7 billion of undiscounted GVA (equivalent to increased GDP of £70m per year), £0.6 billion in taxes and average employment of 800 jobs per annum.

The finding of a wider economic benefit is driven by four key factors:

1. The differences in the scale of expenditure between SMRs and the alternative technologies (large nuclear, CCGT and offshore wind) assessed, with SMR incurring a greater degree of spend over the modelled period due to the high costs of the initial plants;
2. The extent of local firms' involvement in the SMR supply chain, particularly if the UK is able to attract manufacturing facilities to be situated in the UK;
3. The export potential of SMRs being greater than the counterfactuals if the global market develops for SMR and if the UK can achieve a 10% market share; and
4. The existence of an output gap, such that initial expenditure on the SMR programme does not necessarily displace other activity.

The findings from the economic assessment are summarised in Table 5-1 below for a generic SMR. The SMR programme is estimated in the central case to have an NPV of +£0.4bn to -£8.4 billion, depending on the technology displaced. This should be considered in the context of the macroeconomic benefits appraised for the SMR programme which suggests that it could potentially generate NVA of up to £1.3 billion (central scenario) for the UK economy.

Table 5-1 Summary of direct and indirect impacts of 2GW UK SMR deployment

Counterfactual	Direct Welfare Impact (Discounted)	Net Value Added (Discounted)	Qualitative Impacts of SMR
Large Nuclear	-£4.8bn NPV (-14.2bn to +2.0bn range)	£1.2 billion NVA; 300 jobs per year	• Potentially easier to finance SMR • Greater potential for long run cost reduction from SMR
Offshore Wind	+£0.4bn NPV (-9.0bn to +7.2bn range)	£1.0 billion NVA; 200 jobs per year	• SMR more flexible/ 'dispatchable' • Offshore wind more subject to competitive pressure on costs
CCGT	-8.4bn NPV (-17.8bn to -1.6bn range)	£1.3 billion NVA; 300 jobs per year	• SMR reduces imports of fossil fuels • SMR health benefits in cleaner air • CCGT potentially inconsistent with decarbonisation targets

Further sensitivities considered the impact of a programme of SMR deployment out to 2050, including 12 GWe of SMR plant commissioning in the UK and 10 GWe of exports. These are summarised in Table 5-2. These show discounted net impacts of SMR relative to a counterfactual of large nuclear for the life of the plants deployed. The NPV range reflects sensitivities around the cost of capital.

Table 5-2 Summary of impacts of longer-term SMR deployment programme

Counterfactual:	Direct Welfare Impact of 12 GWe SMR	Wider Economic Impact of 12 GWe SMR
Large Nuclear	-£3.5bn NPV (-£6.2bn to +£3.0bn range)	£1.6 billion NVA; 500 jobs per year

5.2. Cost of SMR Generation

5.2.1. First of a Kind Cost

The cost of SMR deployment has been modelled by first estimating the cost of the first SMR plant and then modelling the impact over time of reductions in the build time and cost of capital as more plants are built and the technology becomes more mature.

In establishing an estimate of FOAK costs, this assessment builds on the 2014 NNL Feasibility Study (Ref. 1), which reviewed both the available literature on SMR costs as well as cost estimates from SMR vendors to provide a view of likely FOAK generating costs.

Within this assessment, a number of vendors were engaged to estimate their FOAK costs and to provide a view on the credible range of cost estimates. Costs for new large nuclear provided by DECC were used to enable corroborative checks. The findings of Projects 5-7 on opportunities for cost reduction arising from the application of advanced techniques and processes to SMRs were applied to the FOAK costs to arrive at a likely profile of how costs will vary over time. These SMR costs have been compared with generating cost estimates for alternative technologies (sourced from unpublished reports on Electricity Generating Costs and Hurdle Rates provided by DECC (Refs 59, 60 and 61). Where there are costs or benefits to different technologies that are not fully reflected in the quantitative analysis (such as value of capacity that is better able to load-follow or easier to finance), these have been qualitatively captured.

5.2.2. Metrics

SMR costs have been assessed using two well-established metrics:

1. **Overnight Capital Cost (OCC)**: This provides a view of the principal cost of the plant - the capital expenditure – and presents this without consideration of the development, financing and operating costs or the time involved to operation of the plant. This metric is expressed in £/kW of capacity and

allows comparison of the technologies where there is uncertainty around the financing or operating costs of the technologies. The OCC results are shown in Section 5.2.5.

2. Levelised Cost of Energy (LCOE): This provides a more holistic view of the costs of a technology, accounting for costs (including development, operation, financing and decommissioning as well as the capital costs) over the expected plant lifetime, with OCC as one significant input to the LCOE. The LCOE effectively captures the minimum power price that the plant would need to receive over the life of the plant in order for that plant to be commercially viable. It is calculated by summing the discounted lifetime plant costs and dividing that by the discounted lifetime generation of the plant, providing a metric of cost in £/MWh for a plant commissioned in a given year. The LCOE results are shown in Section 5.2.10.

It should be noted that LCOE costs are calculated on the basis of the technologies running at baseload for all the time that they are available to generate. This provides a consistent benchmark for assessing generating technologies and is consistent with the modelling of levelised costs in Leigh Fisher's report for DECC (Ref. 59) on the generating costs of other technologies. Nevertheless, one of the identified benefits of SMR is its potential for improved load following in comparison to large nuclear plants (as discussed in the Project 5-7 report). This could be a benefit in the future if there is a greater proportion of intermittent renewables in the system. However if SMRs were to run at a lower load factor in future, the consequent LCOE for SMR would be higher to compensate for the lower number of running hours.

5.2.3. Assessment of vendor information

Of the 14 vendors that submitted responses, 5 vendors provided sufficient cost and technical data to enable an economic assessment to be made of their technology design, with other vendors either not having sufficiently mature designs to enable cost estimates or not being willing to share cost information. In order to assess the OCC and LCOE for those five SMR vendors who provided detailed cost estimates, the underpinning evidence was reviewed to determine where it was necessary to make adjustments to the data. This includes assessment of the following aspects of SMR project economics:

1. Development costs;
2. Overnight capital costs;
3. Technical specifications;
4. Timelines for construction and operation;
5. Operating costs;
6. Financing costs.

Vendor cost estimates have been assessed on the basis of the plant size and configuration put forward by the vendor, with plants ranging between 95 MWe and 570 MWe and comprised of between one and twelve reactors per plant. For most of the vendor cost estimates, this involves two reactors within a plant, although there was a range of up to twelve reactors in designs assessed.

5.2.4. Development Costs

Four principal types of development expenditure have been identified as necessary to bring SMR technology to market:

- R&D for a technology so it is ready to begin GDA;
- Taking the technology through the GDA process;
- Development of manufacturing facilities; and
- Site licensing.

The process of developing and certifying a technology needs to be completed before the first plant can be taken forward, whereas the process of site-licensing is required for each subsequent plant as well.

5.2.4.1. R&D Costs

A discussion on SMR R&D cost estimates is included in Section 4.2.4.1. R&D costs are excluded from the LCOE and NPV assessment. This is partly due to the scale of uncertainty around these costs, but also in recognition that R&D costs may be partly funded through grants from other countries, and it is therefore not clear over what timeframe or volume of deployment that vendors would seek to recover their development costs.

5.2.4.2. GDA Costs

GDA costs for an SMR technology are assumed to equal those for a large nuclear design, estimated by Leigh Fisher at £362 million (with a range of £190 million to £673 million) (Ref. 59). The Leigh Fisher costs are used instead of vendor cost estimates as they are considered to represent a more credible view of GDA costs, reflecting the technical assessment finding that licensing of an SMR design would require the same amount of effort as the licensing of a large nuclear design. Further discussion of GDA costs for SMRs is presented in Section 4.4.2.1.

If borne entirely by the first SMR plant, a £362 million GDA cost would add £21/MWh to the FOAK LCOE for a generic SMR. GDA costs are not reflected in the FOAK cost estimates presented in this report as it would be likely that a vendor would seek to recover the GDA cost over multiple plants. This situation is different to large nuclear plants, where the FOAK plant production is of the order of GWe and so developers would be more likely to expect GDA costs to be recovered through a single plant.

5.2.4.3. Development of manufacturing facilities

The SMR vendor is expected to incur a significant cost in developing manufacturing facilities to support the construction of SMR plants. However the costs of building factories are not explicitly modelled within the assessment for a number of reasons:

- SMR vendors did not provide information on the cost of building manufacturing facilities, and so there is no evidence on which to base an estimate of this cost;
- SMR vendors may have already factored in the recovery of the cost of factory build into its estimates of plant construction, in which case adding the cost of factory build may “double count” this expenditure; and
- It would not be appropriate to entirely recover the cost of facilities within the revenues of the first SMR plant. As with R&D costs, the cost of building factories could be spread across a longer time horizon of deployment as well as over multiple markets – and some of this expenditure may have already been incurred

5.2.4.4. Site licensing

The cost of site licensing is assumed to be £51 million per site based on the highest estimate provided by vendors, as this was judged to provide a sufficiently conservative basis for the cost estimate. Provided the plant configuration remains consistent with the design submitted for the GDA, then the site-licensing cost could be considerably less than the GDA. It is acknowledged that the site licensing process could result in design changes due to site specific characteristics (e.g. heat sink design, flood protection, changes to site layout). However, vendors have generally accounted for site specific design costs within their overnight cost estimates. The time and cost of site licensing for the FOAK plant is assumed to occur only after the GDA process has completed.

5.2.5. Overnight capital costs

OCCs have been estimated for 5 vendors. The starting point for the OCC estimates was the vendor’s own FOAK cost estimates. A number of adjustments were then made to ensure estimates are credible, consistent, and reflect the degree of uncertainty around the technology. These adjustments are discussed below.

The detailed cost breakdowns from the vendors were reviewed for consistency and comparability in terms of both the type and level of cost included within the estimates. An adjustment was made to the vendors’ capital cost estimates to reflect the potential for optimism bias in the estimates. Optimism bias is the established tendency to underestimate costs and overestimate benefits when initially establishing the business case for a project or programme. Optimism bias was applied to vendor OCC estimates, although any contingency assumed in vendor estimates was netted off from the rate of optimism bias applied to avoid double counting. A range of different levels of optimism bias guidance was considered as part of the TEA:

1. The International Energy Agency (IEA) applies a 15% contingency rate for new nuclear projects (Ref. 60).

2. Treasury Green Book guidance (Ref. 71) provides standard adjustment rates for six different categories of project. Of these, the category of non-standard civil engineering, which has an upper-bound adjustment of 66%, is the category that best describes SMR build.[8] This factor can then be reduced where there is evidence that underlying risks are not relevant or have been mitigated in the case of a particular project. In the case of SMR, it was considered that the contributory factor of "inadequacy of the business case" was mitigated by up to 50% for SMR vendors considered low or medium risk (assessed in Section 4.2) [9]. This is shown in Table 5-3 below:

Table 5-3 Optimism bias assessment based on SMR as a non-standard civil engineering project

Optimism Bias Assessment		
High Risk	**Medium Risk**	**Low Risk**
66.00%	60.23%	54.45%

3. Treasury guidance suggests an upper bound estimate of 200% optimism bias for "equipment and development projects." It could be assumed that this higher rate applies to the factory produced elements of SMR expenditure (assumed to equal 45% of overall cost) due to the developmental nature of the technology, with the rest of plant cost counting as "non-standard civil engineering". Using such a blended approach and making allowances for mitigation of business case risk, suggests that an overall optimism bias adjustment for a plant of up to 112% could be appropriate.
4. Treasury guidance also allows for a different level of optimism bias adjustment to be made where there is better evidence of the level of cost overruns in a particular industry. If SMR build is comparable to new large nuclear, then the correct level of optimism bias may be as high as 300%, as has been estimated for past nuclear programmes (Ref. 61).

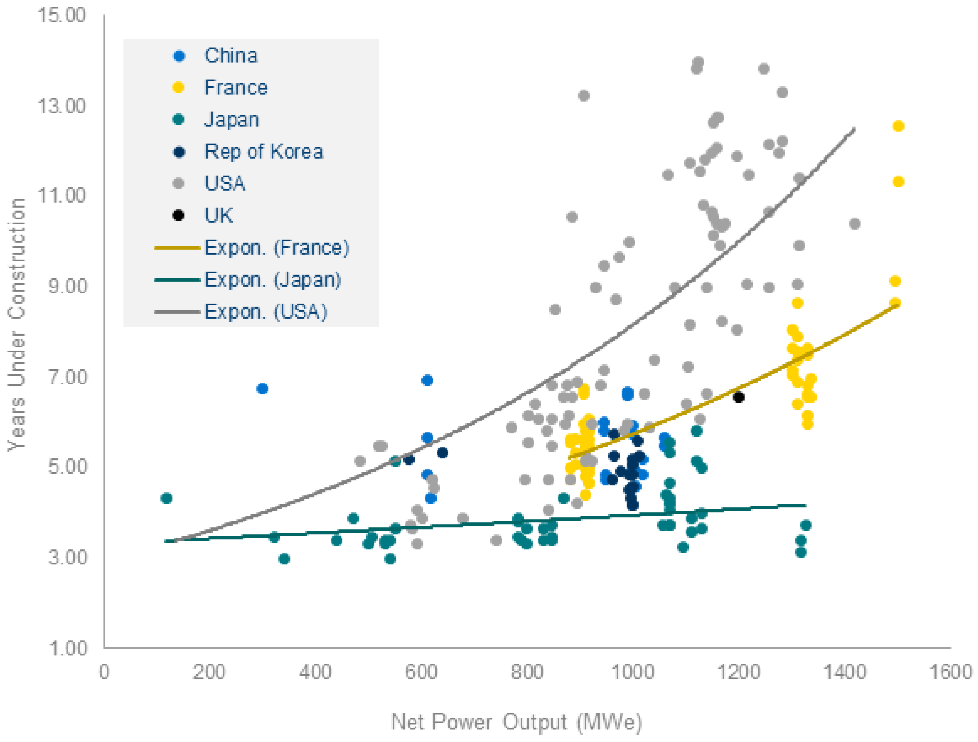
In each case, it is assumed that any allowance for contingency within a vendor's cost estimate could be netted off from the appropriate optimism bias factor so as not to double-count allowance for cost escalation.

Of the ranges considered, option 2 – adjusting for optimism bias as per HMT's Green Book guidance for non-standard civil engineering projects, as outlined in Table 5-3, was selected as it best fits the description of project categories within the Treasury guidance on optimism bias. It is also considered that cost inflation for large nuclear projects may not provide an appropriate comparator for SMR due to a number of reasons:

- The smaller and modular nature of SMRs mean that a more significant proportion of production can take place in manufacturing facilities, where there should be a lower risk of cost overruns.
- More of the production processes can take place in parallel and there should be a materially lower risk of delays than has been seen in large nuclear construction.
- Evidence from reviews of large nuclear build costs has shown that the timescales for new nuclear build (and by implication the man hours involved and therefore the construction costs) increase exponentially with the size of nuclear plant, with larger plants disproportionately likely to incur a risk of delays. Based on the construction data for USA and France, a strong effect of scale is demonstrated – larger reactors taking much longer to build by conventional methods, with the exception of Japan where the effect of scale has been mitigated by the use of advanced techniques and processes (modularisation and lean construction).This is summarised in Figure 5-1.

[8] Non-standard civil engineering projects are defined as "those that involve the construction of facilities, in addition to buildings, requiring special design considerations due to space constraints or unusual output specifications e.g. innovative rail, road, utility projects, or upgrade and extension projects."
[9] As set out in Section 4.2.3, low risk refers to TRLs assessed to be 7 or over; medium risk refers to TRLs of 4 to 6; and high risk refers to TRLs assessed as 3 or less.

Figure 5-1 Effects of size on large reactor construction schedules

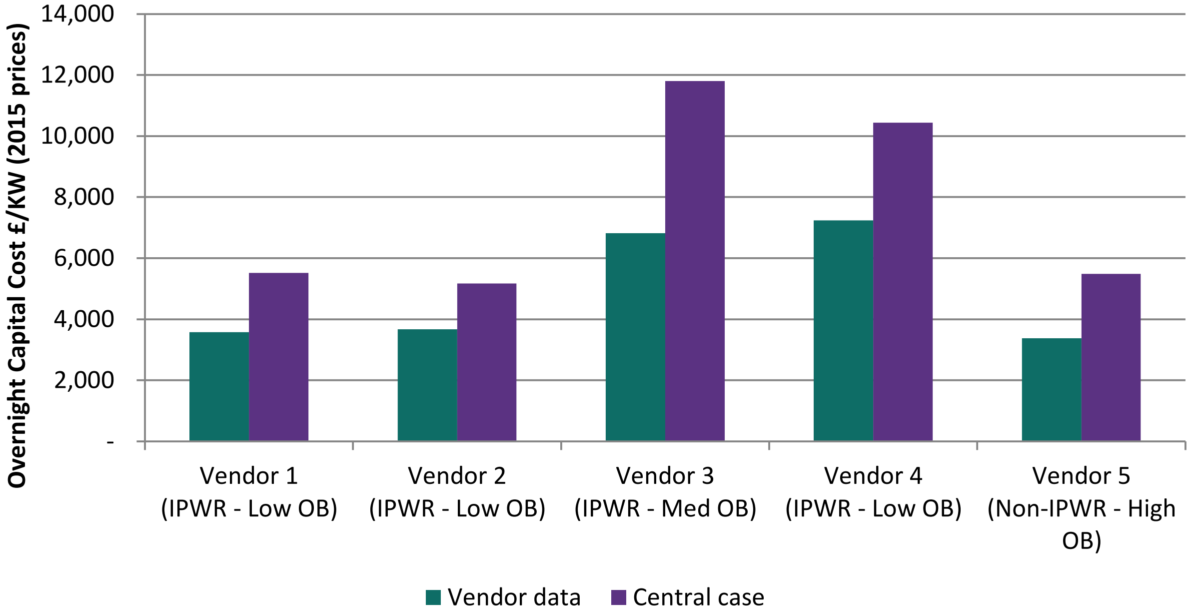


It is also noted that there may be further scope for FOAK cost reductions of up to 20% through the application of advanced techniques and processes, including use of digital engineering, lean construction philosophies, co-siting of reactors, modularisation and factory build. These cost reductions have not been applied to the FOAK cost estimates due to uncertainty over whether these techniques and processes have been included in the vendor cost estimates, and whether it would be possible to incorporate them into the SMR design for GDA within the next two years. Projects 5-7 note that to achieve much of these cost reductions, it would be necessary for vendors to have designed in modularisation prior to the GDA, which may be challenging for those IPWR designs that are well progressed.

OCCs for each vendor that submitted detailed cost data have been calculated by applying the rates of optimism bias to each vendor's estimate (net of any allowance made by that vendor for contingency).

Figure 5-2 shows the original vendor estimates and the revised central case estimate for each vendor, post adjustment, as well as the level of optimism bias applied. The degree of adjustment between the vendor cost estimate and the central cost estimate reflects both the level of optimism bias applied as well as the allowance for contingency within the vendor cost estimate (which is netted off from the optimism bias adjustment).

Figure 5-2 Vendor data and central cost estimates

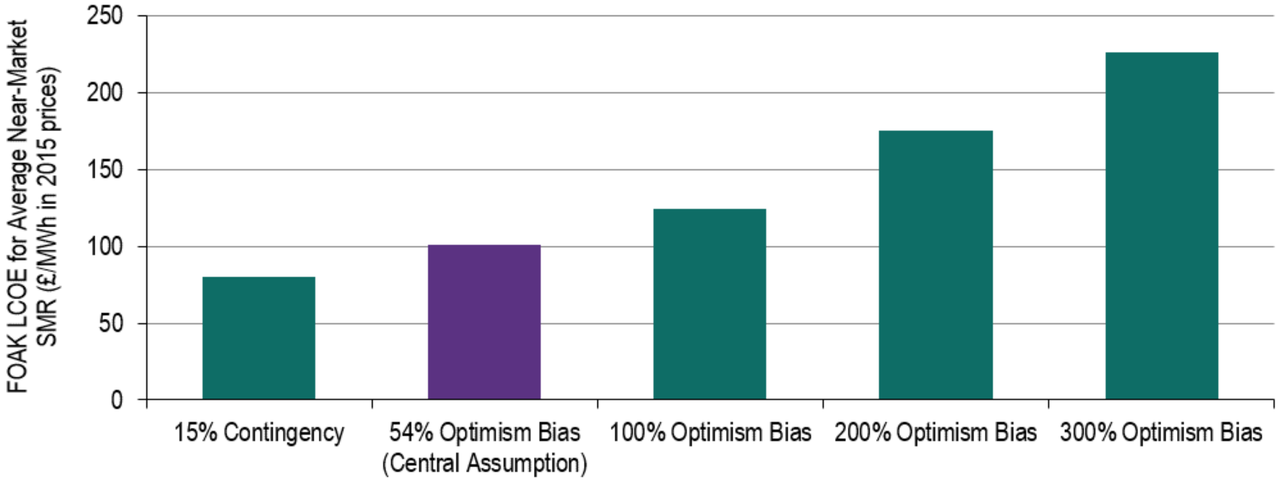


While this assessment has determined that an optimism bias of between 54% and 66% is appropriate for SMR costs, it is recognised that there is a material risk that the costs of SMR could rise over the course of technical development in a similar manner to large nuclear. In particular, modifications to the SMR design may arise through the GDA process which could increase either the construction or operation cost of plants.

Vendors 1 and 2 provided the most detailed set of economic evidence and so are considered representative of the most viable SMR options currently near to market, with the average of the two vendors' costs used throughout the report to illustrate the costs of a "generic SMR".

Figure 5-3 illustrates the impact of sensitivities around the level of optimism bias on generic SMR.

Figure 5-3 Sensitivity of generic SMR FOAK LCOE to level of optimism bias applied (inlcuding contingency)



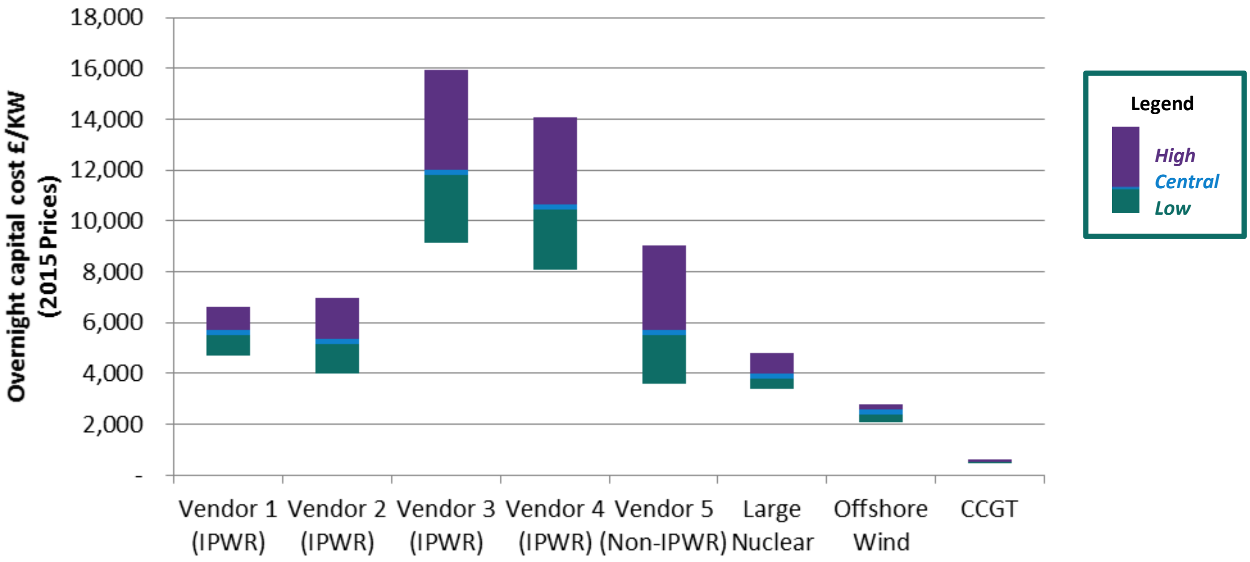
To reflect the level of uncertainty around the capital cost, a range around the central cost estimate has been applied based on vendors' self-categorisation of their estimates within the AACE International classification of cost estimates (Ref. 62). Where vendors have not used this classification system, a categorisation has been assigned, informed by the technology maturity assessment presented in Section 4.2. The midpoint of the expected accuracy range for each category of estimate was applied to determine the low and high estimate of capital costs for each vendor.

Table 5-4 AACE uncertainty ranges

Vendor	AACE Estimate Class	Uncertainty range applied
Vendor 1	Class 3: Used for budget authorisation	-15% to +20%
Vendors 2, 3 and 4	Class 4: Used for feasibility study	-22.5% to +35%
Vendor 5	Class 5: Used for concept screening	-35% to +65%

The chart below shows the range in OCC estimates for the SMR vendors alongside estimates provided by DECC of the cost of alternative generating technologies. This puts a range around the central OCC estimate for each vendor that is based on the expected accuracy range for that vendor's class of cost estimate. This shows that there is a wide range in the estimated FOAK costs between IPWR vendors. Given that only one non-IPWR vendor provided detailed cost evidence and given the degree of uncertainty around non-IPWR costs, this assessment does not provide sufficient evidence to assess how non-IPWR costs would be likely to differ from those of IPWRs.

Figure 5-4 Overnight capital costs for SMR and counterfactual technologies



In addition to assumptions for OCCs, assumptions have been made for capital expenditure relating to infrastructure costs. This has been assumed to be equal to the construction costs for large nuclear scaled according to the capacity of the SMR plant.

5.2.6. Operating costs

Vendor estimates have been used as the basis for fixed operating costs, variable fuel costs, as well as waste and decommissioning costs. Fixed operating costs were compared with those of large nuclear technologies to provide a corroborative check. It is noted that there is potential for optimism bias around the operating costs, although no evidence was identified for applying any particular adjustment factor to this value.

5.2.7. Deployment Timescales

As noted in Section 4.4.2, there is considerable variation and uncertainty around the time needed to bring a technology to the point of being GDA ready, with IPWR technologies likely to be ready within five years while non-IPWR technologies may take significantly longer.

Once a technology has got to the point of starting a GDA, the timeline for bringing a FOAK SMR plant into operation would have three stages:

1. **GDA**: This is assumed to be 6 years, based on an estimate from ONR that looked at the recent experience of large nuclear designs.

2. **Site licensing**: This is assumed to take two years for SMR projects.
3. **Construction:** It is estimated that the FOAK construction period is between 5 to 6 years in the central case for SMR vendors. This is based on vendor estimates of FOAK timescales for construction[10].

It should be noted that there is risk to the construction timescale of a FOAK plant. However an adjustment has not been applied to vendor estimates for optimism bias for three reasons:

1. Vendors provided well-evidenced construction schedules, with estimates that were closely aligned with each other. Vendors also already applied allowance for contingency of between 5-10%.
2. Construction schedules for FOAK large nuclear build is 8 years. It is credible to assume a reduction of at least two years for SMR given the considerably smaller plant size for SMR (up to 600MWe) and the modular nature of production. This allows for a greater degree of construction to occur in parallel and the lower risk associated with factory production. Evidence from international analysis of nuclear projects show that construction times increase exponentially with plant size, as shown above in Figure 5-1, which supports an assumption of a shorter timescale for the construction of SMRs.
3. There may be scope for the timing of the site licensing process to partly overlap with that of the GDA process, reducing the overall time to deployment.

Vendors did not provide estimates for the time required for building manufacturing facilities to support FOAK plant build, and so this has not been included in estimates of construction schedules. However it is understood that construction of manufacturing facilities could take place in parallel with the GDA process and site licensing and so would not necessarily add delay to the timeline for deployment of a FOAK plant.

The assumptions for plant timings for the different vendors are shown below in Table 5-5, alongside the ranges to reflect uncertainty.

Table 5-5 Timescales for SMR FOAK plant[11]

Years (Range in Brackets)	**Vendors 1 & 2**	**Vendor 3 & 5**	**Vendor 4**
GDA	**6** (5-7)	**6** (5-7)	**6** (5-7)
Site Licensing	**2** (1.5 to 3)	**2** (1.5 to 3)	**2** (1.5 to 3)
Construction	**5.5** (5 to 7.5)	**5** (4.5 to 7)	**6** (5.5 to 8)
Operation	**60**	**60**	**60**

Beyond the FOAK plant, there could be a significant reduction in timescales for construction. It has been assumed that the construction schedule for each vendor could be reduced by one year for the second plant onwards, with construction of subsequent SMR plants taking between 4 and 5 years. This is considered to be a conservative assumption for timescales as there is potential for reductions in the construction schedule and as academic research cited by Projects 5-7 suggests that SMR plants could be constructed within 3-4 years.

5.2.8. Load Factor and Availability

For the purpose of this study, levelised costs for SMR, large nuclear and offshore wind have been estimated based on the assumption that plants run at baseload whenever available. CCGT is assumed to run at a lower

[10] Where Vendors provided time estimates for NOAK construction, estimated timescales were increased by a year to provide a FOAK estimate.
[11] NOAK plants are assumed to not require GDA and to have construction schedules that are one year shorter.

load factor[12] reflecting the expectation that unabated gas is likely to have a diminished role beyond 2030 due to its high carbon intensity.

Any reduction in the load factor for SMR would increase the LCOE as it would require plants to recover their fixed costs over fewer running hours. As has been noted in ETI's System Requirements For Alternative Nuclear Technologies report (Ref. 34), new nuclear could in future lower overall electricity system costs by running at a lower load factor of 80% for example. This could depend on factors such as the degree of renewables intermittency, availability of cost-effective storage solutions, and whether regulatory support measures for new nuclear provide incentives for the plant to not run when prices fall below marginal cost.

Availability is estimated at 92% in the central case for the SMR vendors, reflecting the expected level of both planned and unplanned plant outages. This value has been derived using both vendor data and industry operating experience for large nuclear, compiled by WNA (Ref. 63). This is higher than the 90% central case estimated by DECC for large nuclear, due to the comparatively shorter refuelling timescales and the potential opportunity to build up maintenance and inspection experience quickly (if multiple units are deployed).

5.2.9. Financing Costs

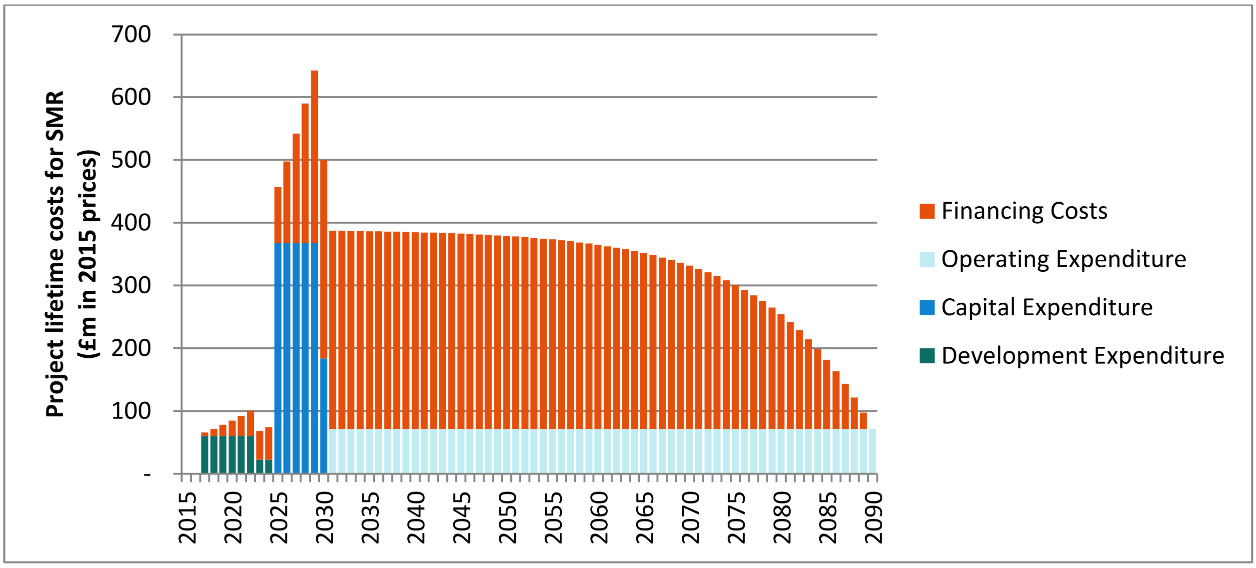
The TEA considered the likely financing costs for SMR relative to large nuclear plants and whether over time SMR would be able to realise benefits in terms of a reduction in the cost of capital, through both reducing the degree of technology risk as well as reducing the amount of capital required to finance a project.

Construction of large nuclear plants is typically capital intensive and involves long-lead times. This is combined with the high risk associated with construction completion, zero yield during construction, and in some instances the perceived reputational risks concerning a potential adverse social or environmental impact (which for the majority of banks is regulated through the Equator Principles, Ref. 64). For these reasons, there are very few market participants globally with a strong strategic interest to develop nuclear. In addition, nuclear construction is seen to have high technology risk – with past construction projects commissioning significantly over budget. As a result, large nuclear projects have typically been led by utilities backed by Government guarantees and investment to ease the financial burden.

The economics of nuclear plants, partly as a consequence of the lack of financial competition in the sector, have been typified by a relatively high cost of capital. At present, the cost of capital for large nuclear is estimated by DECC to be 8.9% in pre-tax real terms, which contrasts with an estimated cost of capital of 7.8% for CCGT. This is despite Government offering a number of measures to de-risk investment in large nuclear, including providing loan guarantees, a 35-year Contract for Difference (CfD) for the power price, and absorbing waste management liabilities at decommissioning. The high premiums charged in large nuclear contributes to the high costs of construction, which constitute 61% of the lifetime cost of a new large nuclear project or 71% of the liftetime cost of a generic FOAK SMR plant (as illustrated in Figure 5-5 below). It is assumed that this cost of capital will equally apply to FOAK SMR at the outset [13].

[12] 32% average load factor net of availability. This assumption was provided by DECC.
[13] Financing costs were modelled in this assessment with the assumption that negative cash-flow balances at the end of each year incurred interest at the Weighted Average Cost of Capital (WACC). This is a proxy for financing costs and is not the exact path that payments to debt and equity would take.

Figure 5-5 Cost Profile for a generic FOAK SMR Plant commissioning in 2031



Consequently, the lack of financing available for nuclear projects at a competitive cost of capital has also acted as a constraint on the rate of deployment of nuclear in the UK and elsewhere, requiring a utility to “bet the farm” on a project’s success. This risk is made acute by the industry’s track record of significant cost and time overruns in the construction of large nuclear plants. This point is illustrated by a downgrade in ratings issued by Moody’s against EDF which was attributed to factors including an increase in perceived financial risks associated with the final investment decision for HPC without addressing its financing more broadly (Ref. 65 and 66).

By introducing SMR power plants, nuclear technology could attract a wider range of financial investors. This is because SMR plants are much smaller in size than traditional large nuclear power plants and therefore are expected to have smaller upfront capital requirements. As a result investors may consider it as a new asset class that fits within their investment remit and an opportunity to back existing strategic corporate relationships. Depending on their risk appetite, they may choose to invest either during operations or during construction, with or without guarantees. Widening the pool of capital available for the financing of SMRs would increase the likelihood of a final investment decision and could lower the cost of capital for nuclear technology (at the same risk level) provided the project benefits from the same Government regulated guaranteed long-term revenue stream (e.g. CfD) and the transfer of waste management liabilities at decommissioning. The financing costs would be expected to reduce as investors could price the revenue streams as regulated assets, as such reducing the required returns.

In addition, SMR could reduce the overall technology risk associated with nuclear construction. The increased modularisation associated with SMRs would mean that plant modules are constructed in-factory, with the whole reactor pressure vessel intended to be provided to the site pre-fabricated. This reduces the time required for construction as well as the risk of cost overruns and slippage to the construction schedule. Construction risk, i.e. the risk to reach completion on time and on budget, is still considered a significant impediment to capital providers investing prior to completion. If the first few SMR plants have been constructed on time and can demonstrate a successful operational track record, investors and financial institutions would be much more likely to lend to / invest in an SMR power plant construction project or to re-finance already constructed plants – so releasing capital for re-investment. This would again widen the pool of capital available to nuclear projects to potentially include commercial banks, utilities and other corporate investors, private equity, infrastructure funds and eventually institutional investors, and further drive down financing costs.

Any improvement in the availability of capital for new nuclear would therefore have a number of likely benefits. It would facilitate deployment of new nuclear with less Government involvement in the form of guarantees or investment than has been required to date, and therefore alleviate a key bottleneck on the deployment of new nuclear. A wider pool of capital available for the financing of nuclear would mean greater competition which in itself should reduce the cost of capital, even if the risks associated with nuclear are perceived to have remained the same. As risks become better understood and managed, the cost of capital is likely to come down even further.

While the smaller project size and lower technology risk could help mitigate barriers to nuclear investment, it is recognised that other structural financing and risk issues which make nuclear investment challenging will persist for SMR. For instance regulatory risk will remain a key concern for investors, with worries, for example, that regulators and Government could in future increase safety standards in a way that curtails operation or increases cost of plants that have been built.

The history of financing offshore wind shows that an increase in the availability of capital is likely to materialise over a number of years and whilst several projects are being deployed. The improved 'financeability' of SMRs once capital becomes more available could include greater technology deployment and a reduced cost of capital

Case study: Financing of offshore wind

The experience of offshore wind provides a positive example of where investors have been willing to take on a greater degree of risk over time as a new generating technology has proven itself.

Offshore wind is considered a major contributor to the UK's and other EU countries 2020 Renewables targets. However, large scale deployment has faced many challenges: regulatory uncertainty, high upfront capital costs as compared to other (conventional) generation technologies, the risks associated with a complex, 'new' technology especially during the construction period, and limited supply chain competition and capability have long restrained many investors and funders from entering the offshore wind market. As a result, the offshore wind sector was predominantly led by large utilities who used their strong balance sheets to both fund and take the risk within projects. As projects have grown and the utilities balance sheets have become strained, alternative sources of both debt and equity have been attracted to the sector as partners to the traditional utilities and occasionally in their own right. This process has transferred risk to the new investors and secured a lower cost of capital for projects.

The nature of the partnerships have developed over time as the market has matured, enabling a greater transfer of risk to the non-utility investors without a corresponding increase in cost of capital. New lenders and investors initially gained exposure to the sector through operational "portfolio" financings (i.e. combined existing onshore and offshore assets) between 2005 and 2009 and then started to view operational offshore wind as a new asset class worth exploring. Competition was created for equity investments into the sector from a wide range of investors – including infrastructure funds, sovereign wealth funds, and institutional capital albeit seeking comprehensive protection from construction (and other) risks. Often utilities' desire to avoid the consolidation of debt within projects led to all equity funded projects.

Financing construction remained the sole responsibility of the utilities and other construction and engineering companies until the first project-financed offshore wind asset in the UK achieved financial close in 2012. After this, the increased experience, better understanding of construction risks and improved contractual structures created competition for project finance from a large range of debt sources including commercial and state banks, international financing institutions and export credit agencies, resulting in considerably lower debt margins and increased liquidity.

The track record demonstrated by certain utilities has recently led investors to now take construction risk alongside the utilities. The investors are international and diverse in nature and include institutional investors, sovereign wealth funds and trading houses. Whilst the vast majority of financial investors are still uncomfortable taking construction risk, recent history has showed this is slowly changing: with the right contractual structures and incentive schemes, infrastructure and pension funds have started to take full construction risk under project finance deals, investing alongside major utilities. This has had the effect of reducing the financial burden on utilities and reducing the cost of capital for the projects.

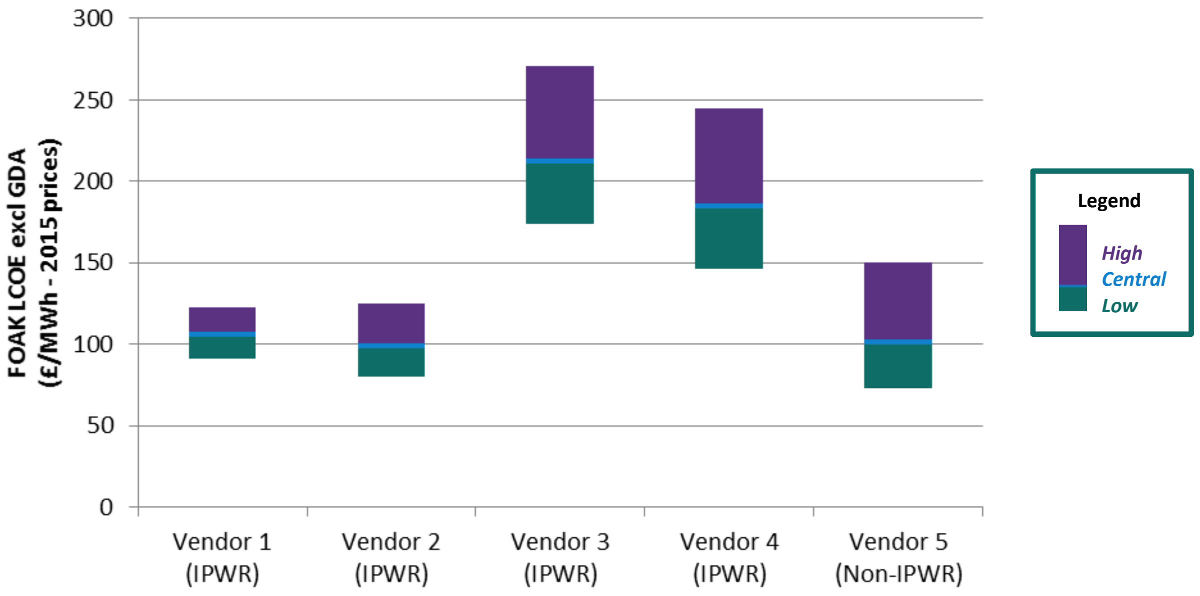
The experience of offshore wind provides evidence that the private sector could take on a greater role in financing new SMR once operational if it can lead to a reduction in technology risk by reducing overall project size and the likelihood of time overruns. The movement towards taking increased levels of risk within projects highlights the increased sophistication of investors and the increasing understanding of the risks associated with offshore construction whilst recognising the role of the key sponsors within the projects. In all this, Government plays a significant role providing long-term stability and (policy) certainty to investors.

Given the timescale for achieving a reduction in the cost of capital, with reductions only likely following successful construction and operation of an SMR plant, it has been assumed that SMRs would initially be financed at the same cost of capital as large nuclear (i.e. 8.9%) for the five year deployment programme modelled in this report. Section 5.3.2.3 considers the potential value of SMR affecting the cost of capital over the longer term.

5.2.10. Levelised Cost for FOAK SMRs

Based on the economic and technical parameters for SMR plant construction outlined in 5.2.4 to 5.2.9, the LCOE has been calculated for the five SMR vendors that have provided detailed cost data. As shown in Figure 5-6 below, the LCOEs for the FOAK SMR plants range between vendors from £97/MWh to £211/MWh in the central case, excluding the cost of the GDA or any further R&D required. The GDA accounts for a further £21/MWh for a generic SMR if recovered in the cost of the first plant. [14] The range in LCOEs reflects sensitivities around the capital cost.

Figure 5-6 FOAK levelised cost estimates for SMR vendors for plant commissioning in 2031



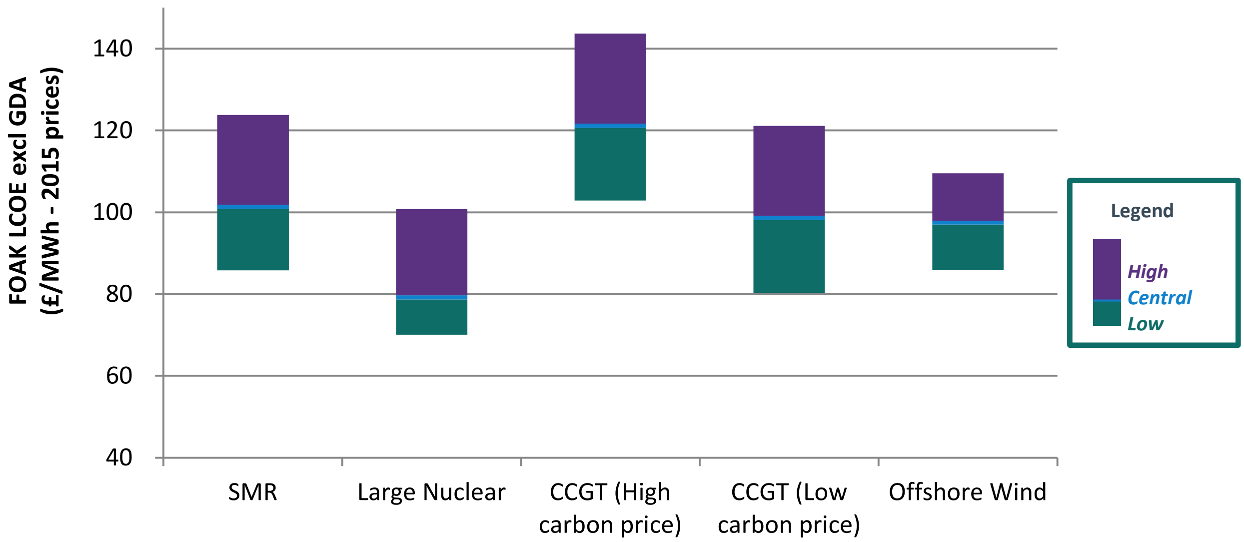
There is significant range in the FOAK cost estimates for the different SMR vendors. It is noted however that of the five vendors, Vendors 1 and 2 provided a much higher quality of cost data, with greater detail around cost items and more supporting explanations. These two vendors can also be classified as having a low technology risk category and relatively low technology costs (i.e. with an OCC or LCOE less than double the NOAK cost of a large nuclear reactor).

The costs for the two best-evidenced vendors (with low technology risk category and relatively low technology costs) have been used for comparing SMR costs against those of counterfactual technologies, for illustrating the potential for cost reduction through learning in Section 5.2.11 and calculating the potential macroeconomic impact in Section 5.4.

[14] The cost of GDA is excluded due to uncertainty around how it will be financed, including around whether the cost of the GDA would be recovered within the cost of the first plant. However the cost of GDA is factored into analysis in Section 5.3 looking at the total cost of an SMR programme of deployment.

In Figure 5-7, the FOAK LCOE for SMRs is compared against the NOAK LCOE for a number of alternative technologies. It shows that the central case FOAK LCOE for SMRs of the most viable vendors is estimated at £101/MWh, with a range of £86/MWh to £124/MWh. These costs have been compared against counterfactual NOAK costs of large nuclear, offshore wind and CCGT, based on draft cost data provided by DECC. The counterfactual costs are £79/MWh for large nuclear, £97/MWh for offshore wind, and between £98/MWh and £121/MWh for CCGT (depending on the assumption around carbon price trajectory)[15]. Thus, SMRs initially have a higher cost than large nuclear and CCGT in a low carbon scenario; however, these counterfactuals are mature technologies that will have already benefited from learning. For SMRs, it can therefore be expected that costs will reduce over time with learning and converge with the counterfactual technologies (refer to Section 5.2.11 for SMR cost reduction potential). The graph also reflects uncertainty around capital costs (as well as commodity prices in the case of CCGT).

Figure 5-7 Levelised costs for FOAK SMR and NOAK counterfactual technologies commissioning in 2031



Therefore, while the FOAK costs for SMRs are likely to be initially higher than for the counterfactual technologies, there may be an economic case for SMRs based on the potential for cost reductions over time due to learning. This is in addition to the potential benefit of SMRs in ensuring security of supply with a low carbon technology that is expected to be both viable without Government debt-financing and that is able to run more flexibly than large nuclear.

5.2.11. SMR cost reductions over time

SMR technology costs are expected to fall over time as the technology becomes more mature and benefits from learning around how to finance, build and operate plants more cost-effectively. The impact of learning on SMR costs has been modelled to show the trajectory with which SMR costs could fall gradually over time, driven by a number of factors:

1. The cost of the GDA need not be repeated following the first plant (although GDA costs are not included in FOAK LCOEs in this report);
2. Learning drives down the capital cost of production;
3. Construction schedules are reduced with further deployment; and

[15] In the high carbon price scenario, prices follow DECC's central projection and reach £224/tonne of CO_2 by 2020. In the low carbon scenario, prices increase to £66/tonne of CO_2 by 2050, rather than as projected by DECC. This trajectory was defined by the CCC as a sensitivity on carbon prices that better reflects UK market expectations (Ref. 15).

4. The cost of capital may fall as institutional investors become more comfortable investing in SMR.

A key part of the economic case for SMRs is the potential for learning to reduce FOAK costs to levels that are competitive against counterfactual technologies.

Large nuclear has seen very limited learning due to a range of factors:

- Due to the large unit size for large nuclear plants, fewer units are built for a given volume of capacity deployed and production is also widely spaced over time (dissipating any potential learning benefit from previous units).
- New reactors are often a different design to previous reactors which inhibits learning. This may be due to the regulatory expectation in the UK to make use of "best practice" with new materials and techniques.[16] Of the 99 nuclear power plants deployed in the US, almost all have different designs (Ref. 67). Similarly, the UK's plans for the next three new nuclear plants are each of a different design (the UK EPR, AP1000 and UK-ABWR).
- Much of plant build takes place on site, rather than in factories. As identified in Project 5-7's report (Ref. 68), site construction provides an environment which is far less conducive to learning.

The potential for cost reduction can be quantified by looking at established learning rates from comparable industries. A learning rate measures the reduction in capital cost that is achieved each time the volume of production doubles. Learning rates differ widely between industries, with large nuclear seeing a learning rate of 1-5% (Ref. 69) while aircraft manufacture has seen learning rates of 18-20% (Ref. 70). SMRs have the potential to significantly increase the rate of learning through a number of factors; the smaller unit size means there is the potential for an increased volume and pace of new orders with greater scope for standardisation, modularisation and factory build.

The SMR learning rate has been estimated in Project 5-7's report by splitting up the constituent parts of the total FOAK cost and looking at benchmarks from other industries. Site material costs are set through global commodity markets and so are not expected to reduce with learning. Site labour costs may achieve a rate of learning of 3-4%, consistent with the experience of large nuclear. However factory production may achieve a learning of 15% where there is production of over 10 reactors per year, or of 8.5% where there is less than one new reactor produced each year[17].

This is illustrated in Table 5-6 below (derived from Project 5-7's findings), which shows four scenarios for the potential learning rates that can be achieved by the SMR industry. The key drivers in the range of learning rates between 5-10% are the share of factory production and the pace of production.

Table 5-6 Application of learning rates to FOAK construction costs

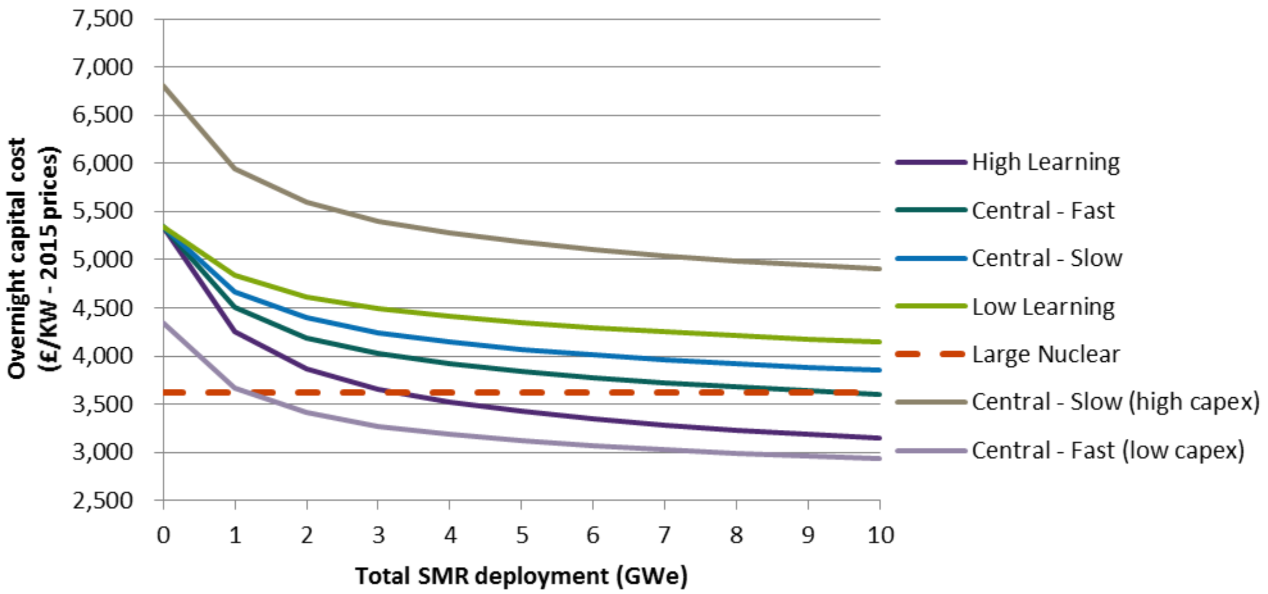
Learning Scenario	CAPEX in factory	Factory learning rate	Reactors / year	CAPEX on site labour	Site labour learning rate	Blended learning rate[18]
High learning	60%	15%	>10/yr.	30%	4%	10%
Central – fast	45%	15%	>10/yr.	43%	3%	8%
Central – slow	45%	11.5%	~5/yr.	43%	3%	6.5%
Low learning	45%	8.5%	<1/yr.	43%	3%	5%

[16] Project 4 emerging findings presentation (reference not available).
[17] Factory-level learning rates are assumed to apply with each doubling in the volume of reactors produced, while site-level learning rates are assumed to apply with each doubling in the volume of plants.
[18] For a single-reactor FOAK plant. Rates will vary according to number of reactors per plant and will reduce over time.

These scenarios demonstrate how SMR OCC may fall over time with learning. This is illustrated for a generic SMR, which reflects the average of the two vendors with lowest cost and technology risk – both of which are multi-module designs. SMR costs fall gradually with learning from incremental deployment and are not modelled as a step-change from FOAK to NOAK costs as other technology costs estimated by DECC.

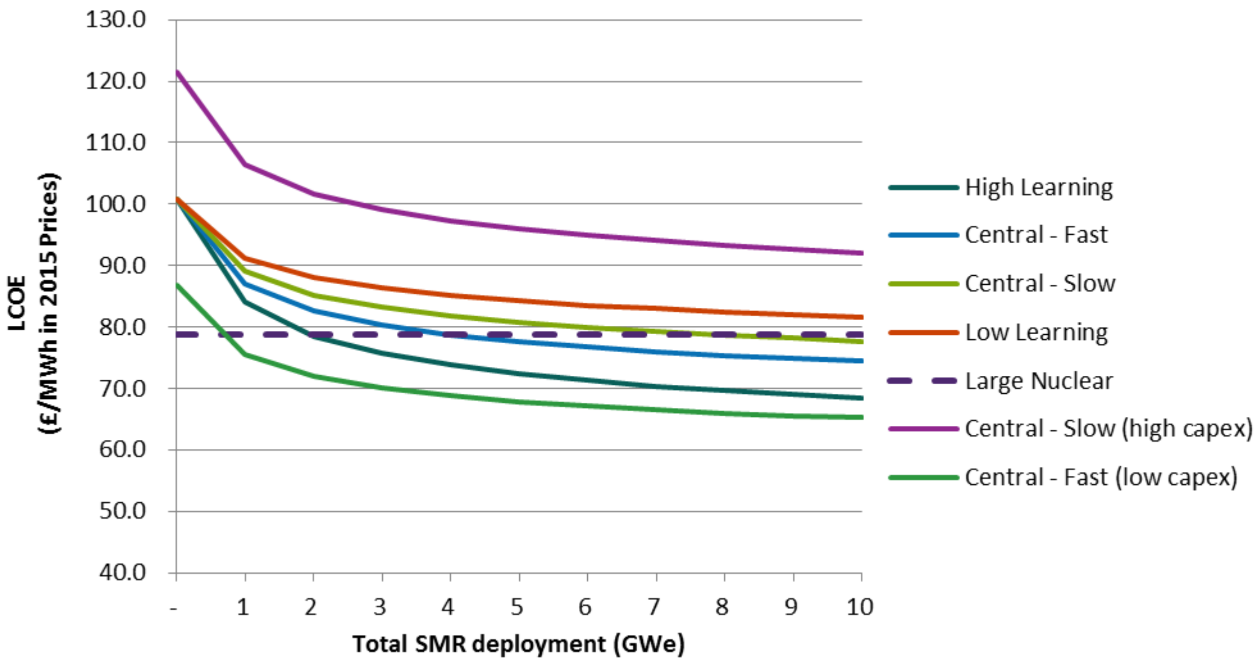
As shown in Figure 5-8, the OCC of SMRs is expected in the central cases to fall below the NOAK cost of large nuclear following around 5 to 8 GWe deployment of SMRs, depending on the pace of that deployment (i.e. over how many years that deployment occurs). However, this also shows that if FOAK capital costs are higher than the central case or if SMRs can only achieve the low learning rate then SMR costs do not become competitive within 10 GWe of deployment against NOAK large nuclear (which is assumed to stay at £79/MWh and not achieve further cost reductions through learning).

Figure 5-8 Effect of learning on construction costs for a generic SMR plant



Construction schedules for SMR sites are expected to reduce by one year for the second plant onwards, which improves the economics of SMRs relative to large nuclear. This is shown in Figure 5-9: SMR levelised costs fall over time with learning, with SMRs becoming competitive against large nuclear after only 5 to 8 GWe of deployment, depending on the pace of that deployment (assuming either Central – Fast or Central – Slow learning rates). To illustrate the scale of this, 8 GWe of SMR deployment could equate to 20 SMR plants each consisting of two 200 MWe reactors.

Figure 5-9 Effect of learning and reduction in build time on levelised costs

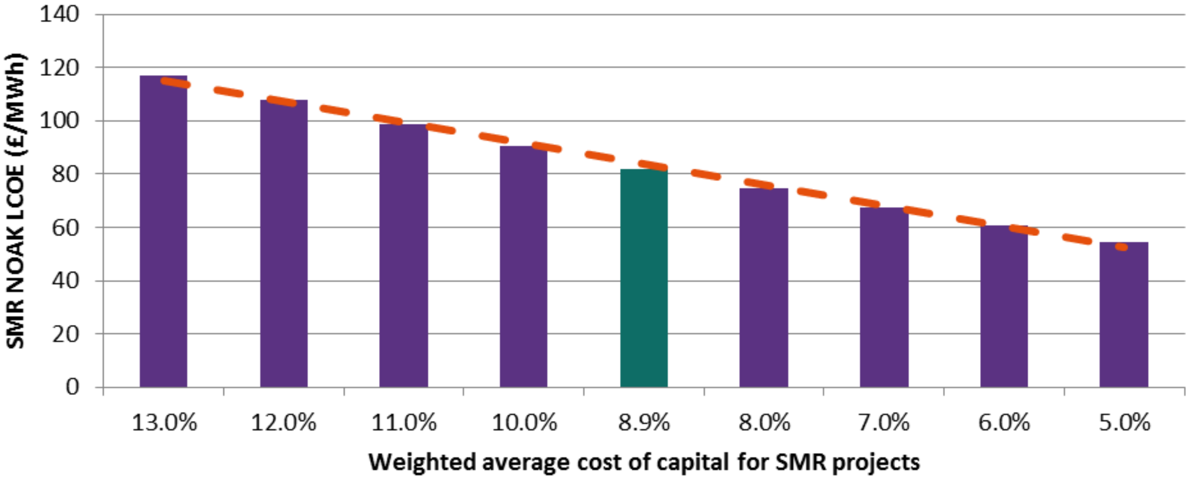


The rate at which SMRs could become cost effective against large nuclear will depend in part on the volume of deployment. If SMRs displaced all new nuclear build expected by DECC in the 2030s (i.e. if 1.65 GWe of new SMR capacity were built per year), then SMRs may become competitive against large nuclear within three years. However, if SMRs are only to be deployed at 400 MWe/year in the UK, and if there are no exports assumed from that design and supply chain, then it may take until 2046 for SMRs to become competitive against large nuclear.

A further significant factor that should be noted is the importance of the cost of capital. If, with greater deployment and learning, NOAK SMRs are able to attract finance from a wider source of investors than large nuclear, and so put downward pressure on the cost of capital, this could have a major impact on the LCOE of SMRs. This is illustrated in Figure 5-10, which shows the LCOE for a NOAK SMR as a function of the cost of capital, with 8.9% as the current estimated cost of capital for large nuclear and for FOAK SMRs[19]. However it is hard to estimate the scale of potential future reductions in cost of capital in the absence of a competitive process facilitating price discovery. The cost of capital will also be sensitive to the types of risk that the Government would be expecting the private sector to take on.

Figure 5-10 Sensitivity of NOAK SMR LCOE to Cost of Capital Assumptions

[19] NOAK costs are used here as it has been concluded within this assessment that it is unlikely that SMR FOAK would be able to achieve a reduction in cost of capital due to lack of operating experience.



NOAK costs, as shown in Figure 5-10, reflect a number of assumptions. Construction schedules are assumed to be a year shorter than for FOAK plants; capital costs incorporate the degree of cost reduction achieved by the end of the five year modelled deployment programme, i.e. reflecting 4.5GWe of global deployment (as set out in Section 5.3.1.2); and GDA costs are not incurred. In the central case, the cost of capital is also assumed to be 8.9%, reflecting the assumption that cost of capital would not be expected to fall within the five year deployment programme modelled for this assessment.

5.3. Welfare Impacts

While LCOE provides an estimate of project costs at a point in time, welfare modelling allows an assessment of the cost of an SMR deployment programme – including consideration of how SMR costs may initially be uncompetitive against mature technologies but then reduce over time with greater learning. This supports an assessment of the trade-off between investing in more established technologies versus SMRs.

5.3.1. Approach

5.3.1.1. Metrics

The welfare implications of a programme of SMR deployment have been modelled, with the use of two key metrics:

1. **Net Present Value (NPV)**: The NPV provides a view of the difference in the cost to society of generation through SMR deployment and that of the counterfactual technologies (over the project lifetime) on the assumption that the technologies are deployed for baseload generation[20]. To calculate NPV, the costs involved in generation from development, financing, and construction to operation of the fleet are calculated, and these costs are discounted using social discount rates to derive a PV. The difference in PV costs between SMR and the counterfactual technologies provides the NPV. It does not include the costs of bringing a technology to the point of initiating the GDA, or the potential benefits of SMR beyond the initial deployment programme. It also does not reflect wider system impacts in terms of affecting wholesale power prices.
2. **Consumer bill impact:** The impact on the annual electricity bill for a typical domestic household of an SMR deployment programme relative to the counterfactual scenario without SMR deployment. The bill impact reflects both the relative cost of electricity generation between technologies as well as assumptions on how costs are ultimately passed on to consumers over time. It has been assumed that the costs of the different technologies are passed on over the entire operational life of the plants in the form of a Contract for Difference (CfD) that tops up the power price to the technology's LCOE.

[20] Except CCGTs, which are assumed to run at a 32% load factor (net of availability), based on DECC input.

5.3.1.2. Deployment Scenario

A five year SMR deployment programme from 2031 to 2035 was modelled, reflecting the earliest credible date of SMR deployment given the lead times of taking technologies through a GDA starting in 2017, and then site licensing and construction.

Over this period, around 400 MWe of SMR deployment in the UK was assumed each year[21]. This level of initial deployment reflects a conservative view of supply chain constraints from the System Requirements for Alternative Nuclear Technologies (ANT) study (Ref. 34), and is supported by some vendor responses that production would initially be limited to building enough reactors for one plant per year. However it is also recognised that the rate of deployment could increase if the environment for new SMR deployment was sufficiently improved. For example, this could include the introduction of measures to address nuclear certification challenges, skills shortages and commitments to minimum volumes of deployment to entice investment in a UK nuclear supply chain.

It has also been assumed that there will be additional global deployment of SMR capacity of the same design and via the same supply chain as the SMR capacity deployed in the UK. This deployment to other markets is assumed to be 500 MWe per year in the central scenario and between 300 MWe and 760 MWe per year in the low and high learning scenarios. The derivation of this is shown in Table 5-7.

The assumption around global deployment builds on the NNL Feasibility Study (Ref. 1). That study estimates that a global SMR market size of between 72 to 86 GWe deployed globally between 2025 and 2035 could develop in a scenario where SMR technology is cost effective against counterfactual technologies. International market assessment is beyond the scope of this study. It is noted, however, that the assumed deployment in the NNL study appears very aggressive and is based on the assumption that SMR is cost competitive against counterfactuals. The assumption around global deployment is important in determining how rapidly SMR costs reduce over time, as well as the macroeconomic opportunities that can be realised from supporting a UK SMR industry (assessed in Section 5.4). Therefore, an investment case for SMRs will need to critically assess the global market potential and its price sensitivity.

Table 5-7 Assumed deployment of SMR capacity (GWe)

Assumption	Source	Low	Central	High
UK deployment 2031 to 2035 (GWe)	ANT assessment of initial constraints on UK SMR deployment	2.0	2.0	2.0
Global deployment up to 2035 (GWe)	NNL Feasibility Study	72.0	75.0	86.0
Global deployment up to 2025 (GWe)	NNL Feasibility Study	20.0	20.8	21.5
Global deployment: 2026 to 2035 (GWe)	Difference between NNL deployment to 2025 and to 2035	52.0	54.3	64.5
Global deployment: 2031 to 2035 (GWe)	Assumed to be half of volume from 2025-2035 estimate	26.0	27.1	32.3
Non-UK deployment: 2031 to 2035 (GWe)	Nets UK deployment assumption from NNL global deployment figure	24.0	25.1	32.3

[21] To ensure a fair comparison between SMR and counterfactual technologies, the capacity deployed has been adjusted to ensure the capacity built supports the same level of generation as each other, with 400 MWe reflecting the level of deployment for large nuclear. Given the assumption of a slightly higher availability factor for SMR than for large nuclear, this means that 392 MWe of SMR deployment is modelled per year.

Assumption	Source	Low	Central	High
Number of global SMR vendors assumed	EY assessment of number of vendors market might support and likely barriers to export.[22]	16	10	8
Non-UK deployment from UK SMR vendor (GWe): 2031 to 2035	Non-UK deployment assumed to divide equally between number of global SMR vendors	1.5	2.5	3.8
Total deployment from UK Vendor (GWe): 2031 to 2035	Addition of UK and non-UK deployment from UK vendor	3.5	4.5	5.8

5.3.1.3. Counterfactuals

The cost of SMR deployment is measured against a counterfactual of the UK sourcing the same level of generation from alternative technologies, in particular, large nuclear, offshore wind and CCGT.

In order to assess technology costs on a comparable basis, the modelling has assumed a deployment capacity of each technology consistent with the generation expected from 400 MWe of large nuclear capacity. In the case of offshore wind and CCGT it is also assumed that plants are replaced at the end of their life in order to model 60 years of generation, consistent with the assumed lifespan of nuclear (plant replacement costs are included within modelling). The costs of counterfactual technologies have been provided by DECC (Refs 59, 60 and 61). NOAK technology costs are assumed for the counterfactuals with no further cost reductions through learning assumed for the counterfactuals.

5.3.2. Results

5.3.2.1. Levelised Cost over deployment programme

The LCOE for a generic SMR plant has been modelled using a low, central and high cost sensitivity for the five years of assumed deployment to enable an assessment of the cost of a 2 GWe total programme of SMR deployment. The scenarios reflect the estimated range in OCCs as well as the range in the rate of learning applied over time[23]. For modelling purposes, it is assumed that the cost of taking SMR through GDA is entirely recovered by the FOAK plant. This is a modelling simplification to ensure that the cost of the GDA is captured within the cost of a fleet deployment. Based on this, the most significant cost reduction in SMR is in 2031, with SMR costs falling 30% by 2032. This is due to the inclusion of GDA costs within plant commissioning in 2031, the reduction in assumed construction schedule from 2032, and cost reduction through learning achieved through the first 0.9 GWe of deployment of the SMR.

Costs of the counterfactual technologies remain broadly constant over time due to the counterfactuals being relatively mature technologies, although there is a modest reduction in the cost of offshore wind and CCGT between 2031 and 2055. This is in keeping with DECC assumptions on technology price adjustment factors.

Figure 5-11 Levelised costs for deployment of SMR and counterfactual units in welfare modelling

[22] Barriers include challenges to having a standardised licensed design, potential requirements for vendors to source from local supply chains, and geopolitical challenges to exporting to multiple global partners (e.g. Russia, USA and China).
[23] The learning rate for the Central scenario reflects the "Central-Slow" learning rate in Table 5-6, in this scenario up to ten reactors per year are modelled to be produced for global deployment via a single supply chain.

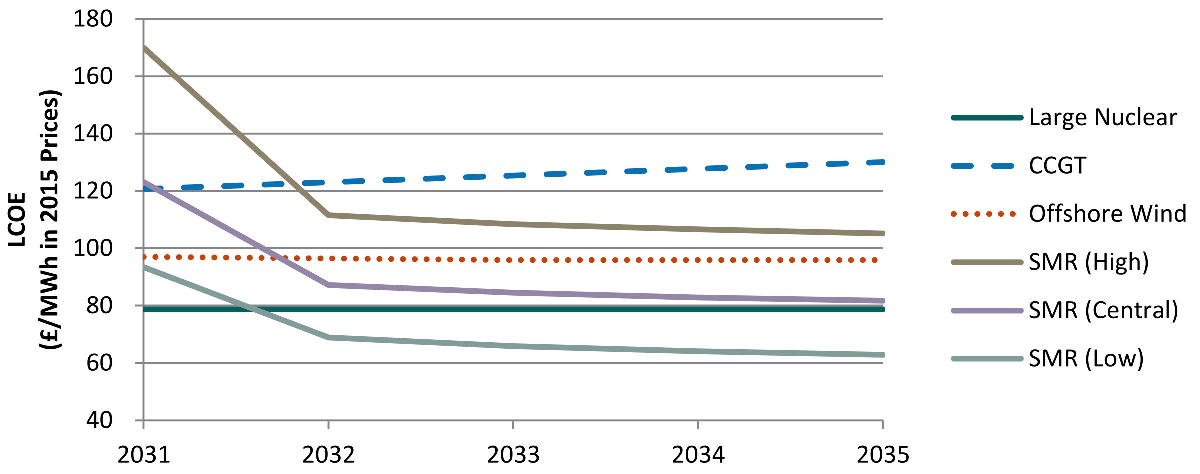


Figure 5-11, the LCOE for new SMR plants in the central case is expected to converge with that of large nuclear over the course of the 5 year deployment programme. SMR costs are also expected to become competitive against offshore wind and CCGT. Large nuclear remains the most cost effective technology throughout the period under the medium case.

5.3.2.2. Net Present Value

The total societal costs of the deployment programme in each year have been modelled, and these costs have been discounted to 2015 using social discount rates to provide a PV, as set out in Treasury's Green Book (Ref. 71), with discount rates starting at 3.5% and falling gradually towards 2.5% by the end of the modelling period.

Equivalent PV costs have been calculated for each of the counterfactual technologies. The difference in costs between the SMR programme and each of the counterfactual technologies provides a NPV, which illustrates the total benefits to society of the SMR deployment programme relative to drawing an equivalent amount of generation from an alternative technology. This is shown in Figure 5-12, which breaks down technology costs into the key constituent parts – development, construction and operating costs, the cost of capital for financing projects over their operating lifetime, and the capacity cost of providing an equivalent level of reliable capacity to CCGT. The capacity cost is calculated by looking at the difference in reliable capacity provided by each technology, based on 2015 Capacity Market Auction Guidelines (Ref. 72) and DECC's 2014 projection for future capacity prices (Ref. 73).[24] The Capacity Market price is used as a proxy for the capital, operating, financing and fuel costs of the extra capacity that would be procured to ensure sufficient generating capacity to maintain security of supply.

It should be noted that there are a number of limitations to the modelling of NPV:

- The modelling reflects the central cost estimate for a generic SMR vendor and the assumption of 2.5 GWe deployment of the same SMR design outside the UK;
- The modelling does not capture the cost of bringing technologies to the point of starting the GDA process;
- The modelling does not reflect uncertainty in the counterfactual costs, for instance around the fuel costs or load factor of CCGT new build, which could vary significantly;

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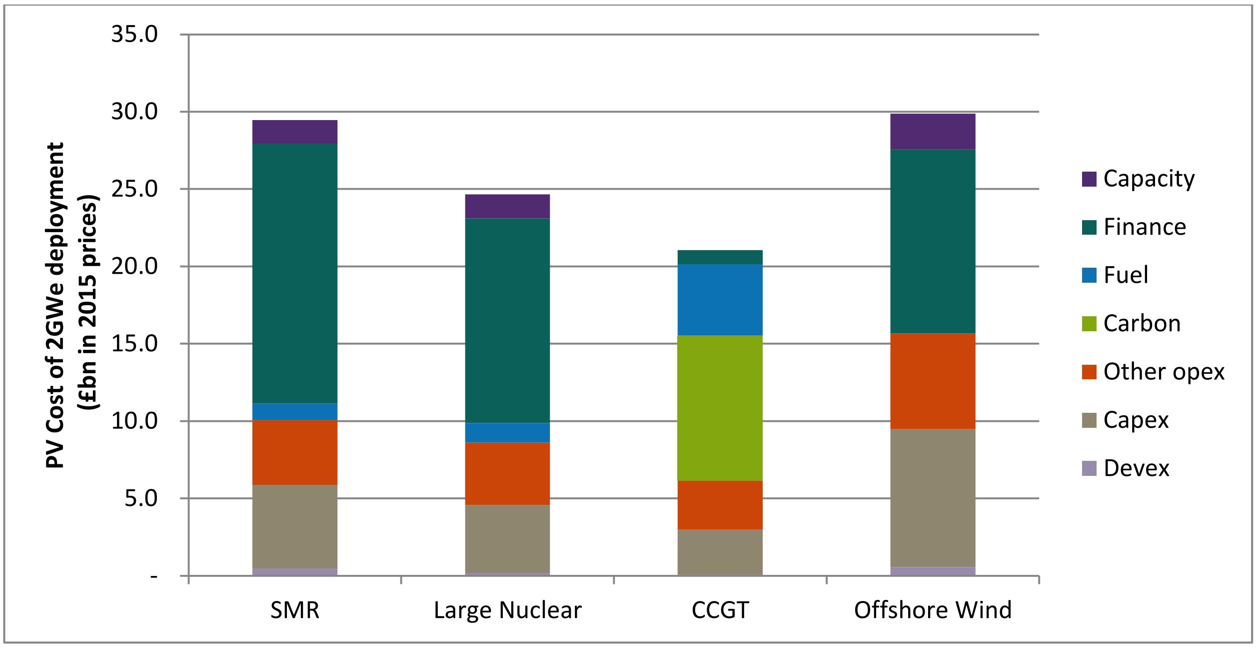
[24] A de-rating factor of 82% for large nuclear and SMR, 89% for CCGT and 22% for offshore wind has been applied, with the factors for thermal plant taken from DECC's 2015 auction guidelines (Ref. 72) and the offshore wind factor provided by DECC. It was assumed that any shortfall in reliable capacity between technologies would have to be procured at a cost of £31/kW year, based on DECC's projection for future market capacity prices (Ref. 73). £31/kW year is derived by taking the average modelled price over the period 2018 to 2030 (replacing projected prices for the first two years with outturn prices), to provide a long-term average price expectation for the capacity market.

- It does not take account of potential macroeconomic benefits to developing an SMR industry, which are assessed separately in Section 5.4; and
- It does not take account of wider system impacts of SMR on the wholesale electricity market which may, on balance, be beneficial.

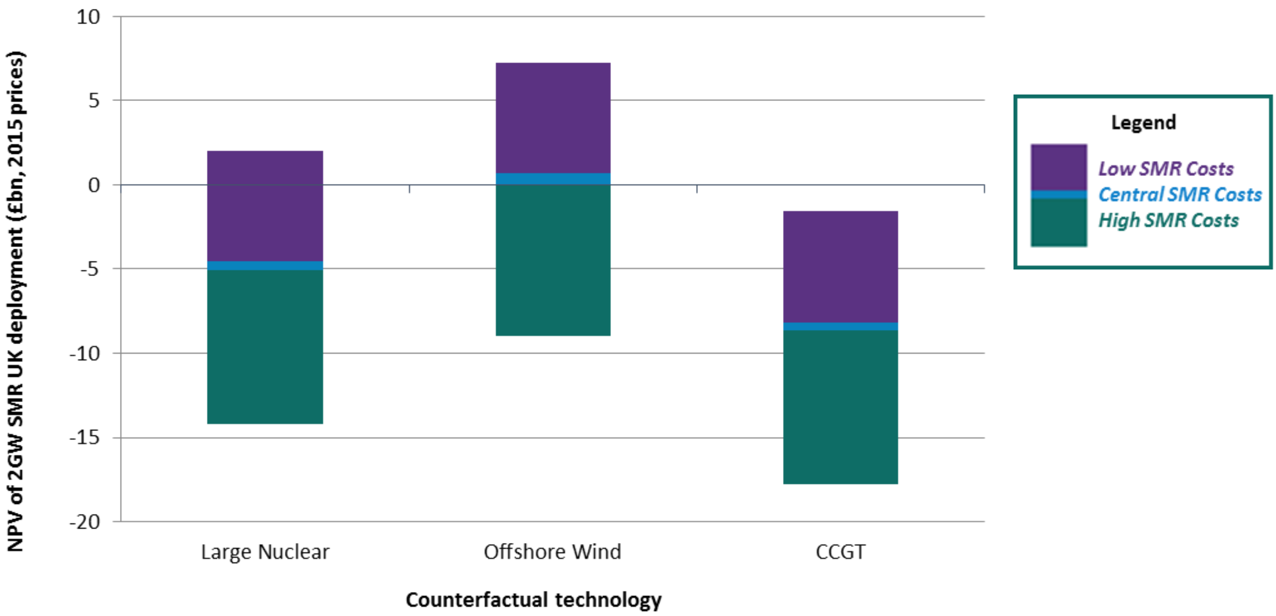
Figure 5-12 Societal cost of 2 GWe deployment programme of SMR and counterfactuals



As indicated in Figure 5-12, SMR has a PV cost of generation at £29.5 billion, which is higher than the equivalent figure of £24.7 billion for large nuclear, a difference of £4.8 billion. The difference can be explained by the high initial construction costs per MWe as well as the additional cost of taking SMR through a GDA process relative to large nuclear (which is assumed to have already gone through the GDA process). SMR has a positive NPV of £0.4 billion relative to offshore wind, and a negative NPV of £8.4 billion relative to CCGT.

The NPV of an SMR deployment programme is sensitive to assumptions around FOAK SMR costs, learning rates and volumes of deployment as well as counterfactual costs. Figure 5-13 below shows how the NPV for 2 GWe of UK SMR deployment varies with high and low SMR costs, with the range reflecting the high and low SMR capital costs as well as a range in learning rates (between 5% and 10%).This range does not however reflect uncertainty around counterfactual costs. In Figure 5-13 'Low SMR costs' reflect low capital cost and high learning at 10%, 'Central SMR costs' reflect central capital cost and learning at 6.5%, and 'High SMR costs' reflect learning at 5% with high capital cost.

Figure 5-13 NPV of 2 GWe SMR deployment relative to counterfactual technologies



There are qualitative advantages to SMR deployment that are not captured in the NPV modelling. SMR capacity provides more reliable baseload capacity relative to offshore wind and is slightly more flexible than large nuclear. There are security of supply benefits of SMR in relation to CCGT, by reducing dependence on fossil fuel imports, and to large nuclear, by making new nuclear easier to finance and so less reliant on the UK government to provide debt-finance. SMR may also provide benefit relative to CCGT in contributing to the decarbonisation of the UK power sector. While the carbon costs for CCGT are priced into the NPV analysis, it is uncertain that running CCGT as baseload over the modelled period would be consistent with the UK's target for reducing CO_2 emissions by 80% by 2050 (Ref. 74), with deployment of CCGT leading to an additional 2700 tCO_2 emitted per year relative to the low carbon technologies[25].

The most significant cost for both SMR and large nuclear is the financing costs. This reflects the assumptions of an 8.9% cost of capital and a 60-year debt payback period. It has been assumed that the economic lifetime of the plant is the same as the technical lifetime – i.e. it takes 60 years to fully recover costs on a nuclear project against 25 years for CCGT and 22 years for an offshore wind farm. However, if the project costs were allowed to be recovered through a shorter period then this would reduce the financing cost for each technology but particularly for nuclear. [26]

5.3.2.3. Longer Term Impacts

The impact of a longer deployment has also been assessed to gauge whether there are benefits to SMR from reduced technology costs beyond an initial 2GWe deployment programme.

To make this assessment it has been assumed that there will be UK SMR deployment of 400 MWe of SMR capacity commissioning in the UK each year between 2031 and 2040 and then increasing to 800 MWe commissioning each year between 2041 and 2050 (based on assumptions around supply chain constraints from ETI's ANT study (Ref. 34)). It is also assumed that global deployment of the SMR design deployed in the UK remains constant at 500 MWe commissioning each year between 2031 and 2050. This equates to a total of 12 GWe of UK deployment and 10 GWe of deployment abroad commissioning over the period to 2050.

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[25] DECC's 2012 Gas Generation Strategy (Ref. 74) notes that "by 2049, unabated gas could still have an important role to play in ensuring a secure and flexible, low-carbon system, albeit operating much less than it does today."
[26] This is because nuclear financing costs apply a 8.9% discount rate, whereas societal benefits from the plant beyond the financing period would be discounted at the social discount rate of 3.5%.

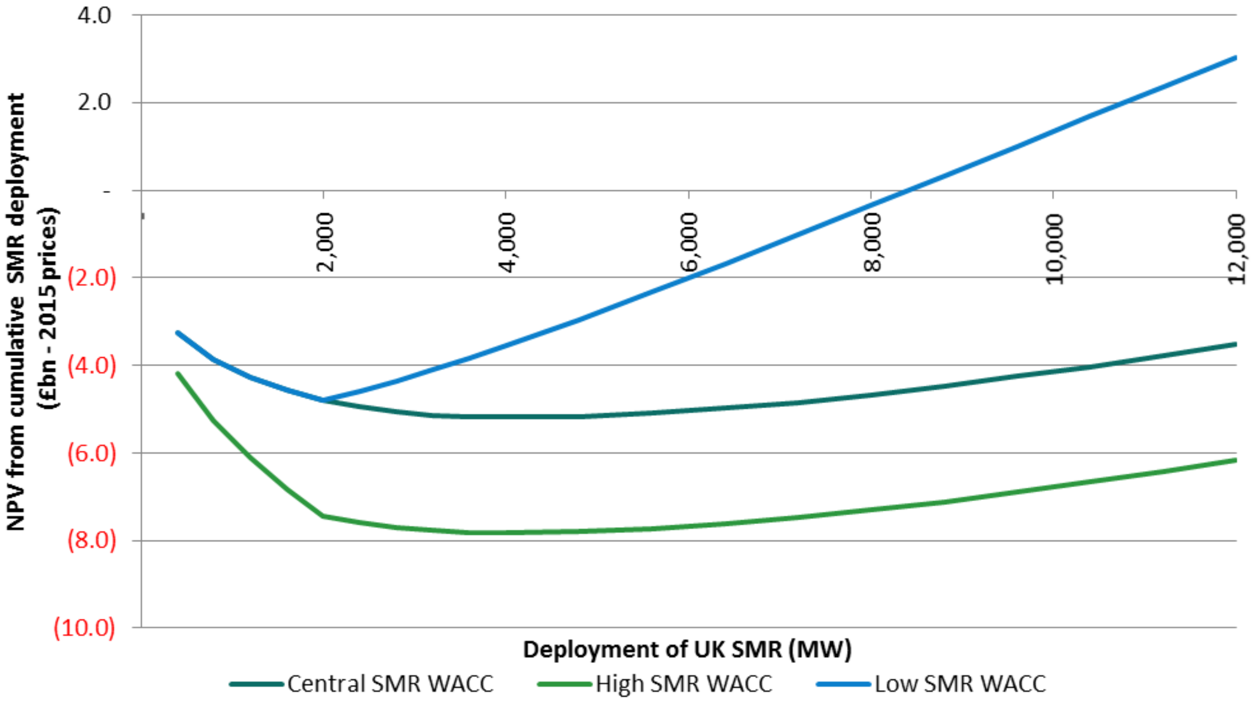
The NPV of long-term SMR deployment relative to large nuclear has been modelled under three scenarios:

1. **Central SMR WACC:** the SMR cost of capital remains the same as large nuclear (8.9%) throughout.
2. **Low SMR WACC:** the cost of capital is initially the same as large nuclear but then falls by 1% (i.e. to 7.9%) for SMR plants commissioning after 2035. This scenario reflects the possibility that investors may in time attach a lower risk to investment in SMR due to the smaller project size and construction risk.
3. **High SMR WACC:** the cost of capital is assumed to be 1% higher than large nuclear (i.e. 9.9%) for SMR plants commissioning over the first five years before reverting to the central case for plants commissioning after 2035. This scenario reflects the possibility that investors may initially attach a high risk premium to SMR due to it being seen as an innovative technology.

In each scenario the central capital costs and learning rate for SMR are applied and the SMR cost is compared against the cost of an equivalent volume of generation from large nuclear (which has a LCOE of £79/MWh throughout).

The results of the long-term NPV analysis are shown in Figure 5-14. This shows that SMR is found to have a NPV of -£3.5 billion for deployment to 2050 in the central scenario. The NPV in this case improves as UK deployment exceeds 4 GWe (at which point incremental SMR plants become cost effective against large nuclear) but remains negative throughout the modelled period. The negative NPV finding can be attributed to the fact that technology cost reductions become slower with greater deployment as the technology becomes more mature and that long-term cost savings from SMR are heavily discounted. This is also the case in the high WACC scenario, with an NPV of -£6.2 billion for deployment to 2050. However if SMR is able to achieve a lower WACC than large nuclear then the NPV becomes positive more quickly, after 9 GWe of UK SMR deployment, reaching +£3.0 billion by 2050.

Figure 5-14 NPV sensitivity for a long-term deployment programme of a generic SMR relative to large nuclear



5.3.2.4. Impact on consumer bills

The implications of the differences in generation costs between technologies has been modelled to provide an estimate of the potential impact of an SMR deployment programme on consumer bills relative to a counterfactual scenario of large nuclear.

It has been assumed that consumers are charged a price that pays the LCOE for output from each technology throughout the operational life of the plant. This is because neither large nuclear nor SMR are modelled to be commercially profitable on the basis of DECC's projected power prices alone. Therefore some form of additional support would be needed to allow the generator to at least break even and this is assumed to come from the consumer.

A further key assumption for SMRs is that the reduction in technology costs with learning is passed on to consumers. However, there is likely to be asymmetric information between the vendor and Government around technology costs, as well as significant barriers to entry for SMR vendors in the UK due to the time required for GDA and the volume of deployment needed to get down the cost curve. This means that the SMR vendor might in practice be able to avoid passing on all the technology cost reductions associated with learning. It is also assumed that SMR deployment does not impact on wholesale power prices. However, if SMR deployment is displacing CCGT, this could dampen wholesale power prices, offsetting the impact of SMR support costs on consumer bills.

The impact of a 2 GWe UK SMR deployment programme relative to large nuclear is increased costs to consumers by on average £200 million per year through the 60-year operational life of the plant. This equates to a typical impact on domestic household bills of +£2/year relative to large nuclear, +£1.10/year relative to offshore wind and -£1.10/year relative to CCGT, based on estimates of support costs and on unpublished data provided by DECC on the value of electricity sales per household.

5.4. Macroeconomic Impact

The objective of this section is to provide a view of the potential macroeconomic footprint of the manufacture of SMRs in the UK. This will offer an insight into the potential for the UK to capitalise on the supply chain opportunities created by the deployment of UK manufactured SMRs.

Data from secondary research, vendor submissions and DECC cost of generation data for counterfactuals was used for the macroeconomic estimates, with assumptions made where necessary to supplement this data. These estimates are largely driven by the scale of investment in SMRs, the export potential and crucially the level of UK firms' participation in the supply chain. The results of this analysis should be viewed as illustrative of a range of possible outcomes (low, medium and high) which are contingent on the underlying assumptions.

The measures that are used to quantify the potential aggregate economic impact to the UK include:

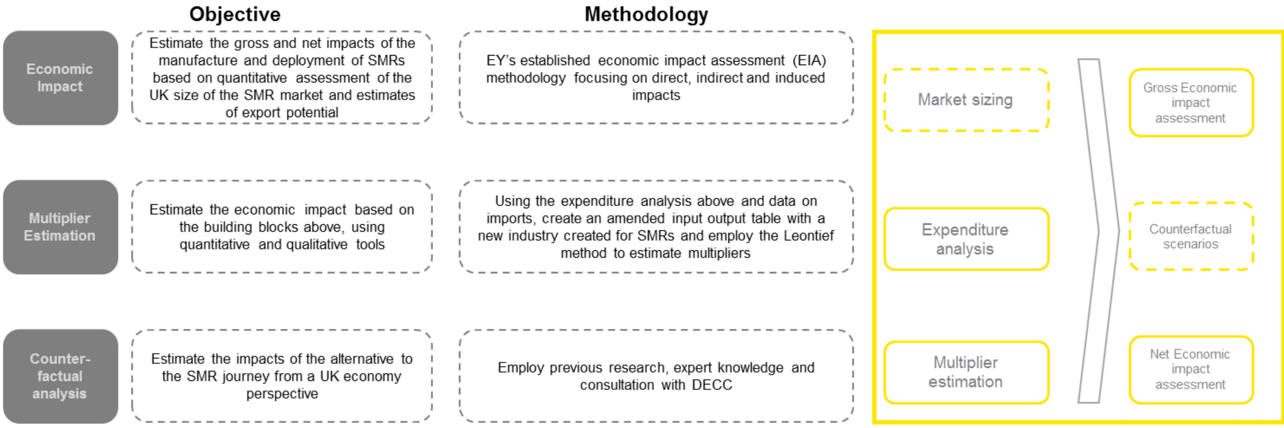
- Output: this measures the sales value of UK manufactured SMRs and related services that occur in the UK.
- Value Added: this is an estimate of value generated for the UK economy as a result of an organisation's or industry sector's activities. This is shown as either the Gross Value Added (GVA), reflecting the impact of the SMR industry, or as the Net Value Added (NVA), reflecting the incremental impact of the SMR industry relative to the counterfactual scenario.
- Employment: this is the number of additional jobs created as a result of the expenditure made by the industry.
- Tax contributions: this measures the total tax revenues (corporate and income taxes) generated for the government.

All impacts are shown as either gross or net. Gross impacts reflect the potential direct economic impact of a UK SMR industry, including the costs to develop, manufacture and operate SMRs in the UK and the wider supply chain, as well as the activity supported through the employment within the supply chain. Net impacts represent the incremental value generated by a UK SMR industry relative to a scenario where an alternative generating technology is deployed.

5.4.1. Approach

The key drivers influencing the magnitude of the macroeconomic impact of the SMR industry include the potential number of SMRs that will be manufactured for UK deployment and the “build and run”[27] expenditure (2017-2050) attributed to it, the level of UK firms’ participation in the UK supply chain linkages (represented by Keynesian multipliers[28]) and the export potential. The approach is shown in Figure 5-15.

Figure 5-15 Approach overview



5.4.1.1. Economic impact analysis

Economic impact analysis provides a quantitative avenue to estimate the wider economic benefits and the contribution that an intervention, project or industry brings to the economies where it is located. This analysis focuses on the interaction of an SMR industry with its supply chain. This enables estimation of GVA and its consequent employment and tax revenue implications. The SMR supply chain assumptions have been developed from vendor submissions and expert analysis.

Three types of economic impacts are highlighted:

- Direct impacts: The impact of direct expenditure on SMR output;
- Indirect impacts: The impact of the suppliers in the SMR industry’s supply chain; and
- Induced impacts: The impact of firms outside the industry or supply chain caused by expenditure from employees in the SMR supply chain.

These economic impacts are shown for GVA, employment, and tax contribution. GVA is calculated as the value of total revenue from SMR less its expenditure on goods or services purchased from other organisations. The GVA impact is then translated into an impact on jobs, using estimates of worker productivity (GVA per worker).[29] The tax contribution is estimated as the potential impact on corporate and income taxes as a consequence of the development of an SMR industry[30].

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[27] Assumed capital and operating expenditure for SMR deployment in the UK (at cost)

[28] Keynesian multipliers measure how much economic activity changes in response to an exogenous change in spending

[29] This is based on data relating to economic activity per worker provided by the Office of National Statistics (ONS) and Business Register and Employment Survey (BRES) to estimate labour productivity for the machinery and equipment manufacturing sectors.

[30] Taxes are estimated on the basis of the average tax rates of the manufacturing sector and the income tax payable (including national insurance contributions) per worker.

Multipliers estimation

Multipliers capture economic interdependencies on respective industries' supply chains and the wider economy. This provides an estimate of the indirect and induced impacts on Gross Domestic Product (GDP).

Economic multipliers were calculated in order to estimate the economic impact. These show how the share of the value of production in each industry is accounted for by inputs from other industries. Supply and Use Tables published by the Office for National Statistics (ONS) were used to calculate these multipliers. These tables map an industry's supply chain through the calculation of input coefficients. These coefficients capture what share of the value of production in each industry is accounted for by inputs acquired from other industries. Using such coefficients, output multipliers can be calculated that capture the additional demand generated in each industry if production is increased by one unit of currency in a specific industry.

Counterfactual analysis

To calculate the net impacts of SMR, the gross impacts of SMR are calculated and compared against that of counterfactual technologies; large nuclear, CCGT and offshore wind. In each scenario, it is assumed that SMR is displacing the level of generation provided by 2 GWe of SMR deployed in the UK, with no export upside assumed.

5.4.2. Drivers of the Economic Impact

5.4.2.1. Potential size of the industry in the UK

The expected number of SMRs that will be manufactured in the UK comprises of an estimate of the number and value of SMRs that will be built and deployed in the UK, and, importantly, the number of SMRs that will be manufactured in the UK and which will be exported and deployed overseas. The underlying assumptions used in the analysis are set out below.

- The deployment of SMRs will contribute 2 GWe of capacity in the UK between 2031 and 2035.
- SMRs deployed in the UK will be manufactured in UK factories.
- There is a potential for UK-built SMRs to be exported to and deployed in overseas markets.
- UK manufactured SMRs will capture about 10% of the global market. [31]

All estimates should be considered in the context of the significant degree of uncertainty around the potential scale of deployment of SMRs in the UK and globally.

5.4.2.2. Potential UK supply chain capability

The ability of a UK-based supply chain to provide a significant proportion of the components for the UK deployment of SMRs is critical to realising the full benefits to the UK economy following investment in a UK SMR industry.

Local participation in the supply chain is important because where demand for intermediate goods and services can be satisfied internally by firms in the UK, further economic activity is generated via multiplier effects. Conversely, imports of intermediate inputs represent leakages from the UK economy and contribute to economic activity elsewhere.

A key challenge for the UK will be to develop a fully functioning and responsive indigenous supply chain capability that will be able to meet the needs and expectations of potential vendors. This could be achieved either through building up UK capability, or through partnering with international vendors to establish local manufacturing facilities.

As discussed in Section 4.3.6, consultations with vendors were used to inform an estimate of the ability of a UK based supply chain to meet the requirements for the development of an SMR industry. According to an analysis of vendor submissions, the UK supply chain could deliver between 68% - 89% of the intermediate

[31] See explanation on Section 5.4.2.3

input requirements of factory manufactured SMRs that will be deployed in the UK. This range was provided by vendors for a variety of different SMR technology types.

The questionnaire categorised the supply chain into a number of constituent elements. Adjustments were made to the vendor responses to account for optimism bias, and any inconsistencies in the response (for example, related to the definition of a UK-based supply chain). These adjustments were informed by studies of large nuclear supply chain capabilities in the UK (Ref. 48 and Ref. 75). The resulting estimate (post adjustments) for the proportion of intermediate inputs for the manufacture of SMRs from a UK supply chain was 70%, assuming the relevant interventions are in place (with current capability of up to 55% as mentioned in Section 4.3.6).

The estimate of 70% assumes a favourable regulatory and economic climate for the choice of technology and reactor design (with Government intervention and implementation of the Nuclear Supply Chain Action plan as mentioned in Section 4.3.6).

5.4.2.3. Export potential

Assuming that manufacturing capability for SMRs can be established in the UK, there is potential for export capability to be developed. This would provide additional sources of income to drive UK economic development and growth. The proportion of the potential export market that UK firms are able to capture will depend on the UK becoming a base for a renowned designer of SMRs as well as the development of an established SMR manufacturing industry.

As set out in Section 5.3.1.2, it is assumed that between 24 and 32 GWe of SMRs will be deployed outside the UK between 2031 and 2035, of which between 1/8th and 1/16th will be produced by the vendor supplying and basing itself in the UK. Export potential is likely to be vendor specific. There is a possibility that certain SMR manufacturers have existing overseas supply chains or favour situating their factories outside the UK, despite the SMR being deployed in the UK. In this scenario, a significant proportion of the value will not accrue to the UK.

Exports could take the form of the development or acquisition of IP rights on a proprietary SMR design and the sale of licences to local manufacturers / vendors. Although IP has not been assessed from a quantitative perspective, it also has the potential to boost UK SMR export revenue.

5.4.2.4. Costs for UK manufactured SMRs

The total costs required to manufacture and deploy SMRs derived from cost modelling discussed in Section 5.2 were used to estimate the economic impact to the UK of the manufacture of SMRs. These total costs include GDA, licensing, construction and operational costs (aggregated from 2017 to 2040) incurred in the deployment of 2 GWe capacity in the UK as well as the 2.5 GWe capacity for exports. These costs exclude any margin taken by the supplier and financing costs. Table 5-8 presents illustrative real SMR total costs for in-country and overseas deployment between 2017 and 2040.

Table 5-8 SMR total programme costs – (£ billion in 2015 prices, aggregated 2017 to 2040)

Location	Capacity (GWe)	Low scenario (£billion)	Medium scenario	High scenario
UK deployment	2.0	9.6	12.4	16.1
Overseas deployment	1.5/2.5/3.8	3.8	9.0	18.9
Total		**13.4**	**21.4**	**34.9**

5.4.3. Results – Gross Impacts (2017 to 2040)

The economic impact is premised on UK manufactured SMRs delivering 2 GWe of UK generation capacity and the UK as an exporter of SMRs to overseas markets.

Except otherwise stated, economic impacts estimates provided in this section are in real terms and undiscounted.

5.4.3.1. UK deployed SMRs and exports

UK deployment assumptions

This analysis is based on three scenarios, each assuming 2GWe of SMR deployment in the UK at a different cost between 2017 and 2040. This gives rise to three different expenditure profiles[32] (Low, Medium and High) as shown in Table 5-9 and Figure 5-16. These expenditure profiles are based on cost data estimated for a generic SMR.

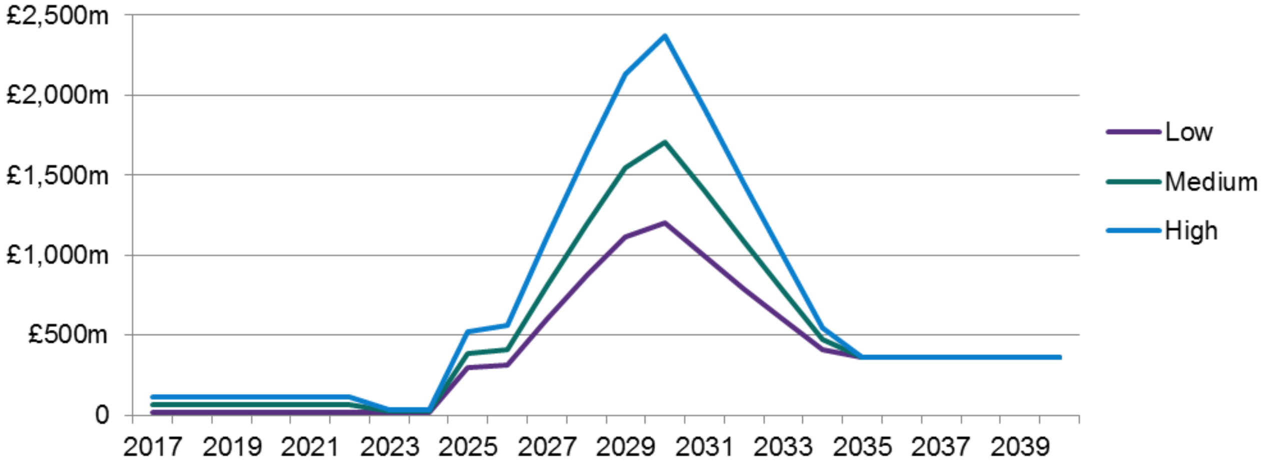
These initial expenditure profiles were then adjusted for a minimum return requirement in the form of a Weighted Average Cost of Capital (WACC) of 8.9% to assess the real "selling price" of an SMR. This is because estimating the impact on an economy is dependent on the change in final demand of a product. In this case the final demand of SMRs is the product of the assessed real selling price and the number of units built.

Table 5-9 Aggregate "build and run" expenditure scenarios for UK deployment (up to 2040)

	Low	Medium	High
Total build and run cost of 2 GWe of SMR (£million)	9,600	12,400	16,100
Total cost per GWe incurred (£million)	4,800	6,200	8,100
Scenarios of % of total SMR cost that could be captured by UK supply chain in the case of UK deployment	70%	70%	70%

[32] Including capital and operating expenditure

Figure 5-16 Annual SMR "build and run" expenditure scenarios for the UK



Export potential

In order to assess export potential, the same three (Low, Medium, High) capacity deployment scenarios have been used for the rest of the world (ROW), coupled with an assumption of "UK supply chain readiness". This market share itself depends on the number of other players who will compete with a single UK manufacturer on the SMR market.

Table 5-10 Global Deployment Assumptions for SMR

	Low	Medium	High
ROW deployment (excluding UK) from UK vendor in GWe	1.5	2.5	3.8
Total cost per GWe incurred (£million)	2,500	3,600	5,000
% of total SMR cost that could be captured by UK supply chain in the case of global deployment [33]	53%	53%	53%

Nature of Gross Impacts

The estimates in this section are gross macroeconomic impacts of the UK manufacture of SMRs. Gross impacts show the absolute size of economic activity and employment generated by the manufacture of SMRs and do not take into account the displacement of alternative technologies.

The expected gross economic impacts of the UK manufacture of SMRs are shown in Table 5-11.

Direct Impacts (undiscounted)

Based on the assumptions detailed previously, this section highlights the direct effects of capital and operating expenditure met by UK-based suppliers as part of the deployment of a defined SMR power capacity in the UK and abroad between 2017 and 2040.

Table 5-11 shows the range of real direct economic contributions that could be expected under the three deployment scenarios, including UK-manufactured exports. In each case, exports are presented in brackets.

[33] It is expected that some construction/deployment/installation work will be required in the country of deployment. This 53% supply chain assumption refers to UK manufactured and overseas deployed SMRs. For UK deployed and UK manufactured SMRs, an assumptions of 70% of the supply chain owned by local firms' participation is used (Table 5-9).

Table 5-11 Direct impacts of UK manufacture of SMRs undiscounted 2017 to 2040

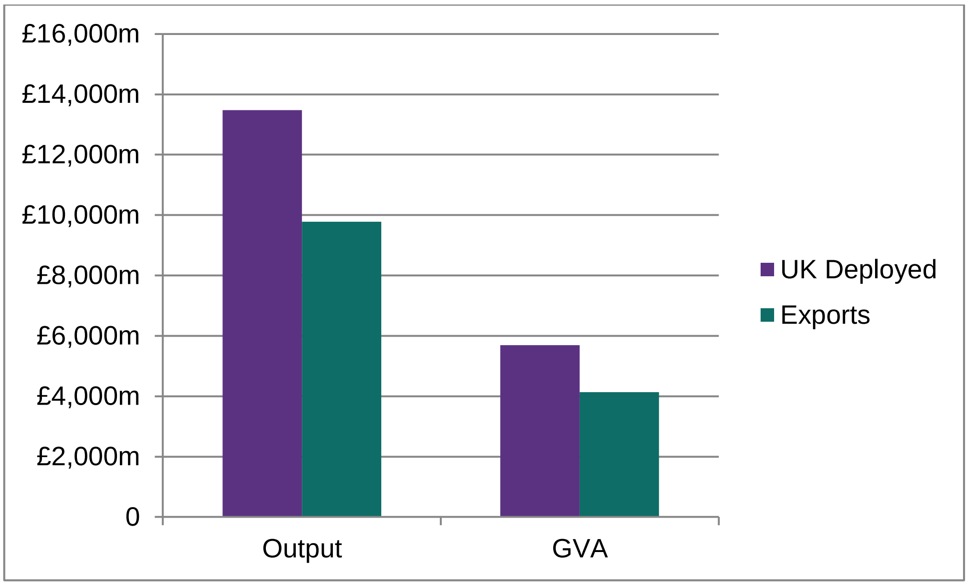
Direct Impacts	Low scenario	Medium scenario	High scenario
Output (£billion)	14.6 (4.1)	23.3 (9.8)	38.1 (20.1)
GVA (£billion)	6.1 (1.7)	9.8 (4.1)	16.1 (8.7)
Tax (£billion)	2.1 (0.6)	3.4 (1.5)	5.6 (3.0)
Average annual jobs	2,500 (1,000)	4,000 (2,300)	6,600 (4,800)

The direct output is derived from the expected revenues that could be generated from the sale of SMRs. These potential revenues are extrapolated from the total SMR costs in Table 5-8 for both UK deployed SMRs, and UK manufactured SMRs that are subsequently exported. The GVA contribution is then gross output less the cost required to produce the output (known as intermediate consumption).

The results (Table 5-10 and Table 5-11) show that the impact of the programme (UK deployed and exports) would result in an increase in output of between £14.6 billion and £38.1 billion to the UK. This will generate GVA of £6.1 billion to £16.1 billion[34].

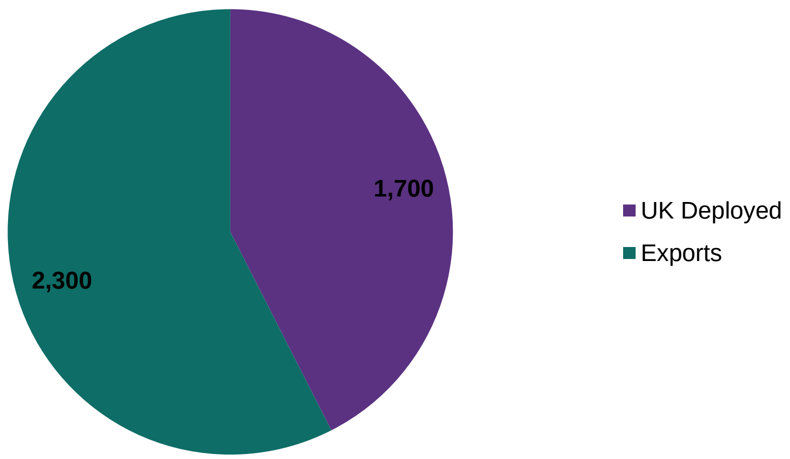
An average of between 2,500 to 6,600 direct jobs per year would be created by the SMR deployment programme. It will also generate between £2.1 billion to £5.6 billion in corporate and income taxes to the Exchequer.

Figure 5-17 Direct impacts (medium scenario) – Output and GVA undiscounted 2017 to 2040



[34] GVA is estimated from output using forecast average GVA to output ratios of UK manufacturing industry sectors

Figure 5-18 Direct impacts (medium scenario) – Average annual jobs 2017 to 2040



Indirect and Induced Impacts (undiscounted)

In addition to the direct effects, there will be indirect and induced effects generated as a consequence of spend on intermediate inputs (supply chain), and employees spending their wages on consumption. The indirect and induced impacts are estimated to generate a further £15.4 billion to £40.3 billion in output, £6.9 billion to £18.1 billion in GVA, and associated employment of annual average of 3,500 to 9,400 jobs. These indirect and induced effects combined with the direct effects result in an estimated total GVA contribution of £13.0 billion to £34.1 billion and average annual jobs of 6,000 to 16,000.

The total economic impacts (direct, indirect and induced) are summarised in Table 5-12. In each case, exports are presented in brackets.

Table 5-12 Summary of gross impacts (direct, indirect and induced) – undiscounted 2017-2040

Measures	Low	Medium	High
Output (£ billion)	29.9 (8.5)	47.9 (20.1)	78.4 (42.2)
GVA (£ billion)	13.0 (3.7)	20.1 (8.8)	34.1 (18.4)
Tax (£ billion)	4.6 (1.3)	7.3 (3.1)	12.0 (6.5)
Average annual jobs (#)	6,000 (2,300)	9,700 (5,500)	16,000 (11,600)

If the supply chain participation of local UK firms is reduced to 60% from 70% (Table 5-12), the estimated gross impacts are lower (as shown in Table 5-13). This highlights the effect that a reduced level of UK firms' participation in the supply chain can have on the scale of the benefits of SMRs to the UK economy. In each case, the component of gross impacts that is related to exports is presented in brackets.

Table 5-13 Gross impacts at 60% UK participation (direct, indirect and induced) – undiscounted 2017-2040

Measures	Low	Medium	High
Output (£ billion)	25.8 (7.3)	41.3 (17.3)	67.6 (36.4)
GVA (£ billion)	11.2 (3.2)	18.0 (7.6)	29.5 (15.9)
Tax (£ billion)	3.9 (1.1)	6.3 (2.7)	10.3 (5.6)
Average annual jobs (#)	5,100 (2,000)	8,200 (4,700)	13,600 (9,900)

Summary of gross impacts (undiscounted)

The medium scenario estimates on potential cost of SMR deployment using the 70% local firms' participation in the supply chain show that between 2017 and 2040:

- About £20 billion in real gross terms could be added to the UK GDP due to SMR manufacturing in the UK, including exports;
- An average of approximately 10,000 total jobs (including indirect and induced) could be created each year;
- Additional income and corporation tax receipts are estimated at above £7 billion.

Assuming the lower local firms' participation in the supply chain of 60%, the impacts show a total GVA impact of £18 billion and average annual employment of 8,200. The gross impact of achieving 70% relative to 60% supply chain participation is therefore £2 billion in GVA and average annual employment of 1,500.

These gross impacts do not take into account the downside of potential substitution of other technologies. The impact of these counterfactuals is discussed in Section 5.4.4 below.

5.4.4. Results – Incremental Impacts

The estimated GVA for the manufacture of SMRs in the UK for in-country deployment and exports is compared to a number of counterfactual scenarios, in order to estimate the incremental UK GVA. This is the UK economic activity that would not exist in the absence of this activity. It takes into account the associated economic activity that would be generated in the counterfactuals.

5.4.4.1. Counterfactual macroeconomic impacts

In consultation with DECC, counterfactuals that consider large nuclear, CCGT and offshore wind have been adopted as alternatives to SMRs.

Counterfactual economic impact estimates have been quantified using a similar, albeit necessarily less detailed approach (due to lack of comparable detail in data availability) than has been employed for SMRs.

The counterfactual scenarios modelled are based on the following assumptions:

- The alternative technologies are assumed to provide an equivalent level of generation as from 2 GWe SMR deployment;
- The counterfactuals are not expected to contribute any exports between 2017 and 2040;
- Multipliers estimated for all 3 counterfactuals are lower than for SMR, as a higher level of leakage has been assumed (i.e. smaller proportion of intermediate inputs provided by a UK based supply chain) compared to SMRs, which generates a lower economic impact per pound of expenditure;
- The level of UK firms' participation in the supply chain of the counterfactuals are included as follows:
    - Large Nuclear – 54%[35]
    - CCGT – 47%[36]
    - Offshore Wind – 47%[36]

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[35] Mid-point of range in the Oxford Economics & Atkins Study on the UK nuclear industry supply chain (Ref. 48).

[36] UK firms' participation with respect to CCGT and offshore wind has been assumed to correspond to the level of participation in the machinery and equipment manufacturing industry (Standard Industry Classification code 28). Studies have been viewed that suggest lower levels of local content participation, using these magnitudes makes this study's estimates relatively conservative.

A counterfactual GVA is estimated for each alternative technology. This is derived by applying the relevant multipliers adjusted for the level of UK firms' participation in the supply chain to the scale of expenditure required to generate an equivalent volume of electricity generation. These adjustments were made to reflect a view that supply linkages would be different for alternative technologies.

In order to translate economic activity into jobs, data on economic activity per worker (GVA per worker) was used to estimate labour productivity for counterfactuals that correspond to the relevant industry sectors.

Table 5-14 shows the macroeconomic impacts of other generation technologies based on the scale of expenditure required for generation equivalent to 2 GWe SMR capacity and based on the level of UK firms' participation in the supply chain.

Table 5-14 Counterfactual impacts – medium scenario (undiscounted 2017-2040)

Measures	Large nuclear	CCGT	Offshore wind
Expenditure	£10 billion	£10 billion	£13 billion
Output	£19 billion	£15 billion	£20 billion
GVA	£8 billion	£6 billion	£8 billion
Employment	3,000	2,600	3,500
Tax	£3 billion	£2 billion	£3 billion

As shown in Table 5-14, the three counterfactuals would generate total gross output over the period 2017 – 2040 of between £15 billion to £20 billion. This would contribute about £6 billion to £8 billion in total GVA and an average of 2,600 to 3,500 jobs per year.

5.4.4.2. The output gap

The output gap is an economic measure of the difference between the actual output of an economy and the potential output if operating at full capacity. Potential output is the maximum level of goods and services an economy can produce on a sustained basis with existing resources.

It is assumed that any incremental economic activity between 2017 and 2025 associated with SMR deployment and exports (i.e. net of activity from displaced counterfactual technologies) is modelled as being additional to the economy and not displacing resource employed elsewhere. This assumption is based on the existence over that period of an output gap, i.e. the UK economy operating at below full capacity.

Beyond 2025, any incremental economic activity is assumed to displace existing economic activity requiring similar skills. Consequently, the net impacts are focused on the benefits to the UK of workers being employed in higher technology, higher skilled and more productive jobs. Therefore, the net impact will only be reflected in the difference in labour productivity between nuclear manufacturing and general manufacturing which SMRs could displace. This difference in labour productivity is assumed at a magnitude of about 17% (Ref. 76).[37]

5.4.4.3. Net impact (undiscounted 2017-2040)

The net impact is the difference between the gross impact that is estimated for SMRs and the equivalent measure of GVA that is estimated for the counterfactuals adjusted for the output gap. This is the incremental GVA attributable to the UK manufacture of SMRs. Except otherwise stated, NVA estimates are assessed in comparison to the large nuclear counterfactual.

[37] Assumption follows the findings in the 2010 paper "Manufacturing in the UK: Supplementary Analysis" (Ref. 76) which shows a 17% productivity per head difference between high tech manufacturing and medium high tech manufacturing. According to the paper, calculations were based on the ONS Annual Business Inquiry 2007.

As shown in Table 5-15 it is estimated that in the medium scenario, SMRs will make a net real, undiscounted cumulative contribution of between £3.8 billion and £4.3 billion to the UK economy compared to the counterfactual scenarios. This will boost GVA by between £1.7 billion and £1.9 billion, compared to the counterfactuals.

This means that, irrespective of the technology displaced, the net economic impact of the UK manufacture of SMRs is estimated to be positive. This can be explained by fewer leakages driving a more localised supply chain supported by a potential export market.

Table 5-15 Net impact summary – medium scenario (undiscounted 2017 to 2040)

Net impacts	Large nuclear	CCGT	Offshore wind
Output	£3.9 billion	£4.3 billion	£3.8 billion
NVA	£1.7 billion	£1.9 billion	£1.7 billion
Tax	£0.6 billion	£0.7 billion	£0.6 billion
Employment (jobs p.a.)	800	900	800

However, if a reduced assumption of 60% UK firms' participation in the SMR supply chain is applied (rather than the 70% which forms the basis of results in Table 5-15); the net impacts on the UK economy will be lower. Table 5-16 shows the resulting net impacts at 60% domestic firms' supply chain participation.

Table 5-16 Net impact summary at 60% UK participation (undiscounted 2017 to 2040)

Net impacts	Large nuclear	CCGT	Offshore wind
Output	£3.3 billion	£3.8 billion	£3.3 billion
NVA	£1.5 billion	£1.7 billion	£1.4 billion
Tax	£0.5 billion	£0.6 billion	£0.5 billion
Employment (jobs p.a.)	700	800	700

5.4.4.4. Net Impact (discounted 2017-2040)

In order to calculate the present value of these impacts, the NVA has been discounted using a 3.5% real discount rate in line with HMT Green Book and DECC Guidance. The analysis shows that:

- Assuming a 70% local firms' supply chain participation, based on the 2 GWe build programme (including 2.5 GWe of exports), the discounted NVA of SMR relative to large nuclear estimated at £1.2 billion between 2017-2040.
- This impact reduces to £1.0 billion when a 60% supply chain participation is assessed.

Table 5-17 Net impact summary at 70% UK participation (discounted 2017 to 2040)

Net impacts	Large nuclear	CCGT	Offshore wind
Output	£2.7 billion	£3.1 billion	£2.7 billion
NVA	£1.2 billion	£1.3 billion	£1.2 billion
Tax	£0.4 billion	£0.5 billion	£0.4 billion
Employment (jobs p.a.)	800	900	800

5.4.4.5. Net impact (2017-2094)

In order to compare with the welfare impacts in Section 5.3, an extended forecast macroeconomic impact scenario until 2094 is modelled (reflecting the period until the SMR plants have retired). The results show:

- In aggregate terms, the undiscounted NVA of the 2 GWe build SMR programme (including 2.5 GWe of exports) is £2.0 billion relative to large nuclear. This reduces to £1.6 billion when a 60% local firms' supply chain participation is assumed.
- However, in net present value terms, the discounted NVA of the programme is £1.2 billion relative to large nuclear. This reduces to £1.1 billion when a 60% local firms' supply chain participation is assumed.

Table 5-18 Undiscounted Net Impact summary at 70% UK participation (2017 to 2094)

Net impacts	Large nuclear	CCGT	Offshore wind
Output	£4.4 billion	£3.9 billion	£2.0 billion
NVA	£2.0 billion	£1.7 billion	£1.0 billion
Tax	£0.7 billion	£0.6 billion	£0.4 billion
Employment (jobs p.a.)	300	300	200

Table 5-19 Discounted Net impact summary at 70% UK participation (2017 to 2094)

Net impacts	Large nuclear	CCGT	Offshore wind
Output	£2.9 billion	£3.0 billion	£2.4 billion
NVA	£1.2 billion	£1.3 billion	£1.0 billion
Tax	£0.5 billion	£0.5 billion	£0.4 billion
Employment (jobs p.a.)	300	300	200

It should be noted that extending the forecasts until 2094 assumes that there will be no significant change to the long-term macroeconomic structure of the UK economy. This may not necessarily be the case.

5.4.4.6. Conclusion

In conclusion, the deployment of SMR has positive macroeconomic impact in terms of output, value added, tax and employment relative to the counterfactuals which is driven by four key assumptions:

1. The differences in the scale of expenditure between SMRs and the alternative technologies (large nuclear, CCGT and offshore wind) assessed, with SMR incurring a greater degree of spend over the modelled period due to the high costs of the initial plants;
2. The extent of local firms' involvement in the SMR supply chain, particularly if the UK is able to attract manufacturing facilities to be situated in the UK;
3. The export potential of SMRs being greater than the counterfactuals if the global market develops for SMR and if the UK can achieve a 10% market share; and
4. The existence of an output gap, such that initial expenditure on the SMR programme does not necessarily displace other activity.

5.4.5. The macroeconomic impact of longer term SMR deployment

The preceding economic analysis considered the macroeconomic impact of an SMR programme delivering 2 GWe of UK deployment and export capacity of 1.5 GWe to 3.7 GWe.

This section models an additional scenario for the SMR programme, delivering 12 GWe of UK deployment and 10 GWe of exports commissioning out to 2050 (consistent with the scenario set out in Section 5.3.2.3). Other assumptions, such as local firms' participation in the supply chain of between 60% and 70%) are the same as those adopted for the 2 GWe scenario.

As with the 2 GWe scenario, it should be noted that extending the forecasts until 2094 assumes that there will -be no significant change to the longterm macroeconomic structure of the UK economy, which may not necessarily be the case.

5.4.5.1. Summary of gross impacts (2017 – 2094)

The undiscounted GVA of the 12 GWe build SMR programme (including 10 GWe of exports) is £163 billion. This reduces to £141 billion when a 60% local firms' supply chain participation is assumed.

Table 5-20 Gross impact summary (undiscounted, 2017-2094)

12 GWe gross impacts	70% supply chain	60% supply chain
Output	£375 billion	£324 billion
GVA	£163 billion	£141 billion
Tax	£57 billion	£49 billion
Employment (jobs p.a.)	14,000	12,000

5.4.5.2. Summary of net impacts (2017 – 2094)

The results show that the undiscounted NVA of the 12 GWe build SMR programme (including 10 GWe of exports) is £3.8 billion relative to large nuclear. This reduces to £2.2 billion when a 60% local firms' supply chain participation is assumed.

However, in net present value terms, the discounted NVA of the programme is £1.6 billion relative to large nuclear; this reduces to £1.1 billion when a 60% local firms' supply chain participation is assumed.

Table 5-21 Net impact summary (2017-2094) at 70% UK supply chain participation relative to large nuclear

12 GWe SMR impacts relative to large nuclear	Undiscounted	Discounted
Output	£8.2 billion	£3.5 billion
NVA	£3.8 billion	£1.6 billion
Tax	£1.5 billion	£0.6 billion
Employment (jobs p.a.)	500	500

Table 5-22 Net impact summary (2017-2094) at 60% UK supply chain participation relative to large nuclear

12 GWe SMR impacts relative to large nuclear	Undiscounted	Discounted
Output	£4.3 billion	£2.3 billion
NVA	£2.2 billion	£1.1 billion
Tax	£1.0 billion	£0.4 billion
Employment (jobs p.a.)	350	350

5.4.6. Other Impacts

SMR LCOE has the potential to be higher than for the counterfactuals (if NOAK cost reductions are not achieved). The implication is that this could translate to higher energy bills for businesses and households. This potential rise in energy prices could have an impact on consumer price inflation, household incomes, and spending and profits of non-energy producing firms. As a result there could be a negative knock-on effect on the level of UK economic activity. The magnitude of this effect has not been modelled as part of this study.

6. Delivery Option Assessment

6.1. Key Messages

- Large nuclear remains more likely to be able to provide deployment of new low carbon baseload capacity by 2030. If Government's objective is to achieve SMR deployment within the early 2030s, IPWRs represent the Government's best technology option.
- To incentivise least-cost deployment of an IPWR technology, Government may want to provide funding towards the GDA and sites for deployment. Commitment to deploying a minimum volume of a single design that is also licensable abroad is also important to enable levelised costs to converge with the cost of large nuclear.
- If Government's strategic priority is to stimulate the development of the UK supply chain, Government may want to take a longer term approach to SMR technology. Government procuring or partnering with a vendor would allow for acquisition of IP. Government could alternatively choose to fund R&D to develop future technology solutions.
- Supporting a non-IPWR technology (i.e. a technology that is not based on light water reactor technology) would delay potential deployment of SMRs until beyond the early 2030s. Government would also be taking on risk in selecting a single design (which is required to achieve cost reductions), given the uncertainties that exist today around the viability of the non-IPWR technologies, including cost, technology risk, 'licensability', and time to deployment.

6.2. Approach

Atkins and EY undertook a review of the arrangements that would help to support deployment of SMRs in the UK. This involved reviewing the strategic and economic case for intervention and assessing how well the different delivery options meet the Government's objectives for the SMR programme. The criteria used to assess the delivery options are a set of policy objectives, which have been adapted from the policy considerations set out in the SMR Specification Development report (Ref. 2). The policy objectives are:

1. **Minimise time to SMR deployment:** The intervention should accelerate the potential commercial deployment of SMRs to contribute to decarbonising the power sector and ensuring security of supply. According to the SMR Specification Development report (Ref. 2), Government's objective for SMR deployment is that SMR plants should become operational by the early-2030s.
2. **Minimise upfront cost of SMR deployment:** The intervention should minimise the costs to the UK of bringing SMR technology to market, including funding for GDA or R&D and the administrative costs to DECC of implementing the delivery option.
3. **Minimise technology cost of SMR deployment:** The intervention should facilitate SMR technology costs falling over time to become competitive against counterfactual technologies.
4. **Minimise risk to Government:** The intervention should limit financial risk to Government, with the market bearing as much of the risk as is feasible in bringing SMR plants to market. Relevant metrics include the profile of risks borne by Government with SMR projects and the ease with which Government can exit from support arrangements.
5. **Develop UK supply chain:** The intervention should enable a UK-based supply chain for SMRs and enable increased jobs and GVA, for the deployment of SMRs within the UK as well as exports to other markets. There may be particular macroeconomic benefits to the UK regaining its former strategic leadership in nuclear reactor design in order to capture particularly high-value work within SMR deployment.

The delivery options assessed are also based on those in the SMR Specification Development report (Ref. 2) and are set out in Table 6-1. The table also sets out the assumptions have been made to underpin how each option would work in practice.

Table 6-1 Definition of delivery options

Delivery Option	Definition
Do nothing	Government does not intervene in market to specifically support SMRs. SMR technology is allowed to come forward, if commercially viable, using existing market structures, including the CfD (via allocation rounds).
Facilitation	Government introduces a framework for the development of SMRs that mirrors the current Government approach for new large nuclear. Government will provide facilitative actions to support SMRs including the provision of a GDA slot and a process for siting SMR plants; a bespoke CfD, with a longer construction and payback period; and loan guarantees for a proportion of project debt.
Facilitation plus	In addition to 'Facilitation', this option includes Government providing funding to bring a technology to market – including Government bearing up to 50% of the cost of the GDA process, or providing funding for R&D in the case of non-IPWR technology.
Commercial partnership	In addition to 'Facilitation Plus', this option includes the UK buying a non-controlling stake of up to 50% in an SMR vendor or developer.
Government partnership	This is as "Commercial Partnership," with Government also making a partnership agreement with another government to bring forward SMRs. The outcomes of the partnership agreement would be to agree a single design that can be licensed in both countries and to deploy a FOAK plant in the country. The UK would take a 25% owning stake in the company and would provide incentives to site a proportion of the manufacturing facilities within the UK, for instance through contributing to the cost of factory build.
'Procurement option'	Government purchases a design and delivers deployment of initial SMR plants until the private sector is able to step in and buy out the Government's stake. Support would be provided on an arms-length basis – potentially through a CfD arrangement.

For all the options it is assumed that Government is only looking to support one SMR design in order to maximise potential for cost reduction through learning.

Separate assessments of delivery options are carried out for UK supporting deployment of a single IPWR plant, a programme of IPWR deployment (including a commitment at the outset to a volume of SMR deployment from a single vendor), as well as for R&D funding for a non-IPWR technology.

The assessment is informed by the TEA of the viability of SMR deployment in the UK as well as the review of vendor responses received on support from Government, as shown in Figure 6-1.

Figure 6-1 Summary of vendor responses on support from Government

The questionnaire sent to vendors included a question on assumptions they had made about government support in their submitted business cases. Twelve vendors responded to the question, of which:

- Ten vendors discussed the need for, or benefit of, Government support – both financial and regulatory.
- Eight stated that either financial support from Government was assumed (not necessarily in their business case), or discussed its benefits. One vendor said its progress would be slower without financial support from Government.
- Two vendors highlighted the need for financial support from Government specifically for licencing activities.
- Four stated identification and/or provision of a suitable site would be beneficial.
- Other specific forms of support highlighted by vendors include: loan guarantees, production tax credits, CfDs, regulator risk insurance, and regulation based on incremental testing.
- Two vendors stated their ambition to progress the project without direct support from UK taxpayers.

6.3. Assessment of Delivery Options

The requirements for each of the objectives for SMR technology have been reviewed and assessed against the options outlined in 6.2. The detailed options assessment is set out in Appendix K of Vol 2 (Ref. 3). This section sets out a high-level overview of the options assessment against each objective.

6.3.1. Delivery Options for IPWR FOAK Plant

Table 6-2 summarises the options assessment for Government to bring forward a FOAK SMR plant

Table 6-2 Delivery option assessment summary: IPWR – No commitment to volume

Delivery Option	Time to deployment	Upfront cost	Technology cost	Minimise risk to UK	Develop UK supply chain
Do Nothing	Grey	Grey	Grey	Grey	Grey
Facilitation	Red	Green	Red	Green	Red
Facilitation Plus	Green	Red	Red	Amber	Red
Commercial Partnership	Amber	Red	Amber	Red	Red
Government Partnership	Red	Red	Amber	Red	Amber
Procure UK SMR	Amber	Red	Amber	Red	Red

Legend:

- Grey: Delivery option will not lead to SMR deployment;
- Green: Delivery option achieves the objective;
- Amber: It is uncertain whether the delivery option would achieve the objective;
- Red: Delivery option does not achieve the objective.

- **Time to deployment:** Facilitation Plus is the option that has the best potential to deliver SMR deployment by the early 2030s. Do Nothing will not lead to deployment of UK SMRs due to the likely requirement for a bespoke CfD while vendors under Facilitation are likely to find the cost of GDA prohibitive. Options for partnership or procurement will likely add delay due to the greater complexity of implementation.
- **Upfront cost:** All the options involving greater intervention than Facilitation require Government to bear greater upfront cost than would be provided for large nuclear, including the cost of part-funding the GDA and potentially of buying a stake in an SMR vendor.
- **Technology cost:** SMR deployment is unlikely to achieve cost parity without a commitment to a significant volume of deployment. However, Government ownership could potentially allow for lower financing costs and Government Partnership could allow for greater potential for exports.
- **Risk:** Options involving Government ownership (full or partial) significantly increase the risk to Government relative to large nuclear as Government would take on construction and operational risk**.**
- **UK supply chain:** It is unlikely that SMR vendors would be attracted to invest in building manufacturing facilities in the UK without a commitment to a minimum volume of deployment, although Government could choose to provide incentives to situate in the UK (subject to state aid compliance).

Table 6-3 summarises the options assessment for Government committing to a programme of deployment:

Table 6-3 Delivery option assessment summary: IPWR programme with commitment to volume

Delivery Option	Time to deployment	Upfront cost	Technology cost	Minimise risk to UK	Develop UK supply chain
Do Nothing	Grey	Grey	Grey	Grey	Grey
Facilitation	Red	Green	Amber	Green	Red
Facilitation Plus	Green	Red	Amber	Amber	Amber
Commercial Partnership	Amber	Red	Amber	Red	Amber
Government Partnership	Red	Red	Green	Red	Green
Procure UK SMR	Amber	Red	Amber	Red	Amber

Legend:

- Grey: Delivery option will not lead to SMR deployment;
- Green: Delivery option achieves the objective;
- Amber: It is uncertain whether the delivery option would achieve the objective;
- Red: Delivery option does not achieve the objective.

A commitment to volume is important for enticing vendors to invest in deployment of SMRs in the UK. The impact of the UK committing to a minimum volume of deployment has the following impacts on the assessments of delivery options:

- **Time to deployment:** Commitment to volume makes it more likely a vendor would be willing to bear part of the GDA cost under Facilitation Plus.

- **Upfront cost:** There may be increased administrative cost to DECC in making commercial arrangements for a programme of deployment.
- **Technology cost:** SMR deployment is more likely to achieve cost reductions if there is deployment over a larger scale. There is however a risk that a vendor would not pass the benefits of falling technology costs on to consumers given the likely absence of competition from other SMR vendors.
- **Risk:** Commitment to volume does not change the profile of risks borne by the UK, though it does lock in the UK to building further plants if FOAK costs are higher than expected.
- **UK supply chain:** Commitment to volume makes it more likely a vendor would be willing to situate manufacturing facilities in the UK.

Table 6-4 summarises the options assessment for Government funding R&D for a non-IPWR technology.

Table 6-4 Delivery option assessment summary: Non-IPWR programme

Delivery Option	Time to deployment	Upfront cost	Technology cost	Minimise risk to UK	Develop UK supply chain
Do Nothing					
Facilitation					
Facilitation Plus					
Commercial Partnership					
Government Partnership					
Procure UK SMR					

Non-IPWR technologies are further from deployment, presenting both a higher risk in supporting their deployment and requiring higher initial costs to get them to market. However funding non-IPWR R&D could enable the UK to re-gain its strategic leadership in nuclear reactor design, allowing the UK the potential to capture a greater share of high-value activity involved in SMR design. R&D could also yield benefits in technology cost reduction if their inherent safety measures could enable simplification of nuclear graded safety systems.

- **Time to deployment:** Non-IPWR technologies are unlikely to be deployable until beyond the 2030s.
- **Upfront cost:** There may be significant upfront costs in bringing a non-IPWR technology to market, depending on the choice of technology and the share of R&D costs that the UK would provide.
- **Technology cost:** There is potential for non-IPWR technologies to see lower technology costs than IPWRs if the inherent passive safety systems enable reductions in capital and operating costs. However there remains insufficient evidence to assess the economics of non-IPWR technologies and the technology costs will likely vary by technology and by design.
- **Risk:** By supporting a single non-IPWR technology, the UK would be taking on significant uncertainty around whether and when the design chosen can become technically and economically feasible.
- **UK supply chain:** Funding non-IPWR R&D could enable the UK to re-gain its strategic leadership in nuclear reactor design, allowing the UK the potential to capture a greater share of high-value activity involved in SMR design, particularly if Government takes (full or partial) ownership of the vendor and provides a commitment to developing UK technology leadership in civil reactor design (subject to potential state aid considerations).

7. Key Findings from Projects 2 to 7

The following are the key findings identified by Projects 2 to 7 that have been reported to DECC during the Programme. These findings have been included within this section to provide an overview of the TEA Programme findings. They have not been incorporated or considered elsewhere within this Project 1 report with the exception of those from Projects 5 to 7. For example, learning rates derived in Projects 5 to 7 have been used in the economic assessment presented in this Project 1 report. In addition, these findings have not been verified by Project 1 and their inclusion does not necessarily infer that Project 1 condones these findings.

7.1. Project 2 - SMRs: Systems Optimisation Modelling

DECC's requirements for Project 2 included the delivery of analytical tools to:

- Analyse how SMRs could be operated to allow integration in the UK energy distribution network;
- Enable strategic comparison of SMR technologies to other nuclear and non-nuclear technologies.

Project 2 has been delivered by using the ETI's whole energy system modelling tool ESME combined with a new data capture tool known as the SMR Energy System Opportunity (SESO) model. This contains the energy system modelling and scenario analysis undertaken for DECC as part of Project 2 and leads to the following key findings:

- The role and value of SMRs is critically dependent on the wider energy system configuration.
- The risks associated with other low carbon technologies suggest a role for SMR development as a 'hedge' option.
- SMRs with combined heat and power capability would provide wider system value while tapping into other revenue streams emerging as part of a whole system low carbon transition.
- While baseload generation offers a conventional revenue stream for SMRs, load following and wider system services can form a critical part of the technology and commercial offering.
- In addition to these wider system needs, the role of SMRs out to 2050 will be impacted by technology-specific factors including: capital cost, date of first deployment and build rates. The modelling of SMRs in this project has used a range of dates and capital costs, including adjusted cost ranges and a first UK operations date as advised by the output from Project 1. A range of potential build rates was identified, but nearly all modelling scenarios used an initial rate of 400 MWe per year for the first 10 years, followed by a capability of 1200 MWe per year thereafter.
- The analysis used an energy system transition scenario agreed with DECC in August 2015. Since then DECC have refreshed the data for future cost of generation, and technology constraints have been updated include a delay to potential UK CCS deployment. Additional analysis through a supplementary report by ETI identifies that SMRs are no less attractive as a result of adopting DECC's updated cost of generation assumptions and associated deployment constraints.

7.2. Project 3 – SMRs: Emerging Technologies

Project's 3 objectives were to:

- Deliver a strategic assessment system, including market assessment, for emerging technologies and apply this system to the future nuclear industry. This activity would also provide direction as to where technologies should be developed to provide future solutions.
- Provide an evidence basis that Government can use to assess the suitability of emerging nuclear technologies for investment or deployment in the UK.

The findings from Project 3 on the potential roles for emerging technologies are:

- The economic challenges identified for the emerging technologies make it unlikely that they can compete with the Generic SMR (PWR) in the electricity market unless:

  - The assessment of their capital and O&M costs improves markedly, or
  - Until factors such as disposability and/or uranium scarcity/expense assume a much greater importance than currently seems plausible.
- Emerging technologies show clear advantages as suppliers of high temperature process heat to help to decarbonise sectors, such as industrial process heat and transport (via hydrogen production). HTGRs could offer advantages for this role.
- Current studies of decarbonising the UK's process heat and transport sectors have assigned a relatively minor role to nuclear power, though work by ETI has postulated a significant role for SMRs (PWR technology) in space heating via an 80ºC hot water vector.
- Nuclear high temperature process heat could:
  - Provide the process heat for much of industry, and
  - Provide the bulk of the heat input required for hydrogen production to decarbonise transport either by:
    - Directly using fuel cells or internal combustion engines, or
    - Using the hydrogen to produce liquid fuel, utilising more HTGR process heat.
- This potential role requires much more study, but certainly merits a realistic evaluation alongside the currently proposed options.

7.3. Project 4 – SMRs: UK Regulatory regime

Project's 4 objectives were to:

- Consult with UK regulatory authorities to identify some of the generic issues that would affect the deployment of SMRs in the UK.
- Conduct a study to develop generic safety and environmental arguments to address these issues to support the initial stages of regulation, including GDA.
- Deliver an initial safety justification plan for issues and to develop initial safety claims and arguments against the key challenges that have been identified for SMRs, using lessons learnt from recent experience of licencing in the UK.

The findings from Project 4 on the UK regulatory regime include:

1. The challenging nature of the GDA should be impressed upon SMR vendors; the great level of detail about the design required by the regulator, the need to be able to respond as quickly as possible with either further studies, or design changes which arise from the GDA process.
2. Generically there do not seem to be significant "environmental" issues presented by the 'compact PWR' class of reactor that are more challenging than those faced by large PWRs previously submitted to GDA.
3. The issues of environmental discharge and waste disposal should be addressed at an early stage, particularly for non-PWR reactor types, when conclusions from this are able to influence the design, as required.
4. Decommissioning of the compact integral PWRs will not present fundamentally different challenges from decommissioning conventional large PWRs. However, it seems inevitable that the decommissioning of many of the non-PWRs will be more challenging than for PWRs due for example to the large quantities of irradiated lead, sodium or salt, which are very much less familiar to the industry.
5. The goal-setting licensing requirements in the UK can be flexible: therefore, the onus is on the SMR designer to justify their design against the requirement that risks have been reduced to "As Low as Reasonably Practicable". The interactions with the regulator led to the view that the regulator is very open to such discussions.
6. The SMR designer must take full account of specific UK inspection requirements for High Integrity Components in the early stages of SMR design development. It is thus recommended that the designer identify all such components in their design prior to a GDA to confirm that the required

inspections are feasible. It is further recommended that consideration be given to initiating a significant UK research programme in the Non Destructive Examination area, capitalising on the existing UK expertise and focused on the classes of inspection likely to be relevant for integral PWRs.

7. It is recommended that consideration be given to initiating a significant focused research program in natural circulation analysis and prediction, as this is widely relied upon for passive cooling in SMRs. Such a programme, if specified correctly, should be generic across all reactor types and size.
8. It is recommended that research programs be initiated to identify and understand the way in which software is used in safety critical applications in other industries, along with assessments of how such usage could be mapped across into the nuclear sphere. An additional research programme should be initiated aimed at advancing the general areas of formal software specification, design and testing that might in due course raise the general level of confidence in the use of software in safety critical systems in nuclear applications.

7.4. Projects 5-7 – SMRs: Can building nuclear power become more cost effective?

Project's 5-7 consolidated objectives were to:

- Identify opportunities to reduce the costs of nuclear through the application of advanced manufacture, modularisation and control systems.
- Ascertain whether SMRs could become more viable than large nuclear reactors through the application of the above contexts.

The findings from Projects 5-7 include:

- By manufacturing ten units per annum (equivalent to between 0.5 GWe and 2 GWe per year, depending on reactor size), SMRs could achieve levelised cost parity with large reactors at 5 GWe of total deployment. By manufacturing around 5 units per year (as would be consistent with a scenario where the UK deploys 400 MWe each year and where 450 MWe is deployed elsewhere), SMR parity with large nuclear would be reached after 8 GWe of global deployment.
    - Substantial capex savings come from moving build activity away from a construction site (where the plant will ultimately be situated) and into higher productivity factories, where serial manufacture promotes improved effectiveness and efficiency through learning by doing.
    - The effect of learning has the potential to reduce the capex of SMRs by 5% to 10% per doubling of production; the potential rate of learning for large reactors is 1% to 5%, due to lower proportions of factory build and lower production volumes.
    - An 8% learning rate for SMRs will deliver 20% levelised cost reductions, achieving cost parity (based on LCOE) with large reactors at 5GWe of cumulative deployment, when comparing a generic SMR with a generic Nth of a Kind (NOAK) large reactor (excluding non-recurring costs such as the GDA). At a learning rate of 5%, parity will not occur until after 15GWe, while at 10% it would be achieved at approximately 2GWe.
    - Stronger rates of learning (8% or more) assume a robust delivery programme with production in volume, design standardisation, modularisation and a consistent supply chain. Modularisation, manufacturing and assembly should be considered from the outset in order that the benefits can be realised in full.
- SMRs offer construction schedules of three to four years for a NOAK plant, with improved certainty of the schedule duration than for large reactors.
    - Construction schedule durations have been reduced by a year for large reactors where built repeatedly to a single design and making use of modularisation, advanced construction methods and a consistent construction supply chain.
    - Construction schedule lengths of three to four years are expected to be achievable for an SMR unit after the FOAK (with an extra year for the FOAK); for large reactors this is considerably longer.

    - Schedule improvements are driven by a reduction in scale, modularisation and factory build, and learning through experience.
- One-off capex reductions of up to a further 20% can be achieved for SMRs.
    - Additional cost savings are driven by the application of methods including Building Information Modelling (BIM), increased modularisation and factory build, use of advanced manufacturing techniques and processes, and a strategic decision to install multiple reactors on a single site.
    - SMRs can achieve capex reductions of up to 20% where the opportunities haven't already been exploited; the potential opportunities for large reactors are not expected to be as high.
    - These methods should be considered within a reactor design from the outset in order to realise the savings. Potential cost reductions for large reactors are limited by their increased design maturity and associated lack of design flexibility, as well as by their larger scale and lower proportion of factory build.
- There are substantial challenges in relation to deploying an SMR in the UK, and demonstrating its cost effectiveness, by 2030. These challenges include technical readiness, licensing, costs of bringing an SMR design to market, UK supply chain capability and capacity limitations and achieving the optimal conditions for NOAK cost reduction.
- In order to realise the potential of SMRs in the UK, and to ensure that they are deployed quickly, an integrated development programme must be designed, covering FOAK and series production of NOAK. The UK Government, utilities, the ONR, SMR vendors and the supply chain all have an important role to play in achieving this.

8. Techno-Economic Assessment Summary and Conclusions

A Techno-Economic Assessment has been performed on a number of SMR technologies. The aim of this study has been to understand the potential benefits that can be realised in the UK by the commercial deployment of SMRs. The technology types have been assessed against a set of predefined technical and economic criteria. The study also includes an assessment of the findings against several delivery options being considered by DECC.

The findings from the technical assessment have been presented in Section 4.1, with the main conclusions summarised in Table 8-1 below. The technical assessment has shown that there is a clear difference between IPWR technology and the other reactor types considered in the TEA (collectively referred to as non-IPWRs for ease of reference), in terms of technical maturity, commercial deployment date, impact on the UK nuclear infrastructure and ease of licencing.

Table 8-1 Technical conclusions - IPWR vs Non-IPWR

IPWR	Non-IPWR
• Higher level of technical maturity; • Certified designs or undergoing certification; • Ready for GDA in less than 5 years; • Opportunities for innovation in manufacturing of modules and design of specific components; • Good match with existing UK nuclear infrastructure; • Available operating experience from LWR technology.	• Still undergoing R&D; • Longer time to be GDA ready; • Opportunity to develop a nuclear capability • Wider opportunities for the development of innovative concepts; • Inherent safety benefits (to be substantiated); • New fuel production and waste management infrastructure needed; • Limited operating experience.

This difference between the two sets of reactor types creates two different potential scenarios for the deployment of SMRs in the UK, a short-term and a long-term scenario, each of them with different potential benefits. The short-term scenario is characterised by an IPWR design starting GDA within the next 5 years with the aim of commissioning the first SMR in the UK by 2030. In this scenario, the UK nuclear industry would focus on supporting the selected design throughout GDA, site selection and licensing, manufacturing, construction and commissioning.

The long-term scenario would contemplate a deferred GDA slot and the UK would focus on the development of reactor technology. In this scenario, options are opened to both IPWR and non-IPWR, as some IPWR designs are still at early stages of development. The long-term scenario would allow time to enhance the capabilities of nuclear scientists and engineers to support the deployment, and then later the operation of the new build fleet. Longer timescales would also provide more time for the UK supply chain to develop, and to generate the order book that would attract investment for the construction of an SMR factory in the UK. Non-IPWR designs may have the potential to offer lower costs in the long-term but the current levels of design development are insufficient to substantiate this.

If the UK chooses to be involved in the development of an existing IPWR design, it is possible to have a design ready to commence GDA within the next 5 years. If a non-IPWR design is chosen, it is unlikely that existing technologies will be ready for regulatory assessment for 10 to 15 years. This is the time frame where HTGR or SFR designs could be ready provided that R&D programmes are in place and well resourced. For other technologies such as MSR or LFR there are technological challenges that might extend the timescales for regulatory assessment further.

All technologies will face challenges when going through GDA, as they all present some degree of innovation. ONR and the Environment Agency inspectors are familiar with LWR technology and therefore the timescales for the IPWR designs to go through GDA are expected to be similar or slightly longer than for large nuclear. For non-IPWR with a well-developed design, it is expected that timescales for GDA would extend beyond those for large nuclear.

If the business case to manufacture SMRs in the UK is based on the exports of the technology, the international harmonisation of SMR licensing needs to be closely followed. The business case is based on modules supplied from the factory fully assembled, shipped to the country where they will be installed, and installing them with minor or zero modifications. If differences in regulatory regimes require modifications to the extent normally observed with large nuclear, the economics of SMRs are likely to suffer.

The findings from the economic assessment have been presented in Section 5 with the main conclusions listed below:

- For IPWRs, OCCs per kWe and LCOE are higher than for large nuclear due to a premium on FOAK costs and reduced economies of scale for SMRs. For other SMR designs, cost estimates are currently not sufficiently developed to make valid comparisons.

- The estimated generic SMR FOAK cost of electricity is 30% higher than DECC's estimate for large nuclear commissioning in 2031, 7% lower than offshore wind and between 16% lower and 3% higher than CCGT (depending on the carbon price).

- SMR technology has the potential to reduce costs faster than large nuclear as they can be extensively prefabricated in a factory. SMR costs in the central case are modelled to achieve cost parity with large nuclear after 5 to 8 GWe of global deployment. However, the degree of cost reduction is sensitive to a number of assumptions, including the rate of UK deployment, a change in regulatory approach to consistently commission a single design over time, and a global market for SMR developing, of which the UK design achieves a 10% market share
- The Net Present Value for a 2GWe UK SMR programme is expected to be negative relative to large nuclear (-£4.8bn) and CCGT (-£8.4bn), and slightly positive against offshore wind (+£0.4bn). However, there is significant uncertainty around the costs of SMR: For instance, the NPV of SMR relative to large nuclear varies between +£2bn and -£14.2bn, depending on the level of SMR plant capital costs and the rate of learning that is achieved. There is also uncertainty around the cost of the counterfactual technologies, although this has not been modelled within this assessment.

- Deploying a larger programme of SMRs than 2GW can improve the overall NPV of the programme, as SMR costs become more competitive with the counterfactual technologies over time. Based on the central estimate of SMR costs, the NPV relative to large nuclear improves to -£3.5bn for an SMR programme out to 2050, including 12GW of UK deployment and 10GW of exports.

- It is possible that SMRs could also make it easier to finance new nuclear by reducing project size. This is partly a security of supply benefit, by reducing dependence on the UK to debt-finance new projects. However, it could also help to reduce costs if there were more parties interested in providing finance, creating competitive price-discovery - although this benefit is dependent on successful initial deployment of SMRs and the scale of the cost saving is highly uncertain.

- SMRs may also present qualitative benefits not factored into the NPV. These include improved air quality and reduced dependence on fossil fuel imports relative to a counterfactual of CCGT, as well as a more ‘dispatchable’ form of low carbon generation relative to offshore wind.

- The UK may be able to deliver up to 70% of the supply chain requirements for SMRs through a number of interventions, including the implementation of the Nuclear SCAP (Ref. 50).
- SMRs have the potential to create broader economic advantages to the UK. Between 2017 and 2040, the estimated total (accounting for direct, supply chain and consumer spending) the estimated net impacts are estimated at £1.7 billion of undiscounted GVA, £0.6 billion in taxes and average employment of 800 jobs per annum. This assessment is driven by a number of assumptions, including potential for 2.5GW exports by 2035, higher initial expenditure, and the UK capturing 70% share of the supply chain and there being spare capacity in the economy out to 2025.

The delivery option assessment has considered the various options against different Government objectives within Section 6, with the main conclusions listed below:

- Supporting IPWR technologies through Facilitation Plus is the option that has the best potential to deliver SMR deployment by the early 2030s.

- Partnership with another government would help to ensure that there is a wider market for the UK licensed design, although agreeing such an arrangement could add significant delay to the deployment programme.
- There is no guarantee under any of the options that the vendor would choose to situate their manufacturing facilities within the UK, particularly if there were no minimum commitment to volume of deployment.
- A minimum commitment to volume of deployment from Government would be helpful to entice vendors to go through a costly GDA process. It is also important in achieving cost reductions through learning and developing a UK supply chain for SMRs.
- There is a risk around whether vendors would pass the benefits of falling technology costs on to consumers given the likely absence of competition from other SMR vendors. Government ownership may be one solution to avoid that risk.
- Support to development of a non-IPWR design would require greater up-front investment, and would delay deployment as well as involve higher risk. It could however enable greater UK supply chain benefit and lower long-term cost if a simpler intrinsically safe design could be developed.

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