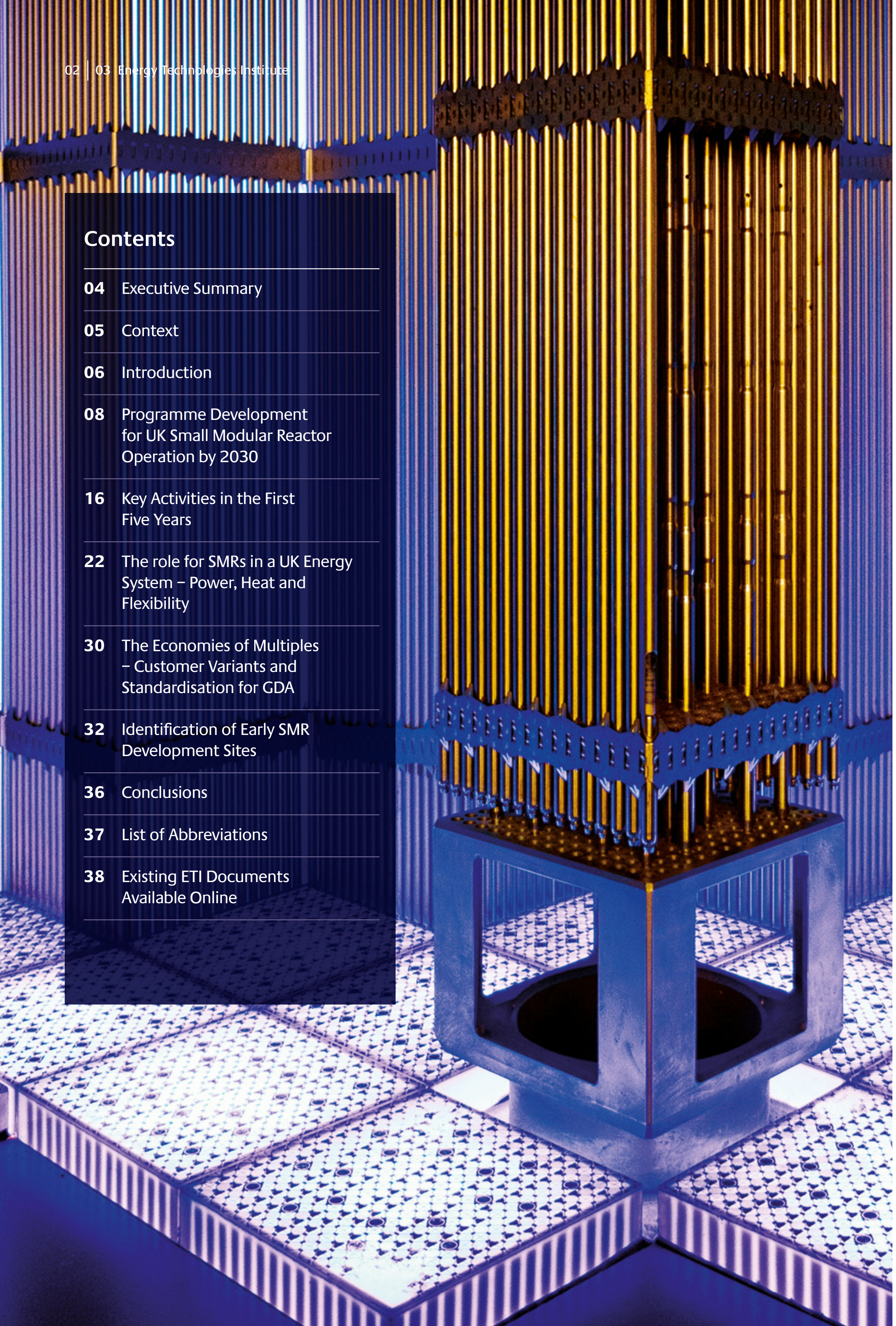
energy technologies institute

PREPARING FOR DEPLOYMENT OF A UK SMALL MODULAR REACTOR BY 2030

An insights report from the Energy Technologies Institute



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A credible integrated schedule for a UK SMR operating by 2030

depends on early investor confidence

The Government has a crucial role to play

in delivering a policy framework which supports SMR deployment and encourages investor confidence

If SMRs are to become an integral part of a 2050 UK energy system, deployment should address future system requirements including:

power | heat | flexibility

PREPARING FOR DEPLOYMENT OF A UK SMALL MODULAR REACTOR BY 2030

SMR factory production can accelerate cost reduction

UK SMRs should be designed and deployed as 'CHP ready'

Extra costs are small and potential future revenue large

UK SMRs should be designed for a range of cooling systems

including air cooled condensers

There is economic benefit in deploying SMRs as CHP to energise district heating networks; this depends on district heating roll out

There is a range of sites suitable for early UK SMR deployment

Including options for the UK first of a kind site

EXECUTIVE SUMMARY

- A credible integrated schedule demonstrates the potential for a UK SMR operating by 2030; achieving this schedule depends on the creation of early investor confidence.
- The Government has a crucial role to play in delivering a policy framework which supports SMR deployment and encourages investor confidence.
- If SMRs are to become an integral part of a 2050 UK energy system, deployment should address future system requirements including power, heat and flexibility.
- There is economic benefit in deploying SMRs as CHP to energise district heating networks; this depends on district heating roll out.
- SMR factory production can accelerate cost reduction. Standardised construction can be combined with deployment options which may be attractive to SMR developers:
  - UK deployment as 'CHP ready'; the extra cost is relatively small whilst the potential heat revenues are large.
  - Deployment with a range of cooling system options, including 'air cooled condenser' readiness; for the UK this may be important where site availability of cooling water may become more constrained in the future.
- There is a range of sites suitable for early UK SMR deployment, including options for the UK First of a Kind site.

CONTEXT

The ETI published its first insight report[1] on new nuclear in October 2015 which included the following key headlines:

- New nuclear plants can form a major part of an affordable low carbon transition, with potential roles for both large nuclear and Small Modular Reactors (SMRs).
- Large reactors are best suited to baseload electricity production – analysis indicates an upper capacity limit in England and Wales to 2050 from site availability of around 35 GWe – actual deployment will be influenced by a number of factors and could be lower. Alongside large nuclear, SMRs may be less cost effective for baseload electricity production.
- SMRs could fulfil an additional role in a UK low carbon energy system by delivering Combined Heat and Power (CHP) – a potentially major contribution to the decarbonisation of energy use in buildings – but deployment as CHP depends on availability of district heating infrastructure.

The first nuclear insight report provided new understanding of how large reactors and SMRs could contribute in the transition to a low carbon economy and builds upon the UK Government's Nuclear Industrial Strategy.[2]

After nearly a decade of development work, the schedule for the design, construction and operation of new nuclear power stations using large reactors is now well established. By 2017 three separate designs planned for deployment in the UK are anticipated to have been demonstrated through construction and operation elsewhere in the world. Final Investment Decisions (FIDs) are currently scheduled by EDF, Horizon and NuGen within the next few years for three separate new UK nuclear power station projects. In addition, EDF and China General Nuclear (CGN) plan to deploy through joint venture a further twin unit large Pressurised Water Reactor (PWR) next to the decommissioning Magnox power station in Bradwell, Essex. The design of this further twin unit PWR is known as Hualong 1, which is yet to begin the UK GDA.

However, there is currently no programme for UK SMR deployment and no SMR specific policies which would encourage the private sector development of such a programme. In April 2015, the Department of Energy and Climate Change (DECC) now known as the Department for Business Energy and Industrial Strategy, launched a Government inter-Departmental Techno-Economic Appraisal (TEA) to run from June 2015 to March 2016 to gather information to support Government policy development with respect to SMRs. In November 2015, the Government announced a programme of £250m for nuclear research and development including SMRs, and in March 2016 Government announced Phase 1 of a competition to identify the best value SMR design for the UK.[3]

1 http://www.eti.co.uk/the-role-for-nuclear-within-a-low-carbon-energy-system/

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

3 https://www.gov.uk/government/publications/small-modular-reactors-competition-phase-one

INTRODUCTION

Development and construction of a new nuclear power station can span 10 to 20 years. The development phase is delivered by two separate organisations:

- **The vendor, who develops the design for construction and operation by others.**
- **The developer, who initiates and leads one or more nuclear power station projects.**

The developer also requires an operating organisation which will hold the required regulatory licences, consents and permissions to build and operate a nuclear power station. There can be a number of different legal relationships between the developer and operator such as wholly owned, part owned in a joint venture, or long-term contract. The essential requirement is that during the development phase the developer needs to ensure that there is an operating organisation, also known as the licensee, which is established as a distinct legal entity and capable of fulfilling its legal obligations.

The long period of development is delivered in a sequence of related activities. For each activity there needs to be sufficient confidence that the planned goals can be achieved consistent with the level of investment. The activities are inter-related, which requires an integrated development programme with a combined set of requirements and outcomes.

The elements within the pre-construction phases of an SMR development programme are summarised in Figure 1 (page 7) and are described in more detail below:

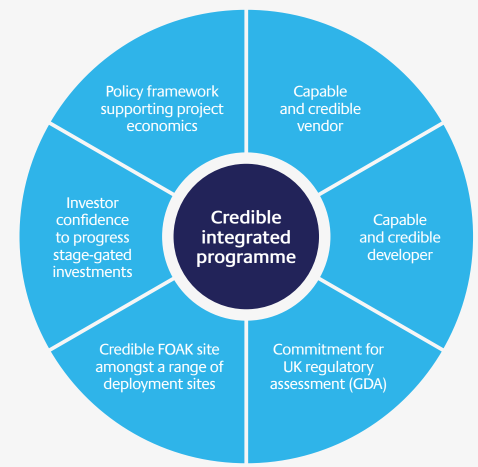
- A capable and credible vendor(s); credible from the perspective of creating investor confidence and capable in terms of access to human and financial resources to complete GDA and move into support to construction and component supply.
- A capable and credible developer(s) with associated operator(s); credible from the perspective of investor, stakeholder and regulator confidence. Capable in terms of access to human and financial resources to successfully apply for the range of licences, permits and permissions in advance of an FID. Capable in terms of implementing a procurement strategy ready to deliver construction.
- Project economics supported by a policy framework, which demonstrate potentially viable business cases across a range of investments related to SMR deployment.
- A commitment by the UK Government to a programme of GDA.
- A credible FOAK site amongst a range of potential early deployment sites.
- Investor confidence to move forward with a number of progressive stage-gated investments.
- A credible integrated programme across vendor(s), developer(s), regulators and Government.

The ETI's first nuclear insight report included the results from a project known as System Requirements for Alternative Nuclear Technologies (ANT), the summary report[4] is available from the ETI's website. This project provided an indicative timeline for SMR development and deployment in the UK which grouped activities as: strategic choices, nuclear policy, enablers and programme delivery. The timeline indicated a UK FOAK SMR operating around 2030 with subsequent plants creating a UK SMR fleet. This proposition would use increased factory-based construction to deliver cost savings from productivity gains within a factory environment together with the economies of multiples. In January 2016, the ETI commissioned a new project, the ETI's SMR Deployment Enablers (SDE) project, to identify in more detail the enabling activities in the first five years of a UK SMR programme which would credibly support UK SMR first operations by 2030. The 2030 date was specified by the ETI, noting the widely reported[5] goal of the UK Government's SMR competition as "...paving the way towards building one of the world's first SMRs in the country in the 2020s". This project was procured through open competition and was delivered for the ETI by Decision Analysis Services Ltd.

The ETI's analysis of decarbonising energy use in buildings identifies the potential for district heat networks to avoid unabated CO_2 emissions with gas boilers. If such heat networks are to be deployed, the ANT project delivered by Mott MacDonald identified the potential for SMRs to be deployed as CHP plants with economic benefits to consumers and SMR operators. Whilst nuclear plants have previously been deployed as CHP, including the energisation of large-scale district heating systems, steam cycle modifications would be required on developing SMRs. Assumptions were made within the ANT project regarding the operational flexibility and cost impact of such modifications. In October 2015 the ETI commissioned a further study, known as ANT Phase 3, which included technical viability and economic impact analyses of the extraction of heat from a PWR-based SMR steam cycle.

Finally, the ETI's first insight report also included the results from a Power Plant Siting Study (PPSS)[6] which was delivered for the ETI by Atkins. In October 2015 the ETI commissioned a further study, known as PPSS Phase 3, which identified a range of potential early SMR sites and undertook further assessment to compare them and thereby better understand the options regarding the potential locations for a UK FOAK SMR.

Figure 1
Key pre-construction elements of a UK SMR development programme



4 http://www.eti.co.uk/wp-content/uploads/2015/10/ANT-Summary-Report-with-Peer-Review.pdf

5 References include https://www.theguardian.com/environment/2015/nov/24/mini-nuclear-reactors-answer-to-climate-change-crisis, http://www.world-nuclear-news.org/NP-UK-sets-aside-funds-for-ambitious-nuclear-research-and-development-program-26111501.html and http://www.publications.parliament.uk/pa/cm201617/cmselect/cmwelaf/129/129.pdf

6 http://www.eti.co.uk/wp-content/uploads/2015/10/PPSS-Summary-Report-with-Peer-Review.pdf

PROGRAMME DEVELOPMENT FOR UK SMR OPERATION BY 2030

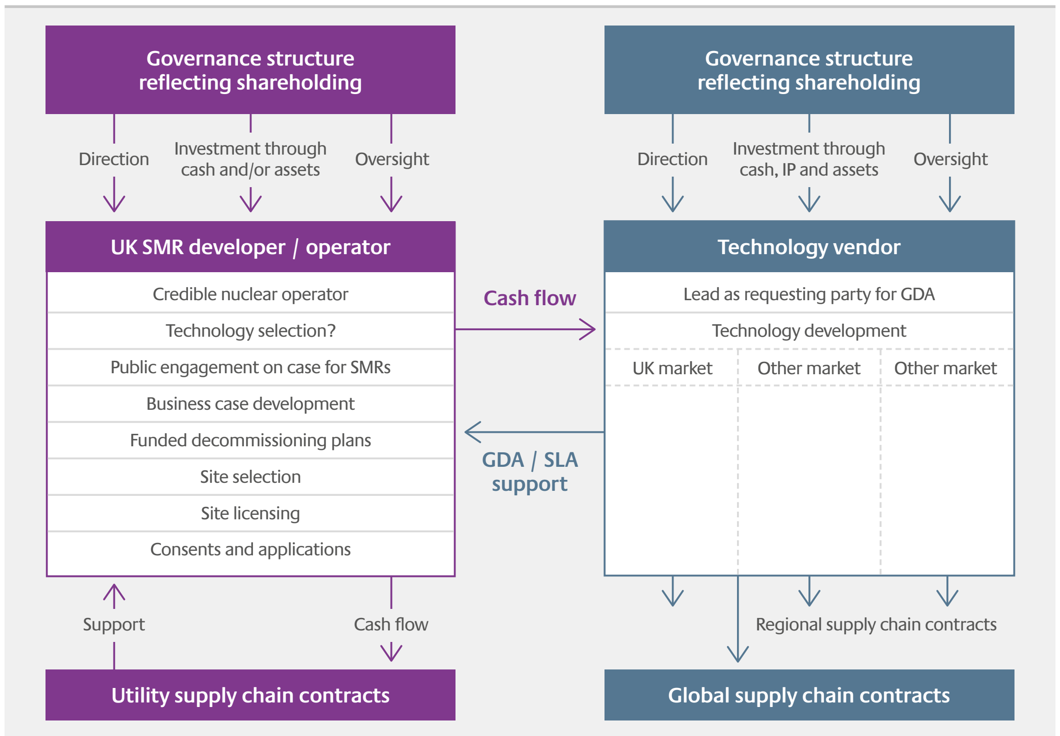
Approach to the SMR Deployment Enablers (SDE) Project

The SDE project used a broad range of inputs including the ANT project report and the expert understanding of the typical relationship between developer and reactor vendor which has become established in the UK. This typical relationship is illustrated in Figure 2.

The SDE project was intended not to be specific to a particular vendor technology, developer, nuclear operator, or any particular commercial relationship between such organisations.
To create a bounding framework it was assumed that a new SMR operating organisation would be formed which would need to establish the required organisational capability and capacity to hold the necessary licences, permissions and consents. Standard programme development tools were applied to this framework including: a work breakdown structure and associated descriptions of each element, schedules of activity, a master assumptions and data list, and a risk register. This approach is illustrated in Figure 3 with more detail on the approach and assumptions in the SDE Summary Report.[7] Organisation selection, design evaluation, business case compilation, and the identification of funding sources or investors were all excluded from the scope of the project. These would be expected to be evaluated within the Government's SMR competition.

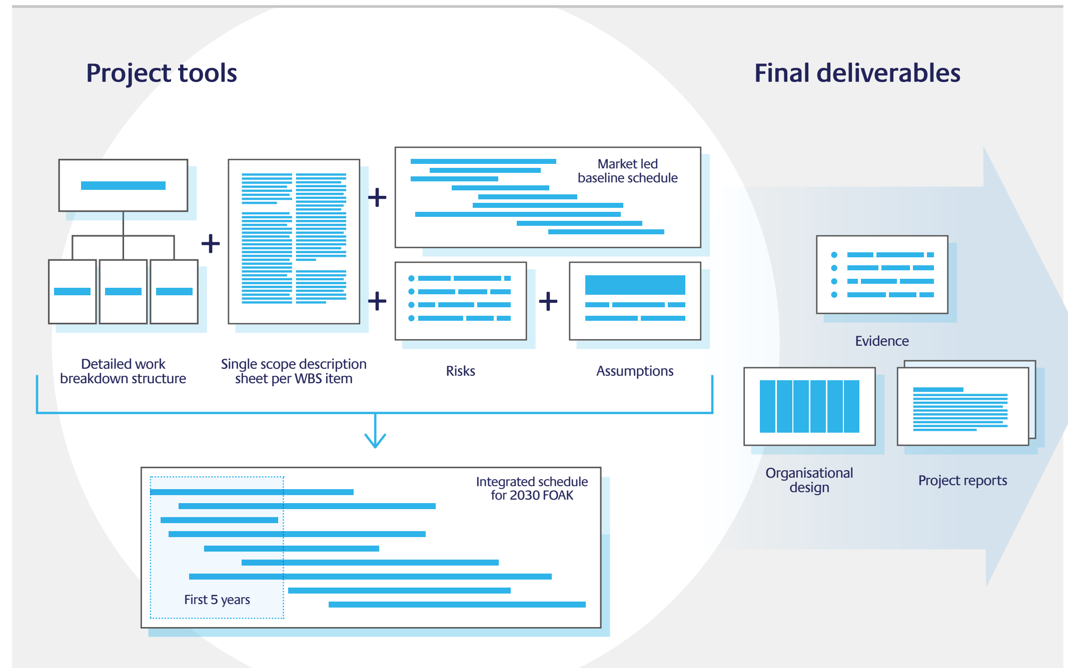
The iterative application of the programme development tools resulted in a work breakdown structure as shown, at the highest level, in Figure 4 (page 10) with three levels of detail as shown in the project summary report.

Figure 2
Typical relationship between reactor developer and vendor showing GDA led by the vendor and site development including licensing led by the SMR developer with associated operator



Source: SDE Summary Report

Figure 3
SDE approach showing project tools and workflow to final deliverables



Source: SDE Summary Report

7 SDE Summary Report DAS-116a/D8 Issue 02 dated 15th July 2016 http://www.eti.co.uk/programme/nuclear/SDE-summary-report.pdf

PROGRAMME DEVELOPMENT FOR UK SMR OPERATION BY 2030

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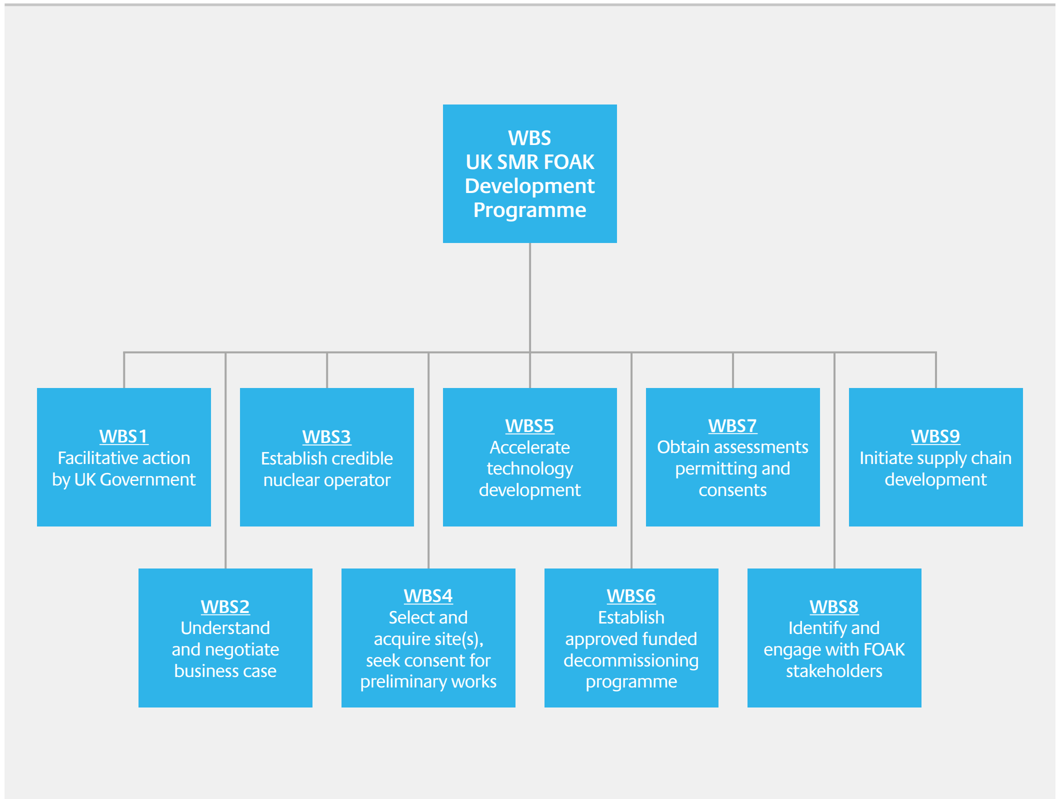
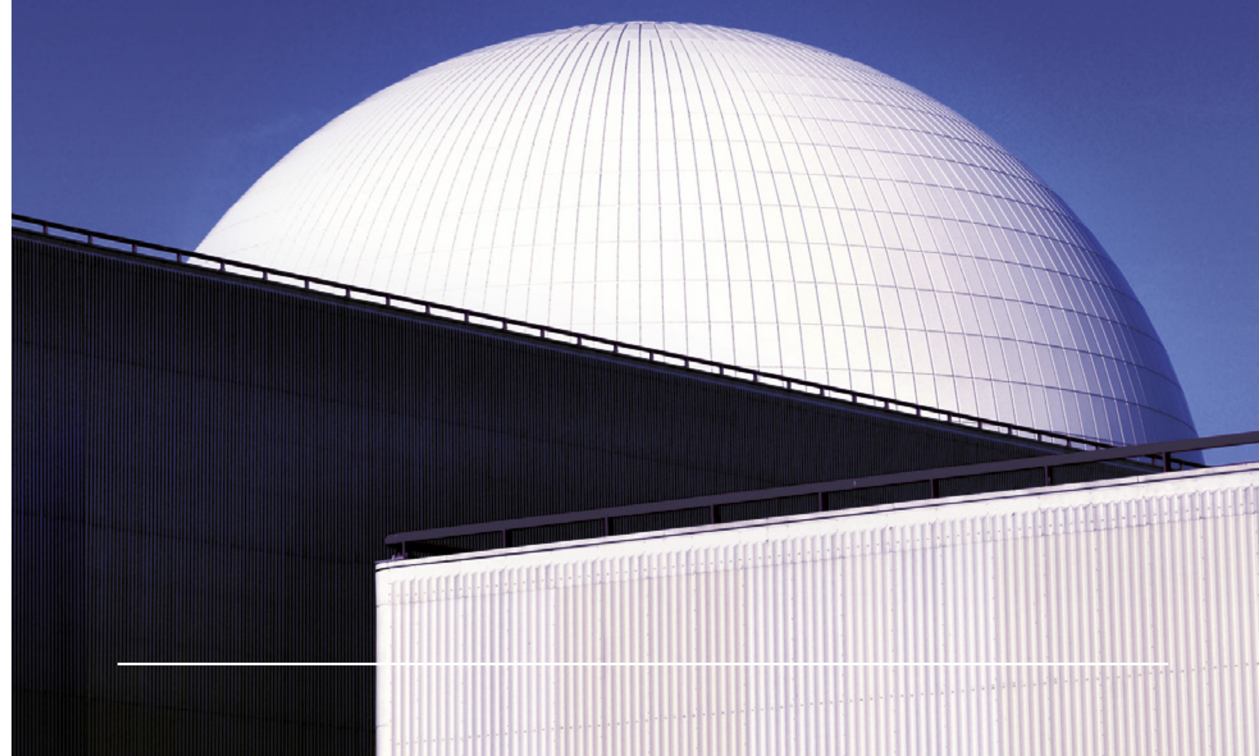
Figure 4
Work breakdown structure



Source: SDE Summary Report

Figure 5 (page 12) shows the integrated schedule which was developed to support UK FOAK SMR operations by 2030. The different colours show activities led respectively by Government (blue), regulators (purple), operator (orange), and vendor (yellow). The construction of the critical path within this schedule is shown in Figure 6 (page 14).

A credible integrated schedule has been developed supporting the potential first operations of a UK Small Modular Reactor (SMR) by 2030



PROGRAMME DEVELOPMENT FOR UK SMR OPERATION BY 2030

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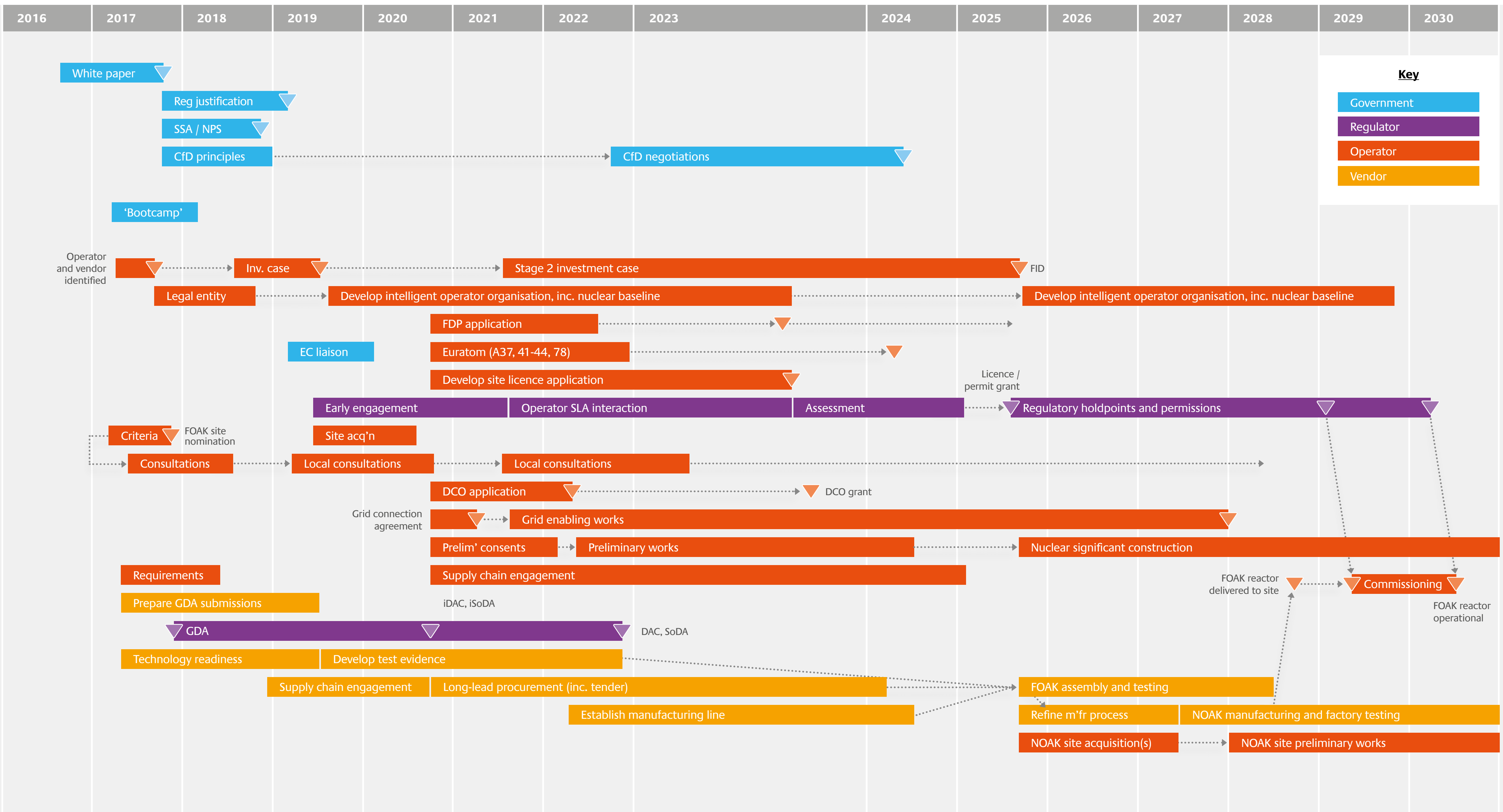
Figure 5

Integrated schedule leading to UK FOAK SMR operations in 2030



Source: SDE Summary Report

PROGRAMME DEVELOPMENT FOR UK SMR OPERATION BY 2030

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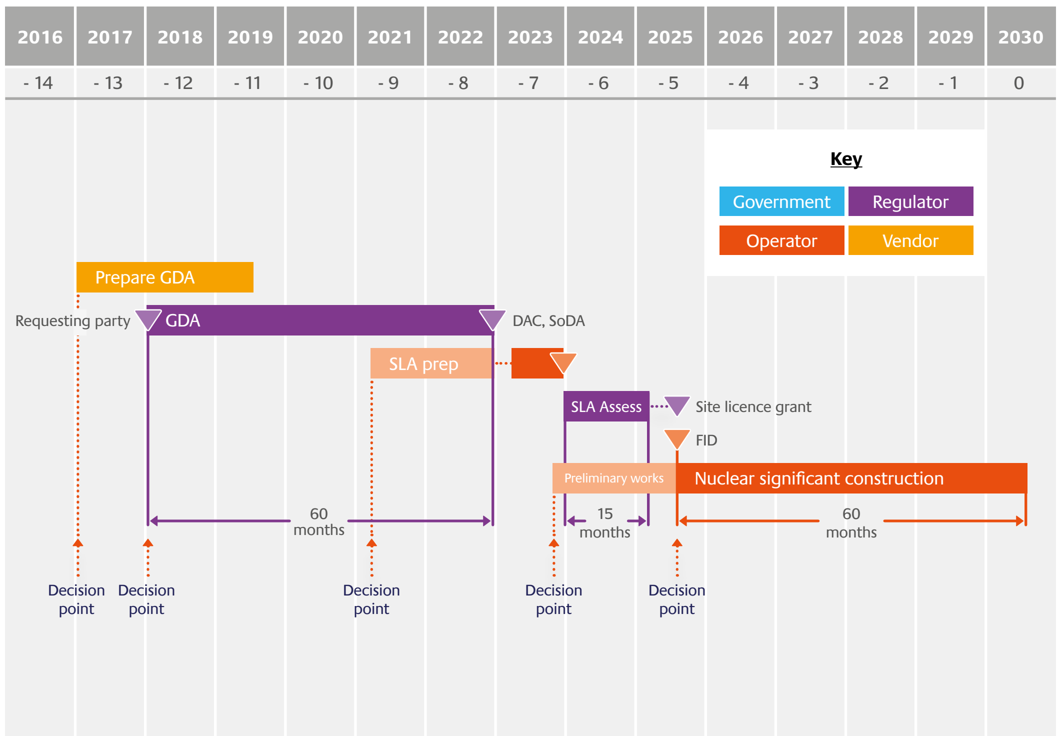
Figure 6
Abridged timeline to 2030 FOAK operation showing investment decision points



Source: SDE Summary Report

The logic of the critical path in this abridged timeline can summarised as:

- Before commencement of step one of the GDA, there would be preparatory discussions between vendor, Government and an SMR developer. These discussions are assumed to begin in 2017.
- Commencement of GDA in early 2018 with completion in late 2022. During GDA this period would also include the themes of
  - (i) the technology, including generic regulatory assessment, Regulatory Justification[8] and development of a mature design;
  - (ii) the site, including selection, acquisition, and ground and ecological investigations;
  - (iii) the operator associated with the developer, including the development of the required structures and capabilities, manning and licensing; and
  - (iv) a series of staged investment cases.
- GDA completion leading to FID. This period involves continued development of the operator organisation leading to application for the nuclear site licence and subsequent assessment by regulators. The timeline assumes that preliminary works at the site and for local infrastructure improvements begin after GDA completion but before FID. Nuclear significant construction can only begin with regulatory consent supported by the grant of a Nuclear Site Licence (NSL) by the Office for Nuclear Regulation (ONR). Nuclear significant construction represents a significant step change in the commitments being made by the developer with associated operator and it is logical to link this to the timing of the FID.
- Construction and commissioning is assumed to take five years[9] for FOAK before operations begin, with preliminary works having been undertaken prior to FID.

The timeline in Figure 6 (page 14) also indicates the timing of investment decision points:

- A vendor and a developer to prepare plans for working together.
- Commitment of the necessary resources (such as technology, personnel, finance) under a shared vision to pursue a FOAK SMR deployment project by 2030.
- Begin preparations for site-specific licensing, permitting and consenting early, ahead of completing GDA and Regulatory Justification (i.e. at risk), in order to secure FID five years ahead of FOAK operation.
- Commence site and local infrastructure preliminary works.
- FID and the start of nuclear significant construction.

It is in this context that the Government's role in fostering investor confidence is crucial for enabling a 2030 timeline for FOAK operation. It is insufficient for Government to set out an aggressive timeline for private sector investment without also taking steps to create an environment that promotes this investment through a systematic reduction of risk.

8 Regulatory Justification is the demonstration to the satisfaction of the Justifying Authority (the Secretary of State for Energy and Climate Change in the case of the design of a new nuclear power stations) that its social, economic or other benefits outweigh the health detriment of ionising radiation.

9 The assumption of a five year duration for construction and commissioning for FOAK was derived within the SDE project and is consistent with the similar assumption in the ANT summary report.

KEY ACTIVITIES IN THE FIRST FIVE YEARS

The UK Central Government would have a crucial role to play in creating the right investment environment to deliver such a schedule. The creation of this environment would require action by the Government from the outset and throughout the delivery of the timeline to FID. Table 1 identifies four key outcomes necessary to achieve the 2030 deployment schedule together with a method for achieving the outcome and the associated enabling role for Government. It should be noted that all four of the required outcomes are enabled by actions within the first five years of the deployment timeline.

Required outcomes to achieve 2030 deployment schedule and enabling role of Government within the first five years of a development programme.

The output from these enabling activities and their integration into the overall development schedule is illustrated in Figure 7 (page 18-19). The timing and combination of these enabling activities together with the issue of an interim Statement of Design Acceptance (iSODA) and an interim Design Acceptance Confirmation (iDAC), are significant in reducing risk and enabling the rate of investment necessary prior to FID to achieve the 2030 deployment schedule.

Table 1

Outcome 1: Early commencement of GDA and Regulatory Justification, and completion within a five year timeframe

Method	Enabling role of Government
Enhance the quality of engagement between vendor(s) and regulators by raising awareness of the GDA process, in particular the UK regulatory standards and expectations, and by promoting progress on GDA and Regulatory Justification processes.	Facilitation / UK awareness: To promote early engagement with vendors, through a UK 'boot camp' (facilitated by an industry body, such as the NIA). Facilitation / commit resource to: › Request the regulators to support GDA (and support headcount implications) › Invite, resource and progress assessment of Regulatory Justification applications › Encourage a positive relationship between vendor and developer with associated operator.

Outcome 2: Criteria necessary for compiling case for FID met by end 2024

Commencement of organisational development and site specific licensing activities in parallel with GDA and Regulatory Justification (at risk), potentially triggered by issue of an interim Design Acceptance Confirmation (iDAC) and interim Statement of Design Acceptability (iSoDA)

Method	Enabling role of Government
Enhance the confidence of private sector investors that future revenue from SMR generation is likely. Identify opportunities for the developer with associated operator to commence wider site licence and consenting work in parallel with vendor GDA (noting that this will represent a commercial risk to the private sector). Limit uncertainty within the investment case that underpins FID (in order to release interim investment ahead of FID and increase investor confidence concerning FID itself).	Facilitation / statement of intent: To set out a clear statement of intent in relation to SMR development in the UK, the required timescales and facilitative actions that may be taken by Government, including a further round of strategic siting assessment. Risk management / facilitation: To review the adequacy of current legislation in light of the proposed SMR development programme and lessons learnt since the publication of the 2008 White Paper; and pass new legislation where required, in order to minimise the risk of challenge by Judicial Review against Government actions or decisions. Risk management / facilitation: To engage early and constructively with developers and associated operators (and their investors) to confirm agreements that underpin cost and revenue models (including negotiations on CfD, Funded Decommissioning Plans (FDPs) and Waste Transfer Contracts, District Heat assumptions, export market facilitation, strategies for waste management and geological disposal). Risk management / facilitation: To engage early with European member states and the European Commission to identify and address potential challenges to Euratom Treaty[10] submissions.

Outcome 3: FID achieved by mid-2025

Efficient process for FID, achieved <12 months after following completion of necessary criteria

Method	Enabling role of Government
Limit uncertainty within the investment case that underpins FID.	Risk management / facilitation: To engage early and constructively with developers and associated operators (and their investors) to confirm agreements that underpin cost and revenue models (including CfD negotiations, District Heat assumptions, export market facilitation, waste strategies / geological disposal).

Outcome 4: Five year timeline post-FID

- Dominated by nuclear significant construction
- Preliminary site works commenced ahead of FID (at risk)
- SMR long-lead procurement commenced ahead of FID (at risk)

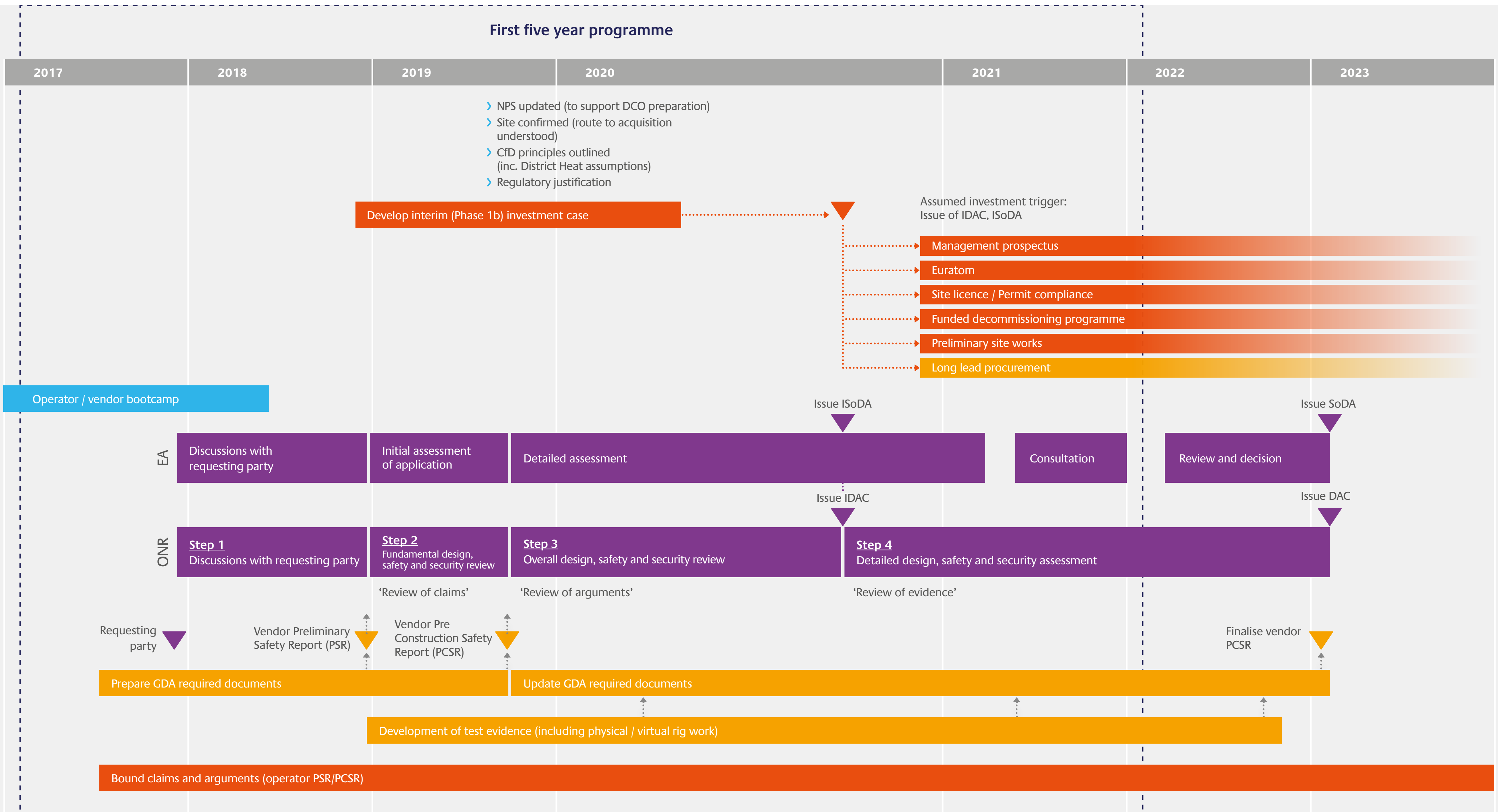
Method	Enabling role of Government
Minimise the scope of post-FID construction to nuclear significant works by undertaking as much preliminary site work as is permissible ahead of Site Licence Grant (i.e. all non-nuclear construction) Ensure the manufacture and assembly of the FOAK reactor is not on the critical path, by commencing the procurement of long-lead items ahead of FID.	Risk management / facilitation: To engage early and constructively with developers and associated operators (and their investors) to confirm agreements that underpin cost and revenue models (including CfD negotiations, District Heat assumptions, export market facilitation, waste strategies / geological disposal).

Source: SDE Summary Report and summarised by the ETI

10 Note: The scope of the SDE project excluded the outcome of the UK referendum in June 2016

KEY ACTIVITIES IN THE FIRST FIVE YEARS
Continued ›

Figure 7
Enabling activities in the first five years – the interaction between investment and the GDA process (iDAC, iSoDA as a trigger for investment)



Source: SDE Summary Report

KEY ACTIVITIES IN THE FIRST FIVE YEARS

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Impact of Different Programme Assumptions

The approach to the SDE project was based on the model of a vendor and developer with associated operator working together, as shown in Figure 2 (page 8) and was applied to the indicative timeline identified in the ANT project. The current deployment schedule is judged to be credible if the enabling actions are delivered. However, other programme assumptions can be applied with the associated consequences as shown in Table 2.

Table 2
Impact of different programme assumptions against the 2030 date for UK SMR FOAK

Changed assumption	Impact To 2030 deployment schedule
Delayed start to GDA	GDA is on the critical path and so delay would present increased risk to the 2030 date unless there is credible schedule improvement elsewhere.
Accelerated completion of GDA	The duration of GDA is influenced by vendor design choices, maturity of the design and the quality of the interaction with regulators. Five years has been the norm for the three designs assessed so far, noting that these reactors are currently being deployed or are operating elsewhere in the world. Assuming a reduced duration for SMR GDA would suggest an increased risk to the 2030 date.
Lack of facilitation through Government enabling actions	Implementation of a FOAK SMR is possible without facilitative action by Government, but the scale of risks through to first operation make it unlikely to be attractive for investors to make investment at the rate necessary to achieve FOAK SMR operation by 2030.
Lack of SMR developer engagement during the first five years	Achievement of FOAK operation by 2030 requires a developer to undertake a range of activities in parallel in a manner that increases the complexity of the schedule interactions and demands that certain activities be performed at risk. Without the parallel activities of a developer, the 2030 date is at increased risk unless there is credible schedule improvement elsewhere.

The role of central Government in the first 5 years of a UK SMR development programme is crucial in delivering an SMR policy framework

THE ROLE FOR SMRs IN A UK 2050 ENERGY SYSTEM – POWER, HEAT AND FLEXIBILITY

Developers with their associated operators will seek to deliver power stations that will become an integral part of a future UK energy system. The strongest influences impacting whether nuclear energy will deliver this are policy and economics. The previous ETI nuclear insights report identified the following conclusions regarding the role for SMRs, noting that there are still significant uncertainties regarding SMR economics:

- Large reactors may be best suited to baseload electricity generation.
- SMRs can deliver additional baseload generation if the deployed capacity of large reactors is constrained.
- SMRs may be less cost effective for baseload generation compared with large reactors.
- If SMRs are deployed in addition to large reactors, flexibility in SMR power delivery may be important in helping to balance the grid particularly with an increased capacity from intermittent renewables.
- If city scale district heat using low carbon sources is to be deployed as one of the means of decarbonising the supply of heat, then SMRs could be cost effective if deployed as CHP for energising district heat systems. This is because the additional costs to deliver CHP are small, whilst potential heat revenues are large, creating significant benefits for operators and consumers.

Phase 3 of the ANT project developed further technical feasibility and cost impact assessments to substantiate the assumptions in earlier work. It is recommended that the potential for supply of heat is considered within the Government SMR competition process.

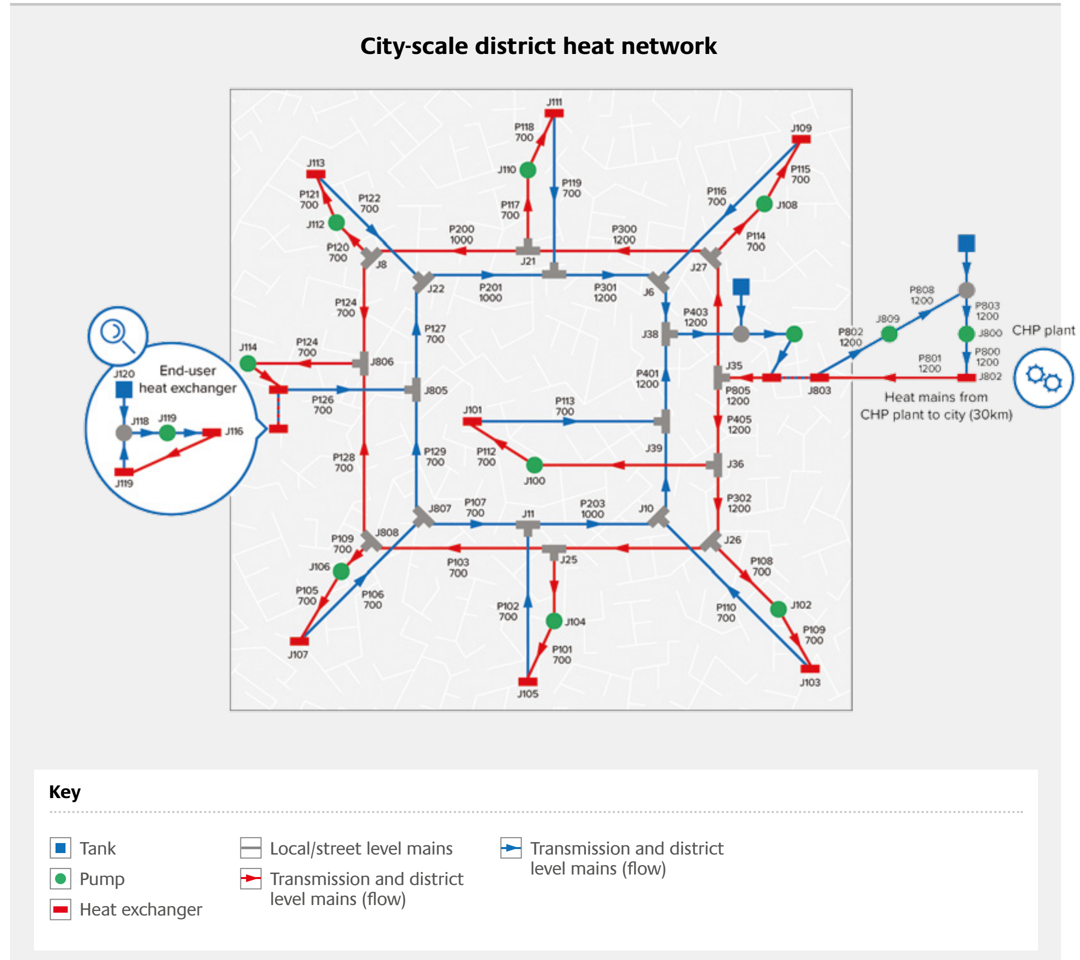
Nuclear Cogeneration and City-Scale District Heating Deployment

The review documented in the ANT Phase 3 report[11] confirms that if the UK does embark on a strategy for decarbonising heat that involves the use of nuclear-powered district heat networks, it will not be without precedent. The review of relevant international examples indicates that the use of a nuclear reactor as a CHP plant is a proven and viable technological partnership which has been successfully used by numerous countries for many decades, including Switzerland and Russia. In addition, large city-scale non-nuclear district heat networks such as Warsaw, Copenhagen and Helsinki have provided reliable heating to hundreds of thousands of people for many decades.

The scope of the ANT Phase 3 report does not assess the costs and economic benefit of district heat deployment against the alternatives for decarbonising heat because this has been addressed elsewhere in the ETI's programme.[12] However, modelling has been undertaken as part of ANT Phase 3 to derive the necessary heat supply characteristics from the PWR SMR steam cycle in order to deliver hot water into a domestic heat exchanger at 80°C. Such a supply temperature enables a typical gas boiler to be substituted with a heat exchanger, but potentially allowing existing domestic radiators and hot water storage tanks to be retained.

The analysis by Mott MacDonald used the AFT Fathom model based on a notional city-scale DH network with multiple tiers of heat mains infrastructure as recommended by the IEA. This was applied to a representative conurbation over 350km^2 in size with around 380,000 homes. This representation is shown in figure 8. Analysis showed that steam would need to be extracted at 97°C from the steam cycle of a CHP SMR plant.

Figure 8
AFT Fathom DH network model based on a conurbation over 350km^2 in size with around 380,000 homes



11 System Requirements for Alternative Nuclear Technologies (Phase 3) – Technical assessment of SMR heat extraction for district heating networks http://www.eti.co.uk/programme/nuclear/ANT-phase-3-report.pdf

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

THE ROLE FOR SMRs IN A UK 2050 ENERGY SYSTEM – POWER, HEAT AND FLEXIBILITY

Continued ›

Technical Feasibility of Heat Extraction

A proprietary design tool, Thermoflex, was used to design representative PWR SMR steam cycles for power generation, and these steam cycles were modified and optimised to enable heat extraction to supply district heat networks across a range of reactor loads. The optimised steam system solution is described in the ANT Phase 3 report. This solution enables the heat take-off to vary from zero to maximum at full reactor output. This solution also enables variable heat take-off at reactor powers less than 100%. With the application of experience from existing CHP plants, such modifications should have no significant impact on steam system availability for power generation, or power output when operating in 'power only' mode.

Size of Reactor Module and Design Thermal Efficiency

Mott MacDonald developed two steam system models in Thermoflex known as A and B. Design A used a smaller reactor module with slightly lower overall thermal efficiency and Design B uses a larger reactor module with slightly higher overall thermal efficiency.

The calculated energy balance for A and B is shown in Figure 9 (page 25), with a 'like for like' comparison achieved by scaling them with the same net power output in 'power only' mode. The diagram illustrates that in 'power only' mode Plant B produces less waste heat compared with Plant A, and this is expected because the Plant B design has been configured with a higher thermal efficiency. However with the maximum level of heat extraction, the level of power generated by Plant B is similar to Plant A, but Plant A delivers 13% more heat to the district heat condenser. Again this is expected because with a lower thermal efficiency than Plant B, more heat is available for extraction to the district heat condenser.

Cooling System Options for Inland Plants

There are economic benefits of using direct cooling whenever this is possible. The earlier ETI PPSS demonstrated that there were locations unsuitable for large reactors which would meet the Strategic Siting Assessment criteria for SMR deployment. The study showed that a typical constraint is the insufficient availability of cooling water. Where water availability is limited and it is not possible to reject heat into the cooling source, the default cooling solution is mechanical draught Evaporative Cooling Towers (ECTs).

SMR deployment inland in addition to coastal sites can deliver shorter district heat supply pipes and lower pumping loads for city-scale district heat energisation and the PPSS identified suitable SMR locations to achieve this. One of the risks for an SMR developer considering a site for an inland plant is the potential for future reductions in the permitted abstraction of water for evaporative plant cooling. This could occur due to climate change with impact on seasonal weather patterns, or policy change reflecting the quality and use of our rivers. The potential impact would be to constrain plant operation and revenues, or at worst, create a stranded asset.

The advantages, disadvantages and relative costs of a range of SMR cooling options are considered in the ANT Phase 3 report including:

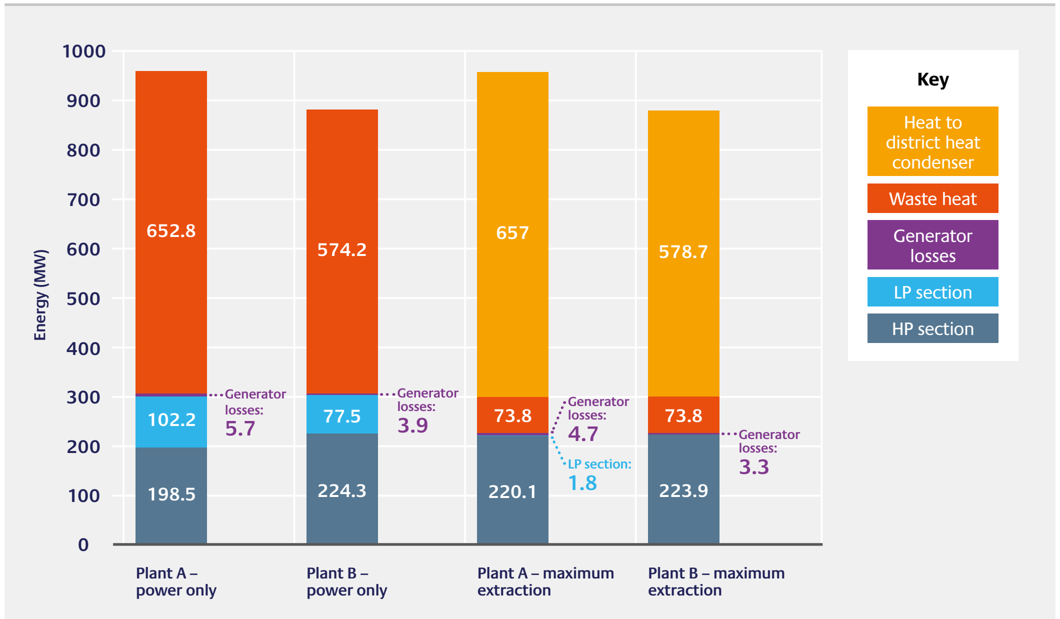
- Mechanical draught ECTs
- Air Cooled Condensers (ACCs) deployed on an unconstrained site
- ACCs deployed on a site which is space constrained
- Long-distance supply of sea water from the coast or estuary
- Dry cooling towers, otherwise known as fin-fan coolers

A core assumption behind the analysis in ANT Phase 3 is that an alternative cooling approach such as an ACC or dry cooling tower would operate alongside an ECT. These hybrid solutions assume cooling water will still be available for safe reactor shutdown. This is important because of the fundamental need to maintain sufficient cooling of the reactor core in the event of system failure or loss of performance. Whilst some plants could be designed for operation using air cooling alone, this would be dependent on both the detailed plant design and a particular deployment location; this was outside the scope of the project.

A hybrid solution with an ACC operating alongside an ECT has the advantage of exploiting the higher steam cycle efficiency of the ECTs, during times of sufficient water, and also of operating with the ACC when water is scarce. There is an efficiency penalty when using an ACC at higher ambient temperatures, but analysis at a selected UK location where sufficient historical weather data was available throughout the year showed reduction of approximately 0.5% net electrical output over the course of the year when using ACCs compared with ECTs.

It is technically feasible to retrofit an ACC to an existing plant with ECTs (whether an electricity-only or CHP plant). This would be greatly simplified and considerably cheaper if the original plant has been designed and built 'ACC ready'. This would involve a steam cycle configuration with space for this modification. Ensuring an SMR plant is 'ACC ready' involves little additional cost but requires selection of a slightly larger site at the outset.

Figure 9
SMR Plant A vs Plant B energy balance when scaled for the same net power output



Source: ANT Phase 3 report

THE ROLE FOR SMRs IN A UK 2050 ENERGY SYSTEM – POWER, HEAT AND FLEXIBILITY

Continued ›

Updated Cost Increment to Deliver CHP Energisation with Different Cooling Options

The details of the cost assessment methodology and associated ranges are documented in the ANT Phase 3 report, with only summarised central estimates shown here for clarity. Table 3 shows the incremental additional specific CAPEX and OPEX for a CHP SMR with a range of cooling solutions when compared with a 'power only' SMR. The impact of these increments is shown later in economic analyses by combining these increments with SMR Nth of a Kind (NOAK) CAPEX levels of £4,700 and £3,600 £/kWe.

The calculated incremental OPEX was comparable to the estimate in the Phase 1 and 2 report. However incremental specific electrical CAPEX for a CHP SMR compared to a power only SMR was found to be higher than estimated in the earlier ANT work (£300/kWe for FOAK and £200/kWe for NOAK) mainly due to the higher estimated cost of installing the district heat pipes for the long-distance district heat main.[13]

Deployment of an SMR which is CHP Ready

A 'CHP ready' facility would be an SMR plant initially built to provide electricity only, but one that could be retrofitted with CHP technology when necessary. This requires the inclusion of some additional features when the plant is initially built, along with space for the systems and components to be installed during the later outage for the upgrade. The estimated potential incremental specific CAPEX of CHP readiness compared with 'power only' is ~£10/kWe.

Table 3

Incremental specific CAPEX for CHP SMRs with different cooling systems compared to a power only SMR with ECTs

Plant configuration	Plant A power only ECTs	Plant A CHP ECTs	Plant A CHP ACCs	Plant A CHP area constrained ACCs	Plant B power only ECTs	Plant B CHP ECTs
CAPEX increment £/kWe	0	544	886	839	0	529
OPEX increment £/kWe p.a.	0	4	18	15	0	4

Updated Economic Assessment of CHP SMRs

The economic modelling reported previously from the work presented in the ANT report was updated with cost and performance inputs obtained from the Phase 3 work. For simplicity the range of economic metrics are represented here by the Internal Rate of Return (IRR). For the CHP appraisals, the analysis is shown for a 40% Annual Capacity Factor (ACF) for heat, with a value for heat[14] of £45/MWhth. Table 4 (page 28) shows the economic appraisal of CHP SMRs, and compares the results of the earlier ANT project with results from ANT Phase 3.

These results support the conclusion from the earlier ANT project that heat extraction from an SMR plant to supply a district heat network has the potential to significantly improve SMR economics. Scenario 1 uses the indicative SMR NOAK CAPEX derived cost from the previous ANT report. The higher base plant CAPEX means the electricity-only plant achieves only a 7.7% IRR, but for CHP Plants A and B achieve IRRs around 11%. Scenario 2 uses the target SMR NOAK CAPEX derived from the previous ANT report, which was set at the level at which SMRs could be cost effective for power generation only and delivering electricity at around £80/MWh. With this lower CAPEX and the low assumption for heat at £45/MWhth, heat extraction raises IRRs higher to around 13%. With the base case price assumption for heat at £65/MWhth, this pushes the IRRs above 15%.

The results also show that there is little difference between the economic performance of Plants A and B when reconfigured from electricity only to CHP. Both plants have a higher CHP CAPEX increment than was assumed for ANT Phases 1 and 2, mainly due to the high cost of the heat mains connecting the CHP plant to the district heat network. However this is compensated for by the higher revenues/additional heat production that result from less efficient steam cycle models than were previously assumed. The overall differences between Plants A and B are small.

Table 5 (page 29) shows the results of the economic appraisal with and without ACCs as applied to Plant A.

As expected, the results confirm that the economics are more favourable with ECTs compared with the ACC. The results also show that a hybrid cooling system built upfront, comprising both an ECT and an ACC, has a relatively small impact on overall plant economics compared to a plant built with only an ECT. With the higher level of CAPEX in scenario 1, the hybrid cooling solution still delivers an IRR above 10%. This analysis suggests that the costs of the upgraded hybrid plant can be considered relatively minor when viewed as an insurance policy against the risk of stranded assets in a changing climate. A prudent SMR developer with associated operator, deploying plants inland on sites where permitted abstraction levels may be marginal, may wish to deploy a design which is 'ACC ready'.

13 A common assumption to both studies was an incremental piping length of 10 km to connect the SMR CHP plant to the district heat main. The PPSS showed that 50% of the SMR site capacity identified was at a distance of 10 km or less from the district heat networks identified in ANT Phases 1 and 2.

14 The values for heat are derived in the previous ANT report. A base case assumption was £65/MWhth, with sensitivity studies using a lower value of £45/MWhth and a higher value of £85/MWhth

THE ROLE FOR SMRS IN A UK 2050 ENERGY SYSTEM – POWER, HEAT AND FLEXIBILITY

Continued ›

Table 4

The economic appraisal of CHP SMRs comparing the results of the earlier ANT project with results from ANT Phase 3

		ANT1&2 (power only)	ANT1&2 (CHP)	ANT 3 Plant A (CHP)	ANT 3 Plant B (CHP)
Model inputs	Gross electrical efficiency in power-only mode	37%	37%	31.4%	34.4%
	CHP CAPEX increment – £/kWe (net)	–	£200	£544	£529
	CHP OPEX increment – £/kWe p/a (net)	–	£5	£4	£4
	H:P ratio	–	1.80	2.23	1.95
	Electrical output derating in CHP mode	–	20.0%	28.7%	28.3%
	Electricity ACF in CHP mode	–	75.0%	73.5%	73.7%
	Scenario 1: Base electricity-only plant CAPEX = ~£4,700 (indicative cost scenario from Phases 1 and 2)				
	Model output – IRR	7.7%	11.0%	11.2%	10.6%
	Scenario 2: Base electricity-only plant CAPEX = ~£3,600 (target cost from Phases 1 and 2)				
	Model output – IRR	10.1%	13.7%	13.7%	13.0%

Table 5

Economic appraisal of Plant A with and without ACCs – inputs and results

	Assumes 12°C dry ambient temperature	Electricity-only (Plant A)			CHP (Plant A)		
		Cooling tower (ECT)	Cooling tower + ACC (unconstrained)	ACC only (unconstrained)	Cooling tower (ECT)	Cooling tower + ACC (unconstrained)	ACC only (unconstrained)
Model inputs	Max. net power output – MWe	47.7	48.2	48.2	34.1	33.9	33.9
	CAPEX increment – £/kWe (net)	£0	£347	£169	£544	£886	£708
	OPEX increment – £/kWe p/a (net)	£0	£10	£7	£4	£15	£12
	H:P ratio	n/a	n/a	n/a	2.23	2.22	2.22
	Electrical output derating	0%	- 1.0%	- 1.0%	28.7%	28.9%	28.9%
	Electricity ACF (adjusted)	85%	85.8%	85.8%	73.5%	73.4%	73.4%
	Scenario 1: Base electricity-only plant CAPEX = ~£4,700 (indicative cost scenario from Phases 1 and 2)						
	Model output – IRR	7.7%	7.1%	7.4%	11.2%	10.4%	10.7%
	Scenario 2: Base electricity-only plant CAPEX = ~£3,600 (target cost from Phases 1 and 2)						
	Model output – IRR	10.1%	9.1%	9.6%	13.7%	12.6%	13.1%

THE ECONOMIES OF MULTIPLES – CUSTOMER VARIANTS AND STANDARDISATION FOR GDA

The previous section considered the requirement for heat extraction as part of the requirement of a UK SMR alongside power generation and flexibility. The analysis suggests that:

- The impacts on CHP cost effectiveness from vendor choices regarding module size and overall thermodynamic efficiency are expected to be of second-order significance. If the most cost effective plant is selected on the basis of power generation economics, it is likely to also be the most cost effective for CHP deployment.
- UK SMRs should be deployed as CHP ready. CHP readiness can be delivered for a small incremental cost (~£10/kWe) and would ensure that SMR plants are ready for a subsequent upgrade to allow heat extraction to supply district heat networks. CHP readiness should be considered for a UK FOAK SMR, even if it cannot initially be demonstrated due to a lack of infrastructure/heat demand.
- Developers and their associated operators may wish to retain the future option to upgrade the ECT cooling system against the risk of constrained or reduced water abstraction limits as a result of climate change or policy change. Retaining this future upgrade option may be important to avoid potentially lower future revenues associated with reduced generation, or potentially a stranded asset.

For UK SMR deployment to become an integral part of a 2050 UK energy system, a UK SMR developer may therefore wish to retain options from a reactor vendor regarding heat take-off and cooling system type. At the same time, it is likely that other SMR developers in international markets may have requirements for heat take-off for a range of requirements including district heat, process steam or for desalination. It is also inevitable that these other potential SMR developers will require plant cooling solutions appropriate to individual deployment sites.

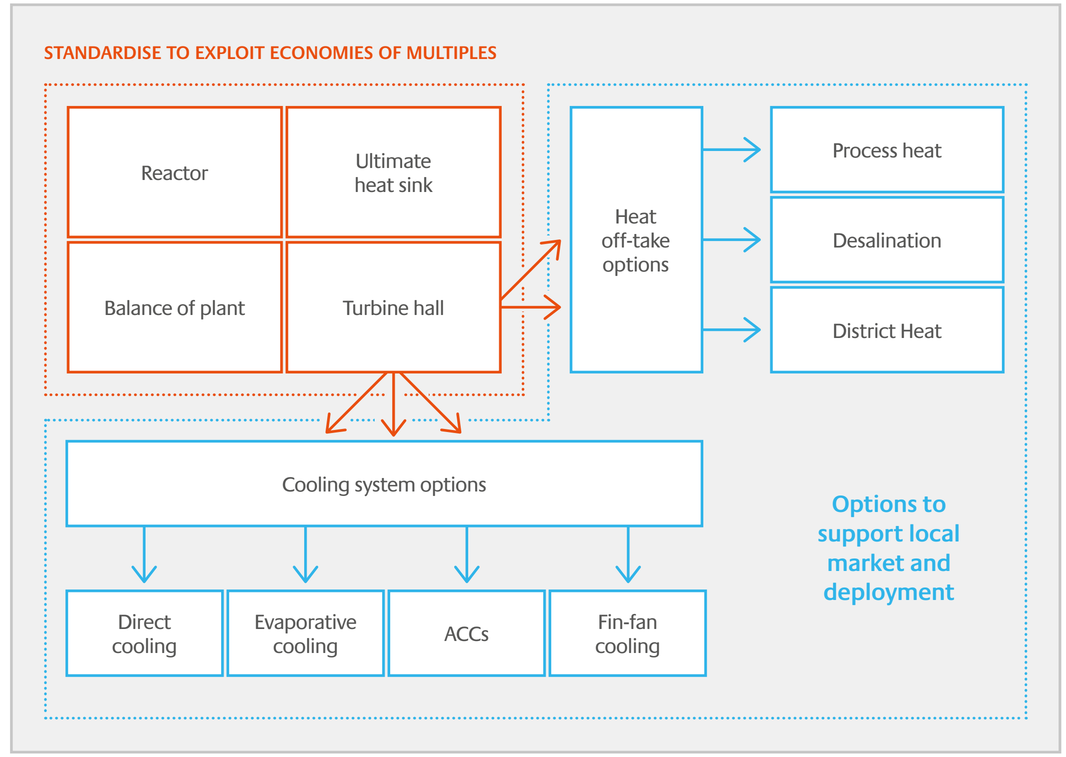
It is suggested that the design(s) taken forward into UK GDA reflect both the heat take-off and cooling system options that can be anticipated will be required by other future reactor vendor customers, whilst applying standardisation to exploit the economies of multiples for the elements of reactor island, turbine island, ultimate heat sink[15] and balance of plant. This combination of standardisation and customer options provided by the reactor vendor is shown in Figure 10 (page 31).

The potential benefits to the UK are:

- A design which is CHP ready for the UK.
- A design offering appropriate customer options which can be deployed in other markets without requiring modification to the design assessed in GDA.
- Potential for accelerated cost reduction in UK deployment if the design is deployed in other markets and the supply chain can deliver the claimed benefits of the economies of multiples.

15 In this context the ultimate heat sink is required to provide a reliable method of cooling of the reactor core (and any stored used fuel) in the event that the normal method of heat removal is degraded or unavailable

Figure 10
Scope of SMR design to be assessed through UK GDA



IDENTIFICATION OF EARLY SMR DEVELOPMENT SITES

One of the seven key elements for a UK SMR development programme as shown earlier in Figure 1 (page 7) is a credible FOAK site amongst a range of potential early deployment sites.

The ETI's earlier PPSS had identified potential sites for the deployment of large reactors as part of the UK energy system transition to 2050. It was found that the capacity from the potential sites in England and Wales is limited and it was recommended that a strategic approach was necessary in managing the sites available for reactor deployment. This earlier work also identified potential sites against criteria compatible with the existing Strategic Siting Assessment criteria which were unsuitable for the deployment of large reactors, but which may be suitable for the deployment of SMRs. These SMR sites broadly fell into three types of location:

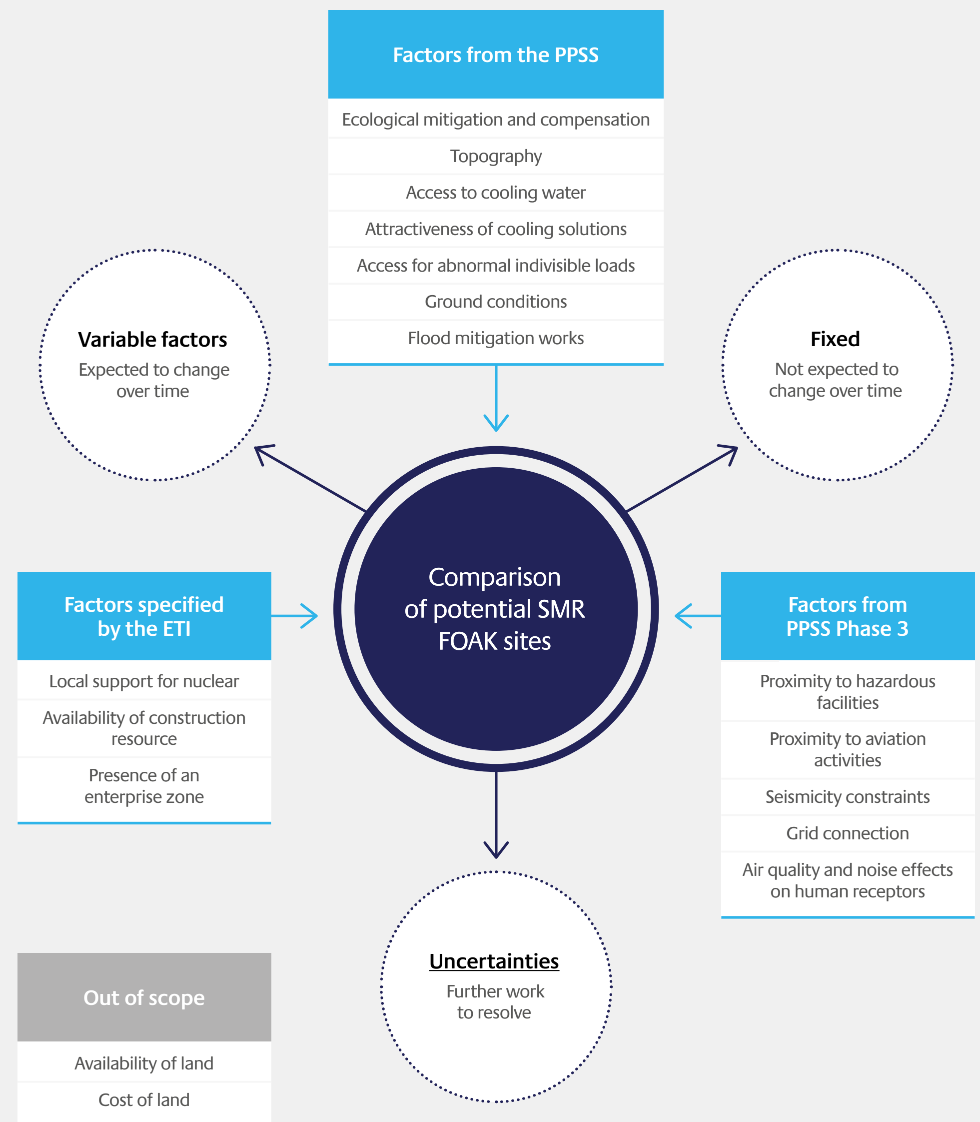
- Adjacent to existing nuclear power stations.
- Adjacent to current or historic thermal power stations.
- Locations not previously used for power generation including greenfield sites.

The PPSS Phase 3 study, informed by the earlier PPSS work, developed a range of potential sites for early SMR deployment and a shortlist has been defined. Shortlisted sites have met the following requirements:

- Satisfied the requirements of the strategic siting assessment criteria from NPS EN-6.
- Adjacent to an existing nuclear licensed site.
- Close to a source of cooling water (within 2 km).
- Cooling capacity and development area capable of supporting two SMR 'units' each with a generation capacity of up to 300 MWe.

Ranking factors were derived to help identify the relative ease or challenge associated with each factor for each individual site. Fifteen ranking factors encompassing engineering, environmental and socio-economic considerations enabled comparison of a range of potential early SMR sites. These are shown in Figure 11 (page 33).

Figure 11
Comparison using ranking factors of potential early SMR sites



Source: Summarised from the PPSS Phase 3 report with additions from the ETI

IDENTIFICATION OF EARLY SMR DEVELOPMENT SITES

Continued ›

Data was sought for each of the factors and applied as an Amber/Yellow/Green traffic light indicator at each of the sites. Although some information was found on the potential level of local support for or opposition to new nuclear power stations across a range of locations it was concluded that this information was neither recent enough nor sufficiently objective to be part of the evidence to compare one potential site with another.

The ranking factors chosen were intended to represent some of the indicators which would be considered by a potential developer in considering where to build and operate SMRs. However there are other relevant factors out of the scope of the project and not included such as:

- Availability of land for use via sale or lease from a willing landowner.
- Variation between sites in the cost of land through sale or lease.

The factors used in the comparison between sites could also be grouped as:

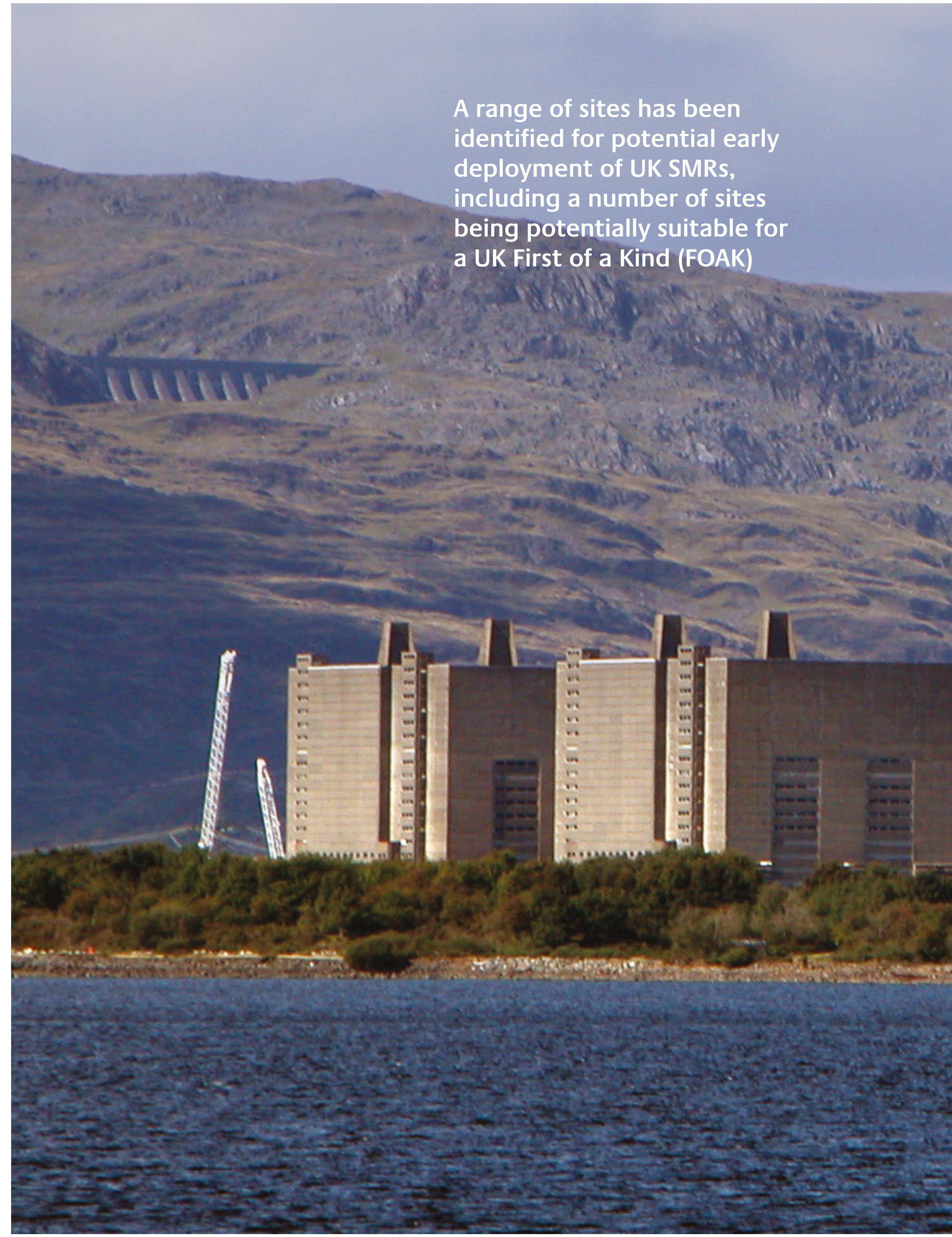
- Fixed; such as aspects related to geology or geography, with no expected change over time.
- Variable; such as socio-economic aspects, with the expectation that they may change over time.
- Uncertainties; which may change over time with further assessment.

The grouping of factors is also illustrated in Figure 11 (page 33). The results from the PPSS Phase 3 show:

- It is clear that the categorisation of sites against some of the individual ranking factors can be expected to change over time. Two examples of such time-dependent ranking factors include grid connection and local stakeholder support.
- Developers with associated operators, landowners and other stakeholders will have different perspectives on the relative importance of individual ranking factors. The comparison between sites, or ranking, is subjective and should be expected to change over time.
- Interest and intervention by a developer with an associated operator at a particular location has the potential to influence the ranking, such as through the early engagement of local stakeholders or an early application for grid connection.

The project has shown that there is a number of sites which could support a first tranche of SMR deployment in the UK and provide options for a potential FOAK SMR site. Different organisations may have differing views on which site may be preferred for a FOAK SMR; some of the factors influencing a particular preference may change over time. This conclusion is significant because it gives confidence that a number of sites could be nominated into a second Strategic Siting Assessment process, which is shown commencing at the end of 2017 in the integrated schedule in Figure 5 (page 12-13). Experience has shown that nominations are best led by the developer, including the requirement for local stakeholder engagement.

The conclusion from the earlier PPSS remains important in that there is a need for a strategic approach to managing potential sites for reactor deployment because of the limited number of sites suitable for large reactors in England and Wales.



CONCLUSIONS

The ETI SDE project provides a credible integrated schedule leading to potential UK FOAK SMR operations by 2030. This integrated schedule identifies activities for a vendor, an SMR developer with associated operator, Government and regulators.

Achievement of the 2030 schedule requires early involvement of the potential SMR developer with their associated operator (known as the licensee) during GDA.

Creating the right environment for increasing investor confidence is critical if timely progressive investment is to be committed by each of the vendor, the vendor supply chain and the SMR developer with associated operator.

The enabling activities in the first five years of this programme include a role for Government in delivering an SMR policy framework and associated actions. These actions are significant against the need to create investor confidence.

The integrated programme developed within the SDE project uses a structured and documented set of assumptions which are not specific to particular combinations of vendor and developer with associated operator. Changes to these assumptions which would delay the completion of GDA, delay the involvement of the developer and associated operator, or reduce the extent of Government facilitation, may delay the 2030 first operations date.

Design and cost assessment has been undertaken on the engineering changes necessary to deploy SMRs for delivery of CHP. It is been concluded that it is technically viable for the steam cycle of a PWR SMR to deliver independently variable levels of heat and power across the range of permitted reactor power. Although details of the performance assessment and cost impact have been updated from earlier work, this further economic appraisal reconfirms the attractiveness of deploying SMRs as CHP plants to energise district heat systems.

Consideration should be given to the concept of deploying SMRs as 'CHP ready', even if there is no firm local demand for energisation of district heat systems at the time of SMR deployment. This is because the costs are small and the potential revenues large, bringing benefits to both consumers and SMR operators. Nuclear cogeneration is well established and the use of heat recovered from a PWR steam cycle to energise district heat is operationally proven elsewhere.

Consideration should be given to the concept of deploying inland SMRs as 'ACC ready'. This may be important to mitigate the risk of future reductions in the permitted level of water abstraction and analysis indicates that CHP SMRs remain economically viable if deployed with a hybrid cooling system comprising ECTs and ACCs.

The SMR design(s) taken forward into UK GDA by reactor vendor(s) should reflect both the heat take-off and cooling system options that will be required by potential SMR developers in the UK and internationally, whilst applying standardisation to exploit the economies of multiples for the elements of reactor island, turbine island, ultimate heat sink and balance of plant.

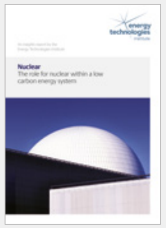
Further work within the ETI's PPSS has identified a range of sites suitable for the early UK deployment of SMRs, with a number of sites being potentially suitable for a UK FOAK SMR.

The conclusion from the previous ETI nuclear insight report remains important in that there is a need for a strategic approach to managing potential sites for reactor deployment because of the limited number of sites suitable for large reactors in England and Wales.

LIST OF ABBREVIATIONS

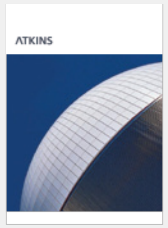
ACC	Air Cooled Condenser
ACF	Annual Capacity Factor
ANT	The ETI's project known as System Requirements for Alternative Nuclear Technologies
CfD	Contract for Difference
CHP	Combined Heat and Power
CGN	China General Nuclear
DAC	Design Acceptance Confirmation
DCO	Development Consent Order
DECC	Department of Energy and Climate Change
EA	Environment Agency
ECT	Evaporative Cooling Tower
FDP	Funded Decommissioning Plan
FID	Final Investment Decision
FOAK	First of a Kind
GDA	Generic Design Assessment
H:P	Heat to Power (ratio)
iDAC	Interim Design Acceptance Confirmation
IEA	International Energy Agency
IRR	Internal Rate of Return
iSODA	Interim Statement of Design Acceptance
MWe	Mega Watt electrical
MWh	Mega Watt hour
MWhth	Mega Watt hour thermal
NIA	Nuclear Industries Association
NOAK	Nth of a Kind
NPS	National Policy Statement
NSL	Nuclear Site Licence
ONR	Office for Nuclear Regulation
PCSR	Pre Construction Safety Report
PPSS	The ETI's project known as the Power Plant Siting Study
PSR	Preliminary Safety Report
PWR	Pressurised Water Reactor
SDE	The ETI's project known as SMR Deployment Enablers
SLA	Site Licence Application
SMR	Small Modular Reactor
SODA	Statement of Design Acceptance
SSA	Strategic Siting Assessment
TEA	Techno-Economic Appraisal
WBS	Work Breakdown Structure

EXISTING ETI DOCUMENTS AVAILABLE ONLINE



Insight report – Nuclear – the role for nuclear within a low carbon energy system

http://www.eti.co.uk/the-role-for-nuclear-within-a-low-carbon-energy-system/

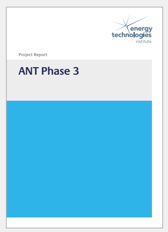


Power Plant Siting Study – summary report

http://www.eti.co.uk/project/power-plant-siting-study/

ANT Project – summary report

http://www.eti.co.uk/wp-content/uploads/2015/10/ANT-Summary-Report-with-Peer-Review.pdf



ANT Phase 3 Project Report

http://www.eti.co.uk/programme/nuclear/ANT-phase-3-report.pdfprogramme/nuclear/ANT-phase-3-report.pdf

SMR Deployment Enablers – Summary Report

http://www.eti.co.uk/programme/nuclear/SDE-summary-report.pdf

Options, Choices, Actions

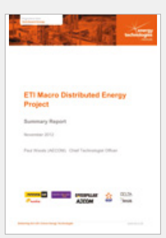
http://www.eti.co.uk/options-choices-actions-uk-scenarios-for-a-low-carbon-energy-system/

Decarbonising heat for UK homes – an insights report by the ETI

http://www.eti.co.uk/heat-insight-decarbonising-heat-for-uk-homes/

ETI's smart systems and heat programme

http://www.eti.co.uk/smart-systems-and-heat-2/



ETI's macro distributed energy project

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

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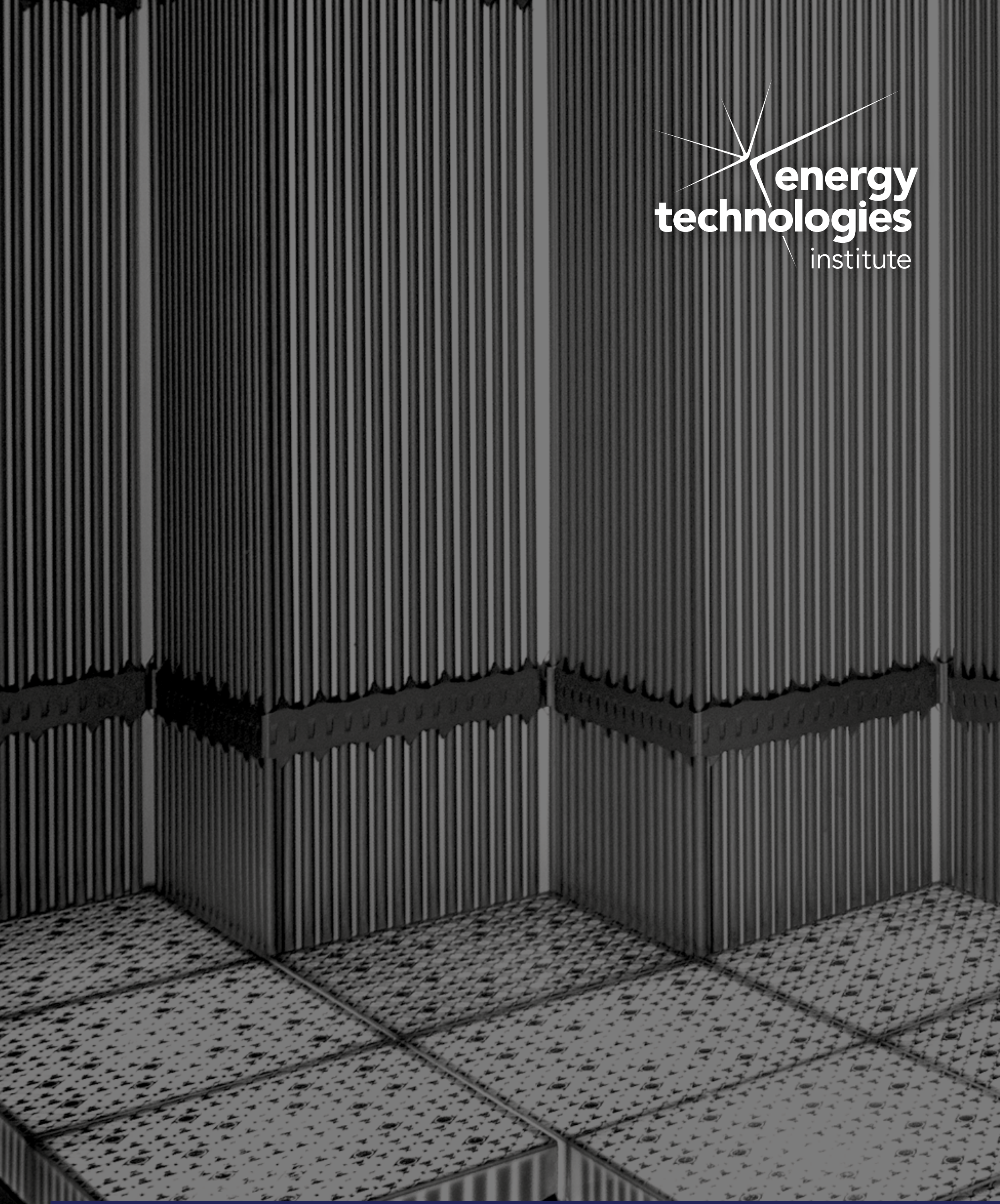

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