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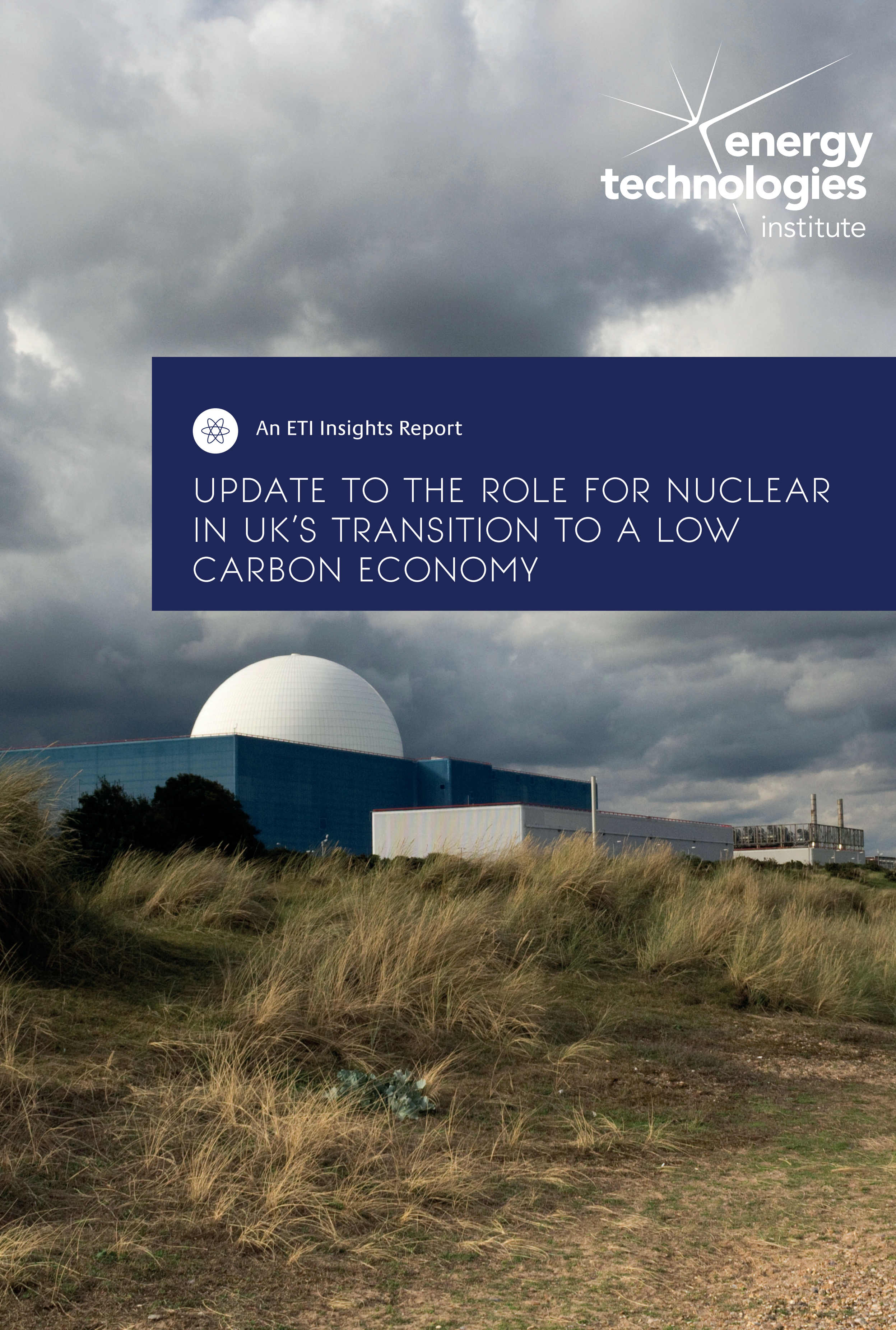
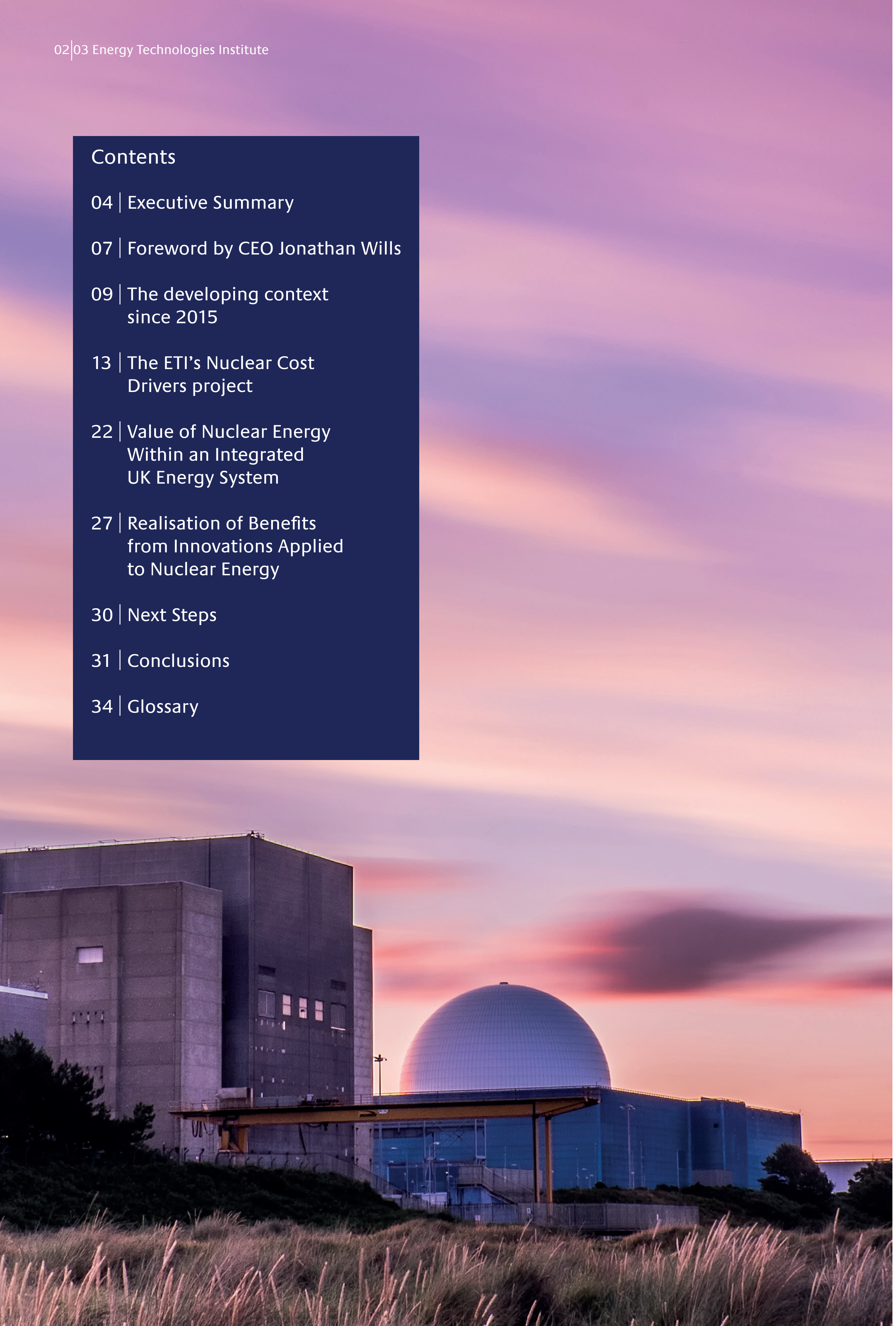
An ETI Insights Report

UPDATE TO THE ROLE FOR NUCLEAR IN UK'S TRANSITION TO A LOW CARBON ECONOMY





Contents

New plants can form a **major part** of an affordable **low carbon transition**, with roles for **large nuclear**, **Small Modular Reactors (SMRs)** and **Advanced Modular Reactors (AMRs).**

Large-scale nuclear reactors are best suited for baseload electricity **production and** are the only option for significant new nuclear **power capacity** in the UK before **2035**.

AMRs and **SMRs** may be valuable for flexible dispatchable **heat** and **power**. High temperature heat could be cost effective for **hydrogen production.**

UPDATE TO THE ROLE FOR NUCLEAR IN UK'S TRANSITION TO A LOW CARBON ECONOMY

Innovations in the **nuclear heat** supply system could be deployed in a range of AMRs **operating** in limited numbers from **2035**.

AMRs and **SMRs** should be encouraged as they **can contribute** to a cost-effective **low carbon energy system**.

Future **nuclear plants designs** must be developed with a **focus on cost**, to be **commercially** successful.

New **nuclear requires** a high degree of **central coordination** from the **UK government** to be **successful**, making a stronger contribution in an ETI **"clockwork"** scenario.

EXECUTIVE SUMMARY

The Energy Technologies Institute, working with the Energy System Catapult, released its report Options, Choices, Actions [updated 2018]. This included updates to two illustrative cost-optimised decarbonisation scenarios for the UK energy system – Clockwork and Patchwork - either of which would meet the UK's 2050 climate targets. One of the supporting conclusions in the report was that commercial development and deployment of new nuclear remained a priority as part of the future energy mix, assuming costs could be contained.

This insight report summarises the learning from the ETI's Nuclear Cost Drivers (NCD) project which was commissioned through open competitive procurement, delivered by the organisation now known as Lucid-Catalyst, and reported in April 2018. It also reports the learning from applying the nuclear cost drivers data and associated learning through sensitivity testing in the ESME whole system modelling tool now operated by the Energy System Catapult.

This report is intended to be an update to the first ETI nuclear insight report released in October 2015, entitled Nuclear – the role for nuclear within a low carbon energy system, and for completeness also summarises developments in the UK nuclear context since 2015.

Contemporary giga-watt scale reactors remain the only designs ready to be deployed in the UK in meaningful numbers between 2025 and 2035. Conservative and pessimistic application of learner effects from a potential UK programmatic approach, using data derived from the ETI NCD project and applied in limited ESME scenario sensitivity testing, indicates that deployment of such reactors continues to be a central part of a UK lowest cost low carbon energy solution.

Innovations in the nuclear heat supply system (Gen IV advanced reactors and fusion) are yet to be proven technically and commercially, although some First of a Kind (FOAK) commercial plants could be operating in limited numbers from 2035. Such commercial plants could offer transformational reductions in cost and consequential growth in economic opportunity through deployment in the UK and elsewhere.

Successful deployment of these innovations as low carbon energy products is expected to depend on the exploitation of the advantages of simpler nuclear heat supply systems combined with delivery through factory based modular manufacture and assembly to reduce costs.

Future nuclear plant designs which are developed without a singular focus on cost, and the associated necessities of minimising labour content and application of nuclear grade quality requirements, are unlikely to be commercially successful.

Nuclear remains a valuable technology in the mix in an affordable UK transition to a low carbon economy as identified in Options, Choices, Actions [updated 2018]. It is also clear that, to be successful, new nuclear requires a high degree of central coordination and hence makes a stronger contribution in a "Clockwork" scenario than it does in a "Patchwork" world.

Contemporary giga-watt scale reactors remain the only designs ready to be deployed in the UK in meaningful numbers between 2025 and 2035.

Photo courtesy of EDF Energy

FOREWORD BY CEO JONATHAN WILLS

Low carbon nuclear energy has been the backbone of the UK's electricity supply since the 1950's, but much of the existing fleet is at or nearing the end of its life. The question of how to replace it and with what has become increasingly important in the face of the UK's transition to a cleaner energy future for electricity, heat, and transport.

The ETI's work has consistently looked at the energy system transition through a systems lens prioritising technologies in order to achieve a cost optimised path to a low carbon future. In all of that analysis, nuclear energy has always remained part of the mix. How much nuclear generation, what type of plant, and indeed where it could be built remain open questions. The answers depend in large part on the UK's policy towards a new build nuclear programme, the cost of the programme (and value for money for the taxpayer), the UK's industrial capabilities, and the pace of development of new technologies – modular reactors, the application of novel manufacturing and installation approaches and so on.

Ultimately, the cost of new nuclear, and more precisely cost certainty, are high on the list of issues to be addressed before any new build programme is likely to receive the sizable investment it requires – regardless of whether this is public or private investment. Other technologies such as offshore wind have demonstrated it is possible to achieve and even beat cost reduction targets and to deliver projects on time and cost and hence attract low risk capital. Can nuclear do the same?

What drives cost in nuclear? Is nuclear really "different"? What causes delays and cost escalations? What can we learn from the past and from others?

The ETI's Nuclear Cost Drivers work set out to tackle these questions and others. It identified eight drivers of cost and concluded that cost and risk reduction are eminently achievable. Finalising design before construction is key. Committing to multiple units of the same design to smooth resourcing and maximise learning is important. Locating reactors on the same site where possible and sharing the same infrastructure helps. However, fleet deployment by itself does not necessarily guarantee cost reduction. To realise cost reduction within a fleet or sequenced multi-unit build, project delivery consortia must also implement and manage a well-designed and intentional programme that incorporates multiple project performance improvement and cost reduction opportunities by all principal actors.

In other words, organising to deliver a programme of similar projects delivers lower costs than a series of disconnected projects.

Looking at nuclear through the system lens once more through the ESME models and scenarios confirms that electricity generation will always be an important role for current and future nuclear technologies. However, as decarbonisation of our energy system, there may be potential future roles for advanced low-cost nuclear technologies operating at higher temperatures capable of supplying power, high temperature industrial heat, and hydrogen. The potential system benefits of deploying such technologies alongside renewables and carbon capture, storage and use are yet to be properly explored. The sensitivity analysis reported in this insight document hints that the potential prize associated with nuclear, even with very pessimistic assumptions, can be significant not only in the value to consumers but also in economic opportunity.

From the perspective of the UK deployment of new nuclear energy, much has changed since 2015.

Figure 3
Nuclear Island Construction at Hinkley Point C courtesy of EDF Energy

DEVELOPING CONTEXT SINCE 2015

ETI Insight – Role for Nuclear

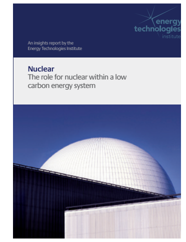


Figure 1
ETI Insight – the role for nuclear in a low carbon energy system

The ETI released its first insight[1] on nuclear energy in 2015 as shown in figure 1. Two of the leading key messages were:

- New nuclear plants can form part of an affordable low carbon transition with potential roles for both large nuclear and Small Modular Reactors (SMRs).
- Large reactors are best suited for baseload electricity production. Analysis indicated an upper capacity limit in England and Wales to 2050 from site availability of 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.

Options, Choices, Actions (Original from 2015)

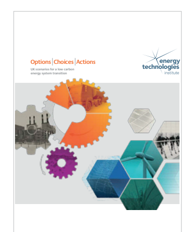


Figure 2
Options, Choices, Actions – UK scenarios for a low carbon energy system

The ETI also released in 2015 its insight paper titled Options, Choices, Actions as shown in figure 2[2]. This paper utilised two scenarios known as patchwork and clockwork to illustrate two different pathways in the potential decarbonisation of the UK energy system. Two of the leading key messages were;

- The UK must focus on developing and providing a basket of the most promising supply and demand technology solutions. Developing a basket of options (rather than a single system blueprint) will help to limit inevitable implementation risks.
- Key technology priorities for the UK energy system include the following: bioenergy, carbon capture and storage, new nuclear, offshore wind, gaseous systems, efficiency of vehicles and efficiency/heat provision for buildings.

From the perspective of the UK deployment of new nuclear energy, much has changed since 2015.

Hinkley Point C in Construction

EDF's new nuclear power station at Hinkley Point in Somerset is in construction with a photograph showing progress at the end of January 2019 at figure 3 reproduced here with permission from EDF. Plans continue for the proposed new plant at Sizewell in Suffolk. Development of these projects is informed by the success of CGN's EPRs in Taishan with unit 1 connected to the grid in June 2018 and commencing commercial operations December 2018[3].

Despite this progress the EPRs at Olkiluoto and Flamanville are yet to enter commercial operation, and contractual and commercial challenges faced by Areva Nuclear Plants forced restructuring and transfer as a new subsidiary to EDF now known as Framatome.

[1] The role for nuclear in a low carbon energy system. Energy Technologies Institute 5th October 2015 https://www.eti.co.uk/insights/the-role-for-nuclear-within-a-low-carbon-energy-system
[2] Options, Choices, Actions – UK scenarios for a low carbon energy system 2nd March 2015 https://www.eti.co.uk/insights/options-choices-actions-uk-scenarios-for-a-low-carbon-energy-system
[3] First EPR enters commercial operation World Nuclear News 14th December 2018 http://www.world-nuclear-news.org/Articles/First-EPR-enters-commercial-operation

Closure of NuGen's Project At Moorside

NuGen was launched in 2009 as the developer of the Moorside site in Cumbria. Initially a venture between GDF Suez, Iberdrola and SSE, in December 2013[4]. Toshiba acquired a majority shareholding of NuGen with plans to deploy three AP1000 reactors at this site. Toshiba's liabilities associated with the subsequent bankruptcy of Westinghouse incurred significant losses and in November 2018 Toshiba, as the sole investor by this stage, decided[5] to close the Moorside project.

Suspension of Horizon's Wylfa Newydd

Horizon was formed as a joint venture between the German headquartered utilities RWE and E.On to develop new nuclear power stations at sites at Wylfa in North Wales and Oldbury on the estuary of the river Severn. It was acquired by Hitachi in 2012 as a vehicle to deploy the HitachiGE Advanced Boiling Water Reactor (ABWR) design which is operationally proven in Japan.

In January 2019 Hitachi[6] decided to suspend its project to develop ABWRs at its lead site on Anglesey, and it is noteworthy that Hitachi's share price rose[7] by as much as 6% as this news began to emerge. One possible explanation of this market response is the market's view that the Horizon project was associated with negative Net Present Value (NPV) based on the perception of risk.

Innovation In Nuclear Energy Technologies

The ETI's second nuclear insight[8] in 2016 examined in more detail the programmatic steps necessary for a UK SMR to be operating by 2030. It also summarised a feasibility study which confirmed the potential for steam extraction to deliver a cogeneration plant capable of delivering power and a variable supply of steam for energisation of a city scale district heating system (or desalination plant in other markets).

A UK consortium led by Rolls-Royce has been developing an innovative light-water SMR design to reduce project risk, schedule and costs, and has been seeking Government support[9]. At the same time, NuScale continues to develop its innovative light-water SMR design and is progressing, aided by a succession of funding grants from the US Federal Government, through regulatory assessment[10] by the US Nuclear Regulatory Commission. These innovative designs use proven contemporary light-water reactor fuel and associated technologies, but from the outset these designs are intended to incorporate changed manufacturing, assembly and project construction methodologies. The goal is to use modular manufacturing methods to reduce project schedule and risk and thereby improve both costs and project investibility.

Since 2015, private sector interest and investment in advanced or Generation IV nuclear technologies has also grown in the UK and elsewhere. The UK Government has implemented a competition targeting the development of Advanced Modular Reactors (AMRs). These are generically segregated from light-water SMRs in that they do not use water as the reactor coolant. Successful applicants in the first phase of the competition secured modest funding to support a feasibility study, and some of these applicants may receive further funding for a second phase. As well as advanced modular fission reactors, the competition scope includes modular fusion reactors. Applicants successful at securing funding in phase 1 have been identified[11] as:

[4] Toshiba stake in UK new-build World Nuclear News 23rd December 2013 http://www.world-nuclear-news.org/Articles/Toshiba-stake-in-UK-new-build
[5] Toshiba decides to scrap Moorside project World Nuclear News 8th December 2018 http://www.world-nuclear-news.org/Articles/Toshiba-decides-to-scrap-NuGens-Moorside-project
[6] Nuclear plant in Anglesey suspended by Hitachi BBC news 17th January 2019 https://www.bbc.co.uk/news/business-46900918
[7] Hitachi UK says no decision taken on British nuclear project. Reuters January 11th 2019 https://www.reuters.com/article/us-hitachi-nuclear/hitachi-uk-say-no-decision-taken-on-british-nuclear-project-idUSKCN1P51F3
[8] Preparing For Deployment Of A UK Small Modular Reactor By 2030. ETI insight 29th September 2016 https://www.eti.co.uk/insights/preparing-for-deployment-of-a-uk-small-modular-reactor-by-2030
[9] UK SMR consortium calls for Government support. World Nuclear News 12th September 2017 http://www.world-nuclear-news.org/Articles/UK-SMR-consortium-calls-for-government-support
[10] NuScale SMR enters first manufacturing phase. World Nuclear News 26th September 2018. http://www.world-nuclear-news.org/Articles/NuScale-SMR-enters-first-manufacturing-phase

1. Advanced Reactor Concepts LLC
2. DBD Ltd
3. LeadCold
4. Moltex Energy Ltd
5. Tokamak Energy Ltd
6. U-Battery Developments Ltd
7. Ultra Safe Nuclear Corporation
8. Westinghouse Electric Company UK Ltd

Technologies which progressed this first phase of feasibility studies may be grouped as:

- High temperature gas reactors (3)
- Liquid metal cooled reactors (3)
- Molten salt reactors (1)
- Modular fusion reactors (1)

Options, Choices, Actions (Updated 2018)

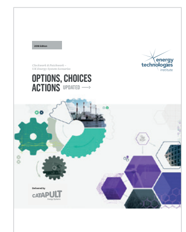


Figure 4
The ETI's Options, Choices, Action [Updated 2018]

The ETI revisited and updated its scenarios insight paper from 2015 through an updated publication released in 2018 as shown in figure 4. The key messages in the context of the transition to a low carbon economy are paraphrased and abbreviated from the executive summary as:

1. a balanced multi-vector approach can deliver an affordable, low carbon UK energy transition
2. cannot be prescriptive about the precise mix – develop a basket of the most promising solutions
3. sustainable biomass for heat and power and also conversion to gaseous and liquid fuels
4. carbon capture and storage (CCS) offers a versatile solution; without CCS abatement costs could double by 2050
5. bioenergy and CCS especially valuable in combination with potential "negative emissions"
6. system flexibility needs will change; storage of electricity, heat and gas (H2) will be important
7. low carbon heat solutions exist but consumer experience is key
8. electrification of transport underway; transition uncertain but whole system coordination needed

The conclusion of the updated 2018 paper states that the priorities for commercial development are bioenergy, CCS, offshore wind, new nuclear, gaseous systems, efficiency of vehicles and efficiency of heat provision. In greater detail it states that nuclear is a priority for commercial development but:

- The technology remains unproven commercially
- Construction of Hinkley Point C is now underway, but long lead time for approvals makes new nuclear deployment before 2030 unlikely
- Small modular reactors delivering power and heat might be valuable in 2030s and 2040s

Specifically, the 2018 scenarios represent different pathways each comprising a different mix of nuclear as part of the scenario definitions:

- Clockwork - 16 GWe large Gen III+ with load factor of 90% in 2050
- Patchwork - defined as lack of central co-ordination meaning new nuclear stalls after 2 new plants

[11] Nuclear Sector Deal announced 27th June 2018 https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/720405/Final_Version_BEIS_Nuclear_SD.PDF
[12] ETI's Options, Choices, Actions. 8th October 2018 https://www.eti.co.uk/news/eti-demonstrates-the-affordability-of-a-uk-low-carbon-transition-in-an-update-of-its-energy-system-scenarios

Photo courtesy of EDF Energy

THE ETI's NUCLEAR COST DRVIERS PROJECT

The period since 2015 has also demonstrated great success through innovation in the increasing deployment of renewables with offshore wind in particular demonstrating a trajectory of reducing costs, increasing deployment rates, and individual projects within a programme that are successful in securing private sector investment.

In the same period, the global story of large nuclear reactor projects has been very mixed. There was a general pause in projects whilst the lessons were learned from the Fukushima nuclear plant accident which affected the schedules of many reactors under construction in this period. But reactor construction continued in Russia, China, Korea, the United Arab Emirates and elsewhere. This period has included First of a Kind (FOAK) plants beginning commercial operations utilising Gen III+ designs. Project success has been mixed, with news dominated by the magnitude of the schedule and cost overruns at Olkiluoto 3, Flamanville 3, Vogtle 3 and 4, and VC Summer 2 and 3 (now cancelled at just under 40% completion[13]). Nuclear power plant construction and progress in Asia and the Middle East has seen greater success but attracted less media profile. Against this context, the ETI specified, procured and delivered its Nuclear Cost Driver's project.

Nuclear Cost Driver Project Objectives

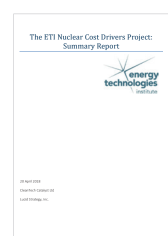

The ETI Nuclear Cost Drivers Project: Summary Report

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Figure 5
The ETI's Nuclear Cost Drivers Project: Summary Report

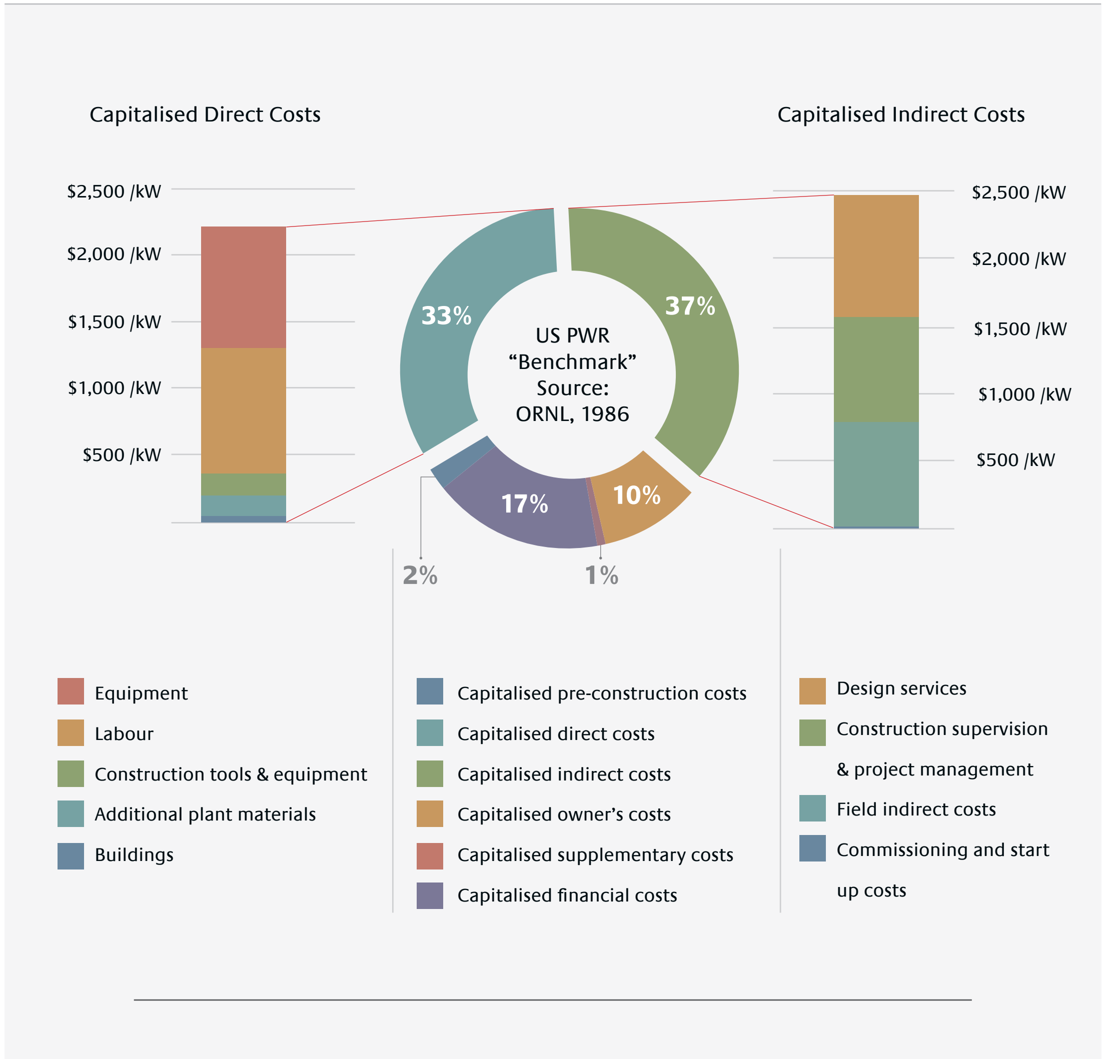
The purpose of the ETI's Nuclear Cost Drivers Project was to use a data led approach, informed by the cost base of water-cooled power reactors, to identify the cost drivers within historic, contemporary and advanced reactor designs. The three principal outcomes from this Project were expected to be improved understanding of:

- the cost drivers within contemporary UK nuclear new build projects and the identification of areas of potential technical or delivery innovation which can support cost reduction;
- the cost drivers within advanced reactor technologies and the identification of areas of potential design, technical or delivery innovation which can support cost reduction; and
- the relative differences in cost base between contemporary and advanced nuclear reactor technologies and the potential to achieve a step reduction in the cost of generating electricity.

The project, delivered by Lucid-Catalyst for the ETI, included the examination of a sample of 33 relatively recently completed (or nearly completed) projects and compared them in a standardised way alongside a historic US PWR benchmark described in the 1986 Oak Ridge National Laboratory cost study[14] which was also treated in the same standardised way. This benchmark is based on the detailed records and learning from building nuclear power plants in the United States captured in the Energy Economic Database Programme (EEDB) version 8. The NCD methodology is described in more detail later, but the difference with this project is the way in which it accessed the knowledge and experience of senor personnel involved in the delivery of the projects recorded in the ETI NCD project database. The intent was not to analyse published costs, but to understand the project experience and context alongside these published costs.

[13] US Nuclear Comeback Stalls as Two Reactors Are Abandoned. New York Times 31st July 2017 https://www.nytimes.com/2017/07/31/climate/nuclear-power-project-canceled-in-south-carolina.html
[14] Phase VIII Update Report for the Energy Economic Data Base Program. Oak Ridge National Laboratory (ORNL). 1986. http://www.osti.gov/scitech/servlets/purl/6927146/

Figure 6
Chart from NCD Project Summary Report Showing Cost Breakdown of US benchmark



The pie chart in figure 6 shows the breakdown of capital costs for the US benchmark when treated in the standardised way used in the Nuclear Cost Drivers project. This shows that direct costs and indirect costs account for approximately a third of the costs each and dominate overall cost. Financing costs are also significant, and are often cited as a large cost driver. While financing costs are indeed important, their project to project variability is a function of construction duration and perceived risk (reflected as the financing interest rate). Different financing models and interest rates were removed from consideration as a cost driver and instead a constant universal interest rate against project debt was applied for much of the analysis. The analysis therefore identified cost drivers which impacted duration and perceived risk.

If financing costs were removed from the cost breakdown pie chart in figure 6, direct and indirect costs make up an even larger share of the remaining total cost, and labour makes up approximately 40% and 80% of these categories, respectively. This dominance of labour within the benchmark provided an indication of how the quantity of labour (and hourly rates, productivity, etc.) might account for much of the cost variation across projects in the projects examined.

Reducing Costs Through Improving Productivity

The cost model and associated database developed for the ETI Nuclear Cost Drivers Project grouped projects together into "genres". It was necessary to adopt genres because it enabled anonymisation of some of the data used in the project analysis. The formation of the specific genres selected was informed by the data gathered and analysed during the project. Examination of the ETI database for large light-water contemporary reactors led to two "genres" for consideration alongside the US historic benchmark.

Figure 7
Cost Comparison of the "North America/Western Europe" genre with the "Rest of The World" genre from the ETI NCD Summary Report

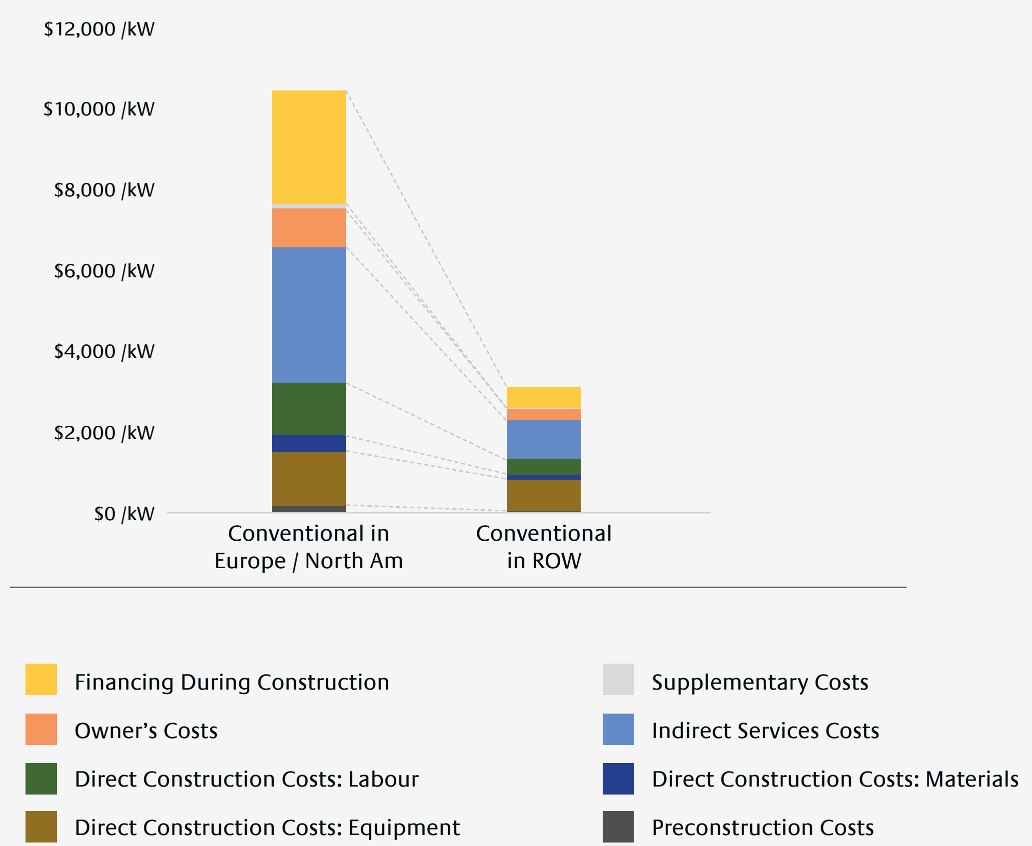


Figure 7 compares the genres of North America/Western Europe (NA/WE) and Rest of the World (ROW). Since the benchmark date in the US of 1986, the capital cost of nuclear projects in North America and Western Europe has risen whilst the comparable capital costs across the Rest of The World including China, Korea and Japan have reduced.

Detailed examination of figure 7 shows that finance costs are considerably lower for the RoW genre but, noting that both genres use the same interest rate in this analysis, the explanation is that the sum borrowed is lower and is borrowed for a shorter period before the plant commences commercial operations. Surprisingly, there is relatively little difference between the genres in the cost of materials and components delivered to site. The remainder of the difference between the 2 genres is largely explained within the costs associated with direct labour and indirect services. Whilst the impact of the variability in local labour rates cannot be ignored, the expert views established during interviews conducted as part of the NCD project confirmed that the proven route to achieving lower costs is in improving productivity of both direct labour and indirect services.

Table 1
The 8 Cost Driver Categories and Associated Principal Actors

Cost Driver	Principal Actor	Description
Vendor Plant Design	Reactor Vendor	Includes all pre-construction efforts related to plant design, including design decisions, design completion, and ability to leverage past project designs. This covers specific plant details such as plant capacity, thermal efficiency, and seismic design, but also includes broader topics related to constructability and project planning processes.
Equipment and Materials	EPC	Encompasses quantities of equipment, concrete, and steel (both nuclear and non-nuclear grade) used in the plant but also covers strategies used to address materials cost.
Construction Execution	EPC	Covers all the decisions and practices carried out and support tools used by the EPC during project delivery. This starts with site planning and preparation and design rework costs and spans all onsite decisions (e.g. project execution strategies, schedule maintenance, interactivity with subcontractors and suppliers, etc.) until the Commercial Operation Date. This includes independent inspection processes, QA, QC, and other major cost and risk centres during project construction. This driver is a measure of efficiency and productivity across the entire delivery consortium. For multi-unit construction on the same site, this should get better with each subsequent unit.
Labour	Labour	Involves all direct and indirect construction labour performed on the project site. This also includes any labour related to offsite manufacturing or assembly. It covers productivity, wages, training and prep costs, percentage of skilled workers with direct applicable experience, etc. This driver measures efficiency and productivity at the individual level.
Project Governance and Project Development	Owner	This driver includes all factors related to developing, contracting, financing, and operating the project by the project owner. This covers topics from the interdisciplinary expertise of the owner's team to number of units ordered (at the same site), discretionary design changes, WACC, and contracting structures with the EPC and suppliers.
Political & Regulatory Context	Government and Regulator	Includes the country-specific factors related to regulatory interactions and political support (both legislatively and financially). This driver includes regulatory experience, pace of interactions, and details on the site licensing process. It also includes topics related to the government's role in financing and how well it plays certain roles otherwise reserved for the project customer.
Supply Chain	Supplier Vendors	Involves factors that characterise supply chain, experience, readiness, and cost of nuclear qualification as well as nuclear-grade and non-nuclear-grade equipment and materials.
Operations	Operator	Covers all costs related to nuclear power plant operations (e.g... fuel price, staff head count, wages, capacity factor, unplanned outages, etc.)

Each of the projects in the ETI NCD costs database were appraised using a score-card to facilitate structured interviews with senior personnel involved in the delivery of these projects. The scorecard was designed in consultation with experts who reached a consensus on eight cost driver categories which are summarised in Table 1. The US historic PWR was defined as the benchmark and each of the cost driver categories was populated with indicators from the benchmark data and associated information. A score of zero attributed to each cost driver category for the benchmark. The score card was then built out for each cost driver supported by associated indicators, with negative scores reflecting attributes which decrease costs and positive scores with increasing costs. This is illustrated in Table 2 and the methodology is described in more detail in the ETI Nuclear Cost Drivers Summary Report[15].

From the eight cost drivers described in Table 1 and compared against the benchmark of the US historic PWR defined with an average cost driver score of zero:

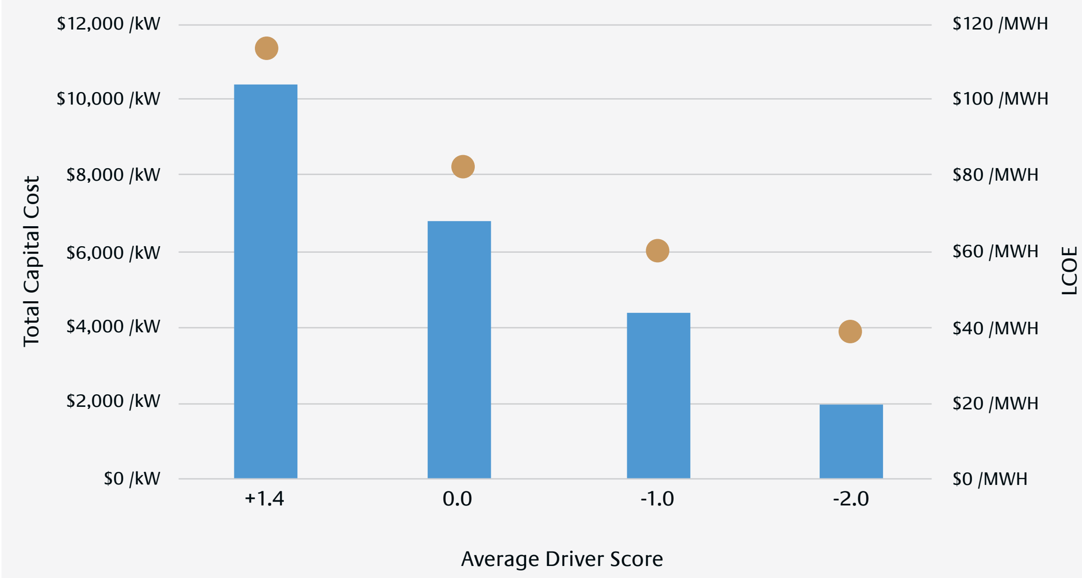
- The average cost driver score for the NA/WE genre was +1.4
- The average cost driver score for the RoW genre was -1.4

This analysis reflects the relative loss in nuclear construction experience and capability in North America and Western Europe since the 1980s compared with the growth in capability and experience elsewhere including China, Japan and Korea.

Table 2
Possible Cost Driver Category Scores

Category	Score
Significantly Reduces Cost	**-2**
Somewhat Reduces Cost	**-1**
Neither Increases nor De-creases Cost	**0**
Somewhat Increases Costs	**1**
Significantly Increases Cost	**2**

Figure 8
Cost Reduction Scenarios for the NA/WE Genre



Alternative Cost Scenarios With Other Interest Rate Assumptions

			7%		6%		9%	
Avg. Score	**Capex/ kW**	**Opex**	**Capex/ MWh**	**LCOE**	**Capex/ MWh**	**LCOE**	**Capex/ MWh**	**LCOE**
+1.4	$10,454/ kW	$25/ MWh	$89/ MWh	$114/ MWh	$75/ MWh	$99/ MWh	$123/ MWh	$148/ MWh
0.0	$6,826/ kW	$24/ MWh	$58/ MWh	$83/ MWh	$48/ MWh	$72/ MWh	$84/ MWh	$108/ MWh
-1.0	$4,386/ kW	$23/ MWh	$38/ MWh	$61/ MWh	$29/ MWh	$53/ MWh	$57/ MWh	$81/ MWh
-2.0	$1,946/ kW	$22/ MWh	$17/ MWh	$39/ MWh	$11/ MWh	$34/ MWh	$31/ MWh	$53/ MWh

[15] The ETI Nuclear Cost Drivers Project: Summary Report dated 20th April 2018
By CleanTech Catalyst Ltd and Lucid Strategy, Inc and now known as LucidCatalyst
https://d2umxnkyjne36n.cloudfront.net/documents/D7.3-ETI-Nuclear-Cost-Drivers-Summary-Report_April-20.pdf?mtime=20180426151016

Figure 8 from the NCD Project Summary Report illustrates, consistent with NCD project assumptions, the impact of reducing average cost driver score, together with a simple sensitivity study varying the interest rate and associated finance costs. It is not suggested here that UK giga-watt scale reactor projects could be expected to be delivered with an average cost driver score as low as minus 2.0, because low cost projects such as in China and the UAE can benefit from lower labour rates plus shift working patterns that are not permitted in the UK. However, a long term UK target for average cost driver score of -1.0 or possibly lower is not unrealistic, particularly when it is considered that Nuclear Electric's plans (supported by contractually bound quotations) would have yielded average cost driver score of -1.1 and -1.5 for units 2 and 3 to follow Sizewell B (average cost driver score of +0.8 for FOAK) on the same site.

The questions for policymakers and project developers relevant in the UK new nuclear market are:

> What is the ultimate average cost driver score and cost ambition for large light-water reactors to be deployed in the UK?

> Is there an appetite to apply the learning from successful nuclear deployment programmes elsewhere as well as from current infrastructure projects in deployment in the UK?

> What are the potential options to drive the nuclear cost reduction curve in the UK?

Uncertainties in Costs Associated with SMRs and Advanced Reactors

The ETI NCD project scope also included SMRs and AMRs and the project methodology and data collection supported 4 additional genres:

- Light-water SMRs
- High temperature gas reactors
- Liquid metal cooled fast reactors, and
- Molten salt reactors

Figures 9 and 10 plot all the genres on the same chart from the project methodology and assumptions with figure 9 showing Total Capital Cost and figure 10 the Levelised Cost of Electricity (LCOE).

The important notes to be read in conjunction with figures 9 and 10 are

> The genres for large reactors are based on data from plants that are either operating or in advanced stages of construction or commissioning.
> The genres for SMRs and AMRs are based on vendor estimates rather than data from projects which are completed and operating or in an advanced stage of construction.
> There is significant uncertainty in the estimates for SMRs and AMRs; none of the proposed designs included in these genres are approved by regulators and neither are they ready for construction.
> The only option for new nuclear power capacity in the UK between 2018 and around 2035 is through large lightwater reactors. Three designs have so far secured UK regulatory approval through the Generic Design Assessment process, and a fourth is being assessed. The earliest of the SMRs and AMRs, if developed successfully, is unlikely to be deployed in numbers before 2035.

The summary report from the ETI NCD project providing a greater level of detail is available from the ETI's website[16] and includes conclusions, recommendations and strategies for cost reduction relevant to each of the eight nuclear cost drivers. The ETI procured an independent review as part of the project; the independent reviewer's final statement is also available from the ETI website[17].

[16] ETI Nuclear Cost Drivers Project Summary Report April 2018
https://d2umxnkyjne36n.cloudfront.net/documents/D7.3-ETI-Nuclear-Cost-Drivers-Summary-Report_April-20.pdf?mtime=20180426151016
[17] NCD Project Independent Reviewer's final review letter D7.4 dated 22nd April 2018
https://www.eti.co.uk/library/independent-review-letter-final-review-of-nuclear-cost-drivers-model

Figure 9
Comparison of Capitalised Costs Across All Genres from the NCD Summary Report

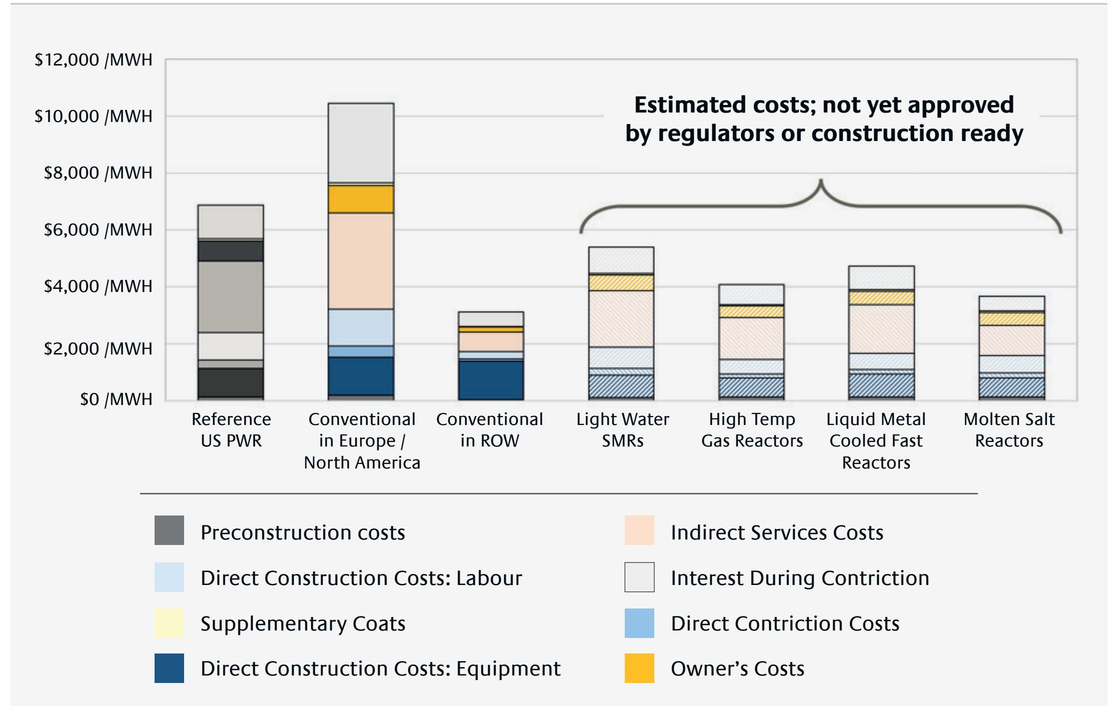
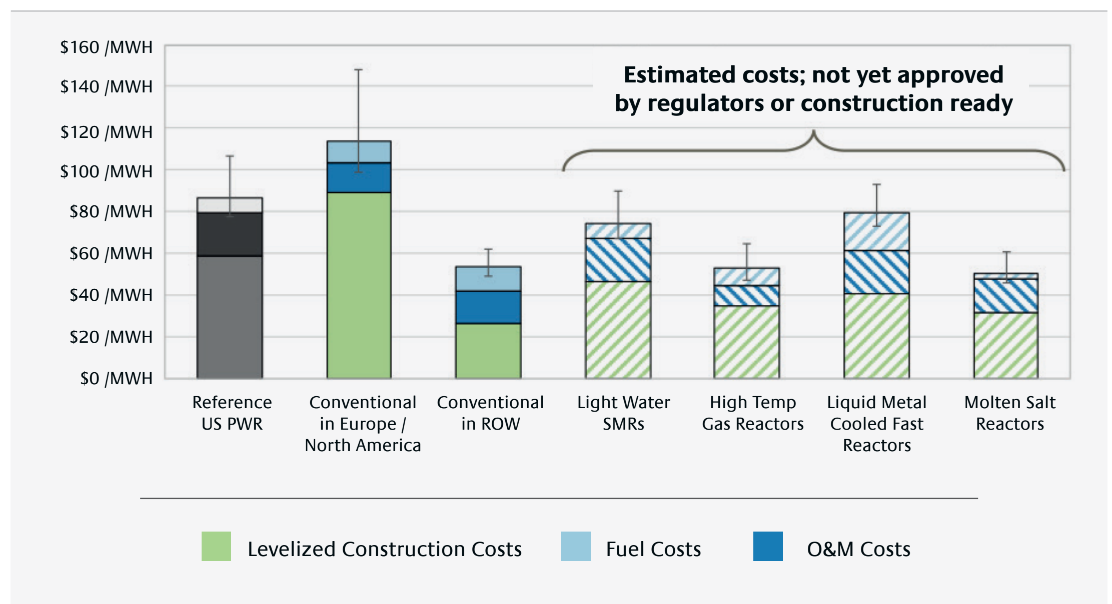


Figure 10
Comparison of LCOE Across All Genres from the NCD Summary Report



VALUE OF NUCLEAR ENERGY IN AN INTEGRATED UK ENERGY SYSTEM

Whole System Analysis

A suite of models known as Energy Systems Modelling Environment (ESME) developed by the ETI is now operated by the Energy Systems Catapult. Large sets of low carbon technologies are characterised together with associated system deployment costs. These models are used to examine wide ranges of scenarios to better understand potential pathways for the transition to a low carbon economy. The models incorporate an optimisation capability to determine solutions which deliver both Green House Gas abatement targets and cost optimisation. Two such scenarios, Clockwork and Patchwork, examined in ESME are reported in Options, Choices, Actions.

LCOE is a commonly used metric to compare different technologies in the cost of electricity generation. Whilst useful in some circumstances, LCOE analysis can be misleading and hide the true system costs incurred by different technologies under different conditions. In practice, the average cost achieved may be very different to the theoretical LCOE. This is described in more detail in a further ETI Insight Report[18]. This is one of the reasons that whole systems analysis is important. It also folds in the additional challenges and uncertainties including decarbonising heat and transport; it enables an energy system overview rather than just an electricity perspective.

Representation of Nuclear Technologies In ESME

Nuclear technologies are currently included in ESME through four different data sets representing:

- Legacy; the existing UK Advanced Gas Cooled reactors plus the Sizewell B PWR all operated by EDF Generation
- New build Generation III+ light-water reactors such as EDF's Hinkley Point project and Horizon's ABWRs (now "paused")
- SMRs using contemporary light-water technology
- Advanced or Generation IV nuclear reactors.

Results from the ETI's Nuclear Cost Drivers project are yet to be incorporated into the datasets for ESME and these are not included in the most recent release of ESME version 4.5 reported by the Energy Systems Catapult[19].

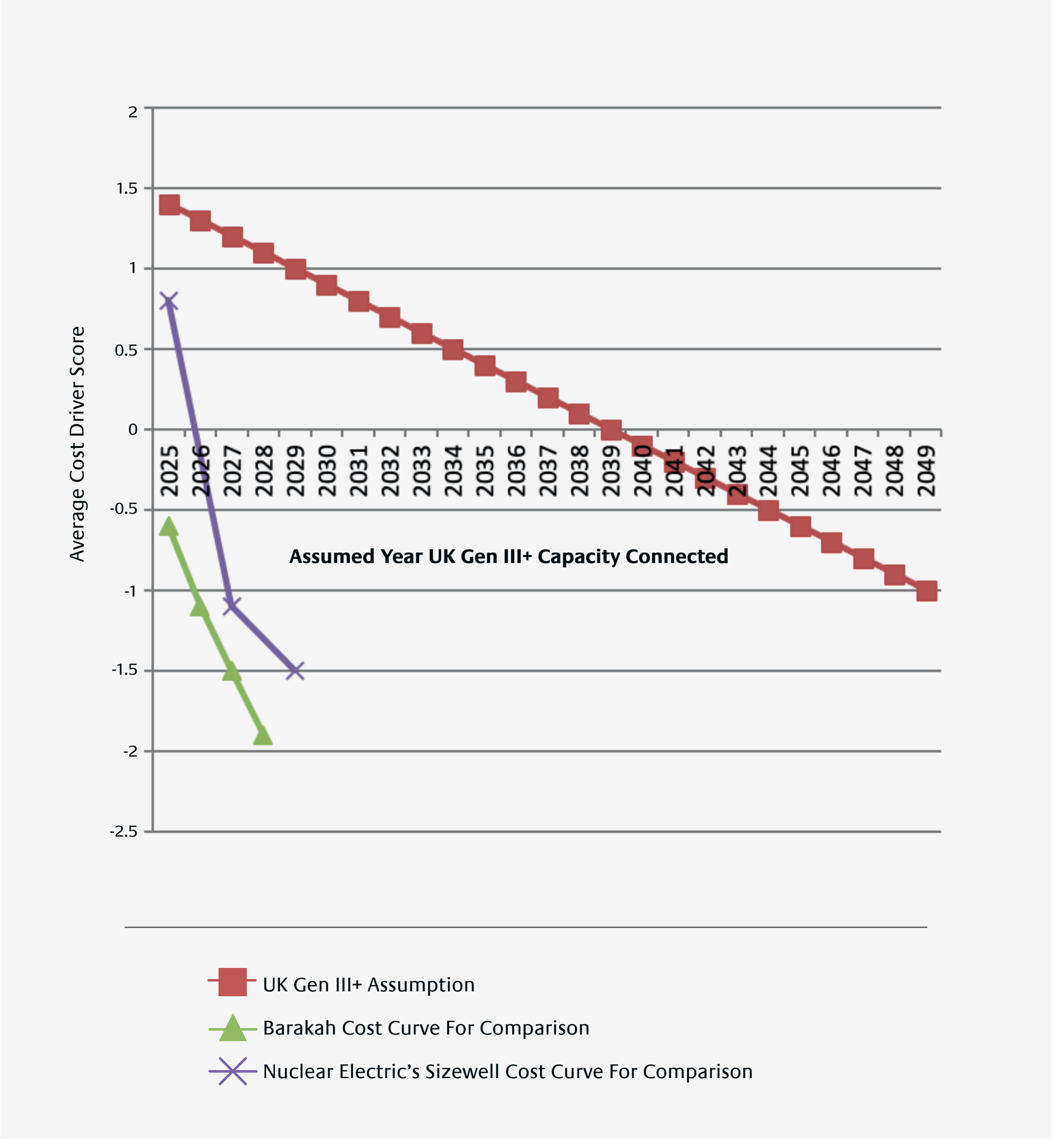
Updated Cost and Deployment Data Derived from The Nuclear Cost Drivers Project

A hypothetical cost driver reduction curve was generated for a UK hypothetical Gen III+ reactor deployment programme based on the learning applied from the NCD projects and applying the following assumptions:

- Initial construction costs reflect the NA/WE genre with an initial average cost driver score of +1.4
- Construction takes place at two sites in parallel with an average new capacity connection rate of 1.4 GWe per year from 2025
- Ultimate project performance improvement results in an average cost driver score of -1.0, but this is not achieved until up to 35 GWe of new capacity is installed just before 2050.

These assumptions are reflected in the chart shown in figure 11 illustrating a hypothetical reduction in average cost driver score over time. The rate of cost reduction and the ultimate level of project cost performance is driven by the extent of application of the measures described in the ETI NCD project summary report, and the extent to which a programmatic approach is applied to project performance improvement and cost reduction. To illustrate the potential pessimism in the shape of this cost driver reduction curve, average cost driver scores from the NCD case studies of the UAE Barakah and Nuclear Electric's Sizewell projects have been superimposed on this chart. The deployment dates for the Barakah and Nuclear Electric's Sizewell projects have been shifted to the right on this chart for the purpose of comparing the shape of their cost reduction curves.

Figure 11
Pessimism in Assumed UK Gen III+ Cost Reduction Curve



[18] Comparing Generating Technologies. ETI Report dated 3rd July 2018
https://d2umxnkyjne36n.cloudfront.net/insightReports/3770-Comparing-Generating-Technologies-FINAL-AUGUST-2018.pdf?mtime=20180813162748
[19] ESME Whole Systems Energy Systems Modelling Tool. ESC Web page dated 18 February 2019
https://es.catapult.org.uk/news/esme-whole-systems-modelling-tool-receives-update/

Figure 12
UK Gen III+ Cost Curve Used for ESME Sensitivity Analysis

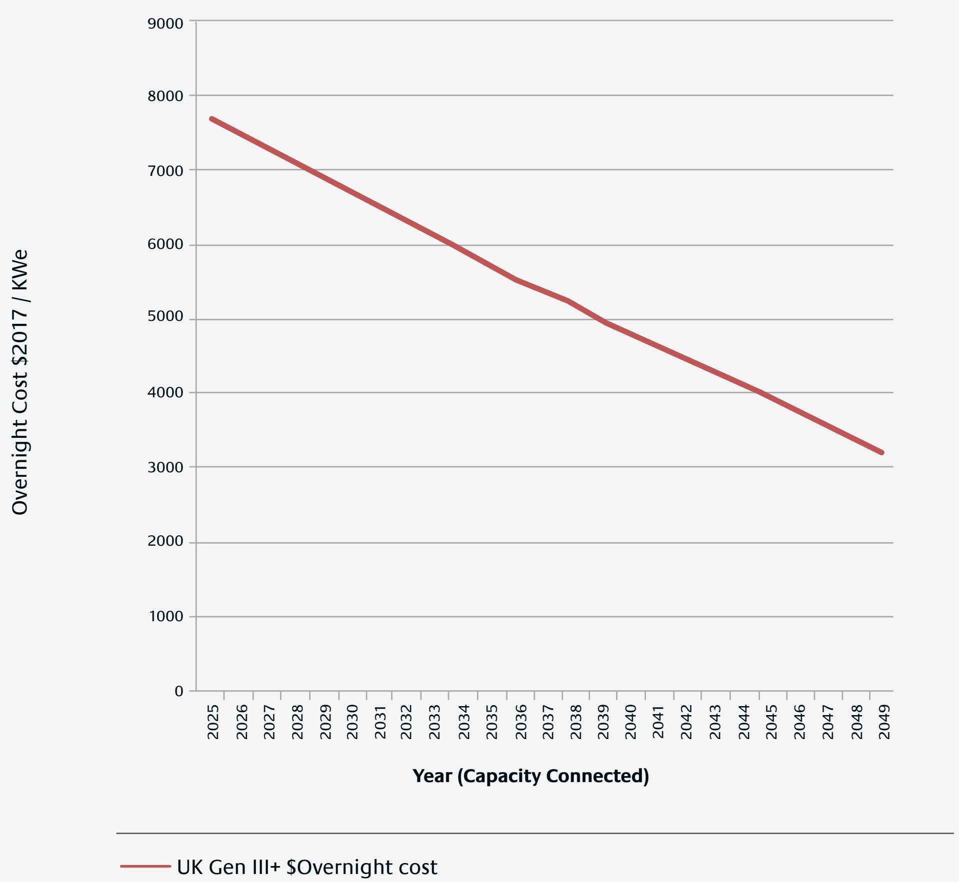
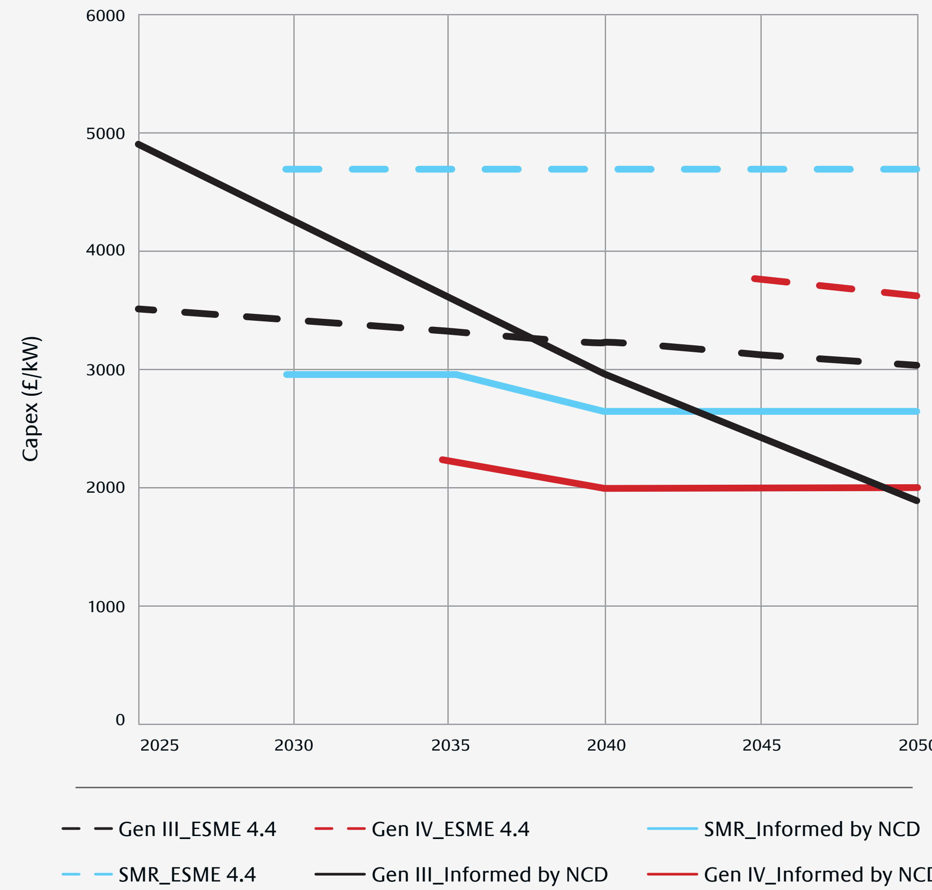


Figure 13
Changes to Nuclear Technology Data Sets for Sensitivity Testing In ESME 4.4



Sensitivity Analysis - Application of ETI NCD Project Data for Testing in ESME 4.4

The cost reduction curve in figure 11 is based on average cost driver score, and this is transposed using the ETI NCD cost model into overnight cost in 2017 dollars in figure 12. For application in an ESME dataset these are further converted to pounds sterling and the ESME base date of 2010. The NCD project also provides Next of a Kind (NOAK) genre data for light-water SMRs. The genre for High Temperature Gas Reactors (HTGRs) is selected to present Gen IV reactors. These data sets are converted in the same way for sensitivity testing in ESME version 4.4.

Figure 13 illustrates changes in first operation dates and overnight cost (2010 pounds sterling) compared with existing ESME 4.4 data, and applied in ESME 4.4 for the purpose of limited sensitivity testing. The three principal changes are summarised as:

- For Gen III+, an initial escalation in deployment costs attributable to UK FOAK, but with potential for costs to fall lower than previously estimated
- For SMRs the deployment date is unchanged but NOAK deployment costs are reduced
- Gen IV or advanced modular reactors are characterised by the genre for HTGRs. NOAK costs are estimated to be lower and first potential commercial deployment advance from 2045 to 2035.

In the lowest cost energy system designs calculated by ESME during this sensitivity testing, deployment levels for nuclear were generally at annual roll-out capacity limits for each of the technologies. This confirms that, from a system perspective, each of the nuclear technologies has the potential to reduce the costs of the UK energy system transition. SMRs were generally deployed in cogeneration applications providing

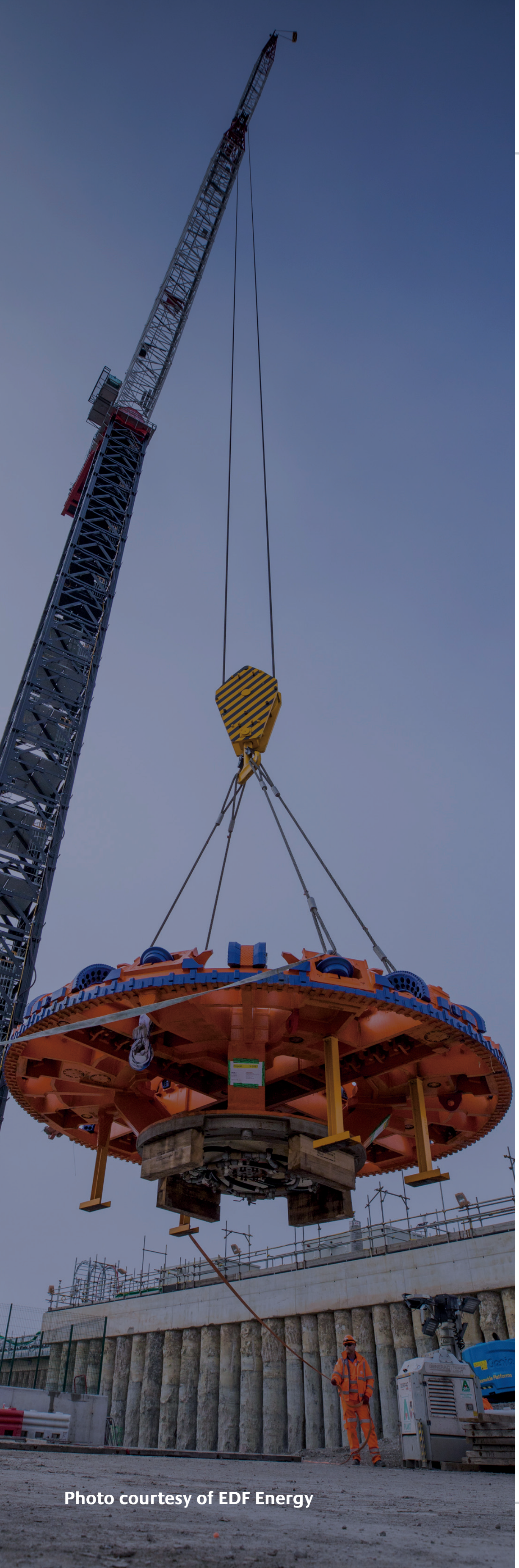


Photo courtesy of EDF Energy

electricity to the grid and heat to energise city scale district heating systems. It was also noted in this sensitivity study that the load factor of nuclear plants from 2040 was lower than their design capacity factor confirming the potential need for new nuclear plants deployed beyond a particular capacity threshold to be technically capable and commercially viable when operating at a load factor below their design capacity factor. It is inappropriate to include here the detailed outputs from the ESME sensitivity testing using the application of the NCD data as described above as more work is required, noting that:

- A fuller range of scenarios, including Monte Carlo analysis to address uncertainties, needs to be completed to support the usual ESME technology appraisal.
- The Gen III cost curve above incorporates UK First of a Kind costs. This disadvantages Gen III+ within the analysis because ESME is an Nth of a Kind (NOAK) model and all other technologies are represented only by NOAK costs in deployment.
- The rate of Gen III+ cost reduction achievable is unduly pessimistic as described earlier. A better understanding is required of the UK programmatic deployment of large-scale Gen III+ as proposed in the ETI NCD summary report.
- Unlike SMRs which can be configured for the co-generation of heat and power, the treatment of the Gen IV technology set in ESME 4.4 is solely as an electricity generation technology. ESME functionality needs to be updated to reflect the capability of some Gen IV designs in development to deliver greater energy system functionality, such as cogeneration of flexible power, high temperature heat supply and hydrogen production.

Nevertheless, the application of NCD data in a simple sensitivity test using ESME 4.4 supports the earlier conclusions in Options Choices Actions 2018 that nuclear remains a priority for commercial development.

Creating Economic Value from Nuclear Energy

Creating economic value may be considered as a combination of:

- Technology designs which are attractive in the market and attract investment to support development.
- Projects which are attractive in the market, can deliver consumer value, and attract developer investment.
- Economic growth through new or better jobs, higher levels of employment, and associated tax-take.
- Sustainable growth via accessing additional markets beyond the UK.

For large contemporary Gen III+ reactors for potential deployment in the UK, designs are largely fixed and optimised for baseload electricity generation. These have the ability to follow a daily power profile when necessary in order to operate within an electricity system with variable demand and intermittent connected renewables. These reactors need to be delivered through projects which are sufficiently attractive to secure both developers and investors. These projects can potentially deliver economic growth associated with the jobs created in construction and the long-term operation and maintenance of the plants. These are also the only nuclear projects which can deliver substantial new nuclear generating capacity within the UK energy system between 2025 and 2035. Their successful realisation depends on success in tackling the cost drivers identified in the ETI NCD summary report. Key to success here is the application of a programmatic approach to performance improvement and cost reduction. This includes constructability reviews prior to the freezing of the design for each project prior to construction. It also includes re-using the construction knowledge gained in prior projects through the replication of as much of the design as is practical. This avoidance of repeated FOAK construction has the potential to deliver shorter projects with reduced risks and lower costs as demonstrated elsewhere.

Changing Delivery Methods to Reduce Schedule, Risk and Costs

The realisation of a strong and positive learner effect is the goal for large contemporary Gen III+ reactor projects. This translates through the ETI NCD model to substantial gains in productivity for both direct labour and indirect services.

For SMRs and AMRs there is an alternative route to realising these productivity gains. They should be developed as customer led products. They should also follow practises used in other industries of using modern factory based manufacturing methods and design optimisation focussed on product costs.

Such products are unlikely to be deployed in significant numbers before 2035[20], but have the potential for contributing to economic growth - particularly if such products can access markets beyond the UK.

Extending the Service Provision Beyond Baseload Electricity

The majority of existing civil nuclear energy applications have been conceived for base load power generation with occasional co-generation applications and the associated delivery of heat for co-located use, or with heat transmission systems for heat supply to manufacturing or district heating energisation.

The challenge of energy system decarbonisation and the associated decline in fossil fuel consumption creates a need for a broad range of alternative low carbon solutions. Nuclear may have a future role in delivering some of the following services beyond baseload electricity generation:

- Flexible electricity generation to complement intermittent renewables and energy storage
- The supply of heat at low, medium and high grade

[20]SMR TEA Project 3 – Assessment of SMR Emerging Technologies Summary Report. National Nuclear Laboratory 15th March 2016
https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/665274/TEA_Project_3_-_Assessment_of_Emerging_SMR_Technologies.pdf
[21]JAEA HTTR Continuous Hydrogen Production for 150 hours. World Nuclear News 28th January 2019
https://wna.informz.ca/informzdataservice/onlineversion/indbWFpbGluZ2luc3RhbmNlaWQ9MTA1MjI2OSZzdWJzY3JpYmVyaWQ9OTEyODQxNjc2

- Hydrogen production through high temperature electrolysis or the sulphur iodine process[21]
- Energy in remote off-grid applications
- Energy production with the ability to cost effectively access air cooling as a heat sink, removing the dependency on access to the sea, rivers, or lakes for cooling
- Isotope production for medical or industrial uses
- Destruction of nuclear waste and other nuclear materials

Whilst electricity generation may not be the only future use of nuclear energy, the expected cost of electricity production might be used as a proxy for testing the cost efficiency of the design. Nevertheless, electricity supply can be expected to continue to be the most important market for future nuclear plants.

Changing the Nuclear Heat Supply System

The Generation IV international Forum (GIF) recognises 6 groupings of advanced nuclear reactors or nuclear heat supply systems. To these may be added current evolutions to light water reactor technologies to realise SMRs in integral or dispersed designs. There are also numerous developers of fusion reactor designs. These new innovative nuclear heat supply systems should not be considered as products in their own right, but as important enablers in developing innovative products which deliver:

- The services required by the market and which are attractive for investors to supply to consumers.
- Lower costs in product delivery and operation compared with contemporary reactors.

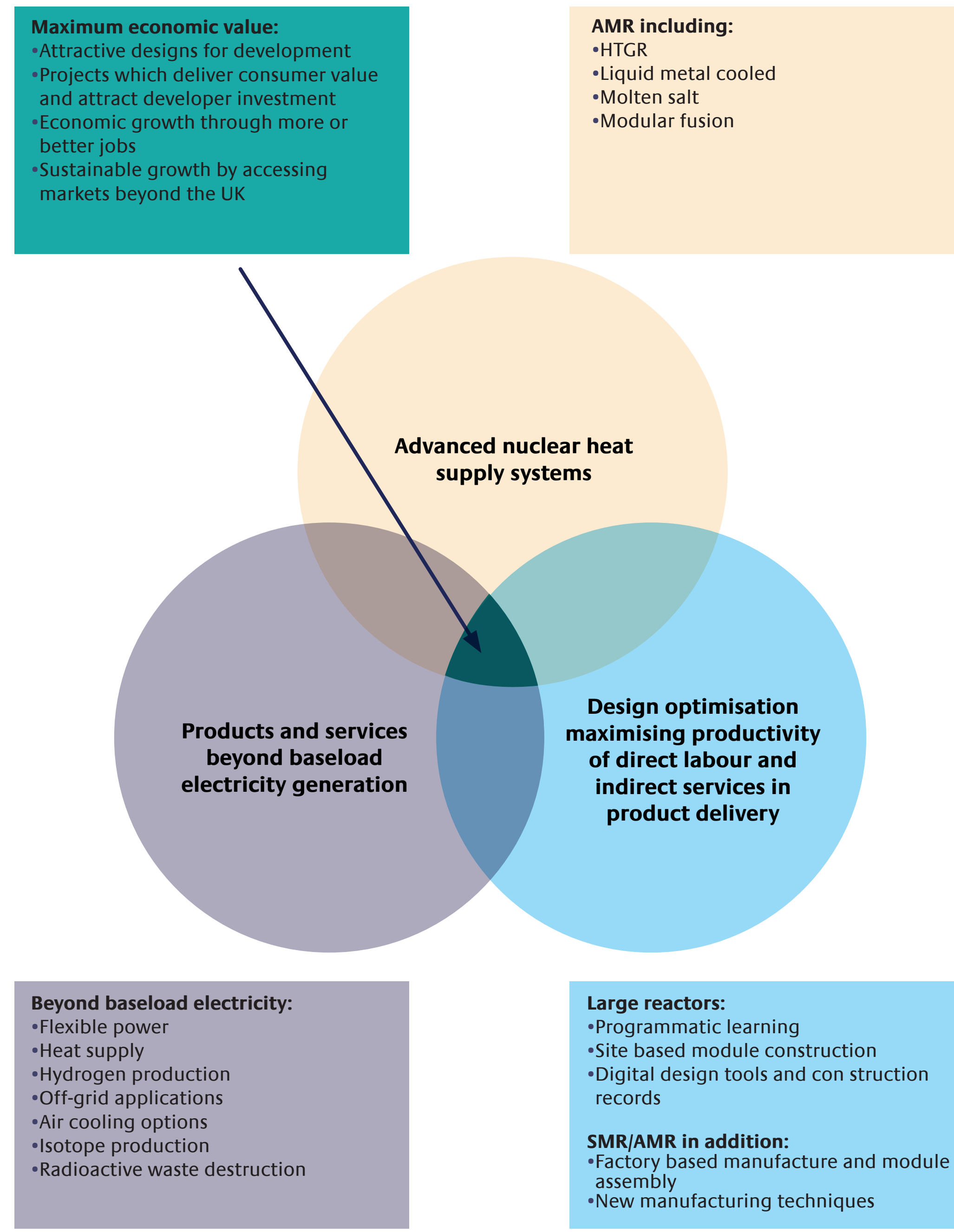
Figures 6 and 7 identified that for contemporary reactors, the cost of components and materials comprising the nuclear heat supply system is a relatively small element of the total capital cost. Deploying advanced nuclear heat supply systems through large infrastructure construction projects are likely to replicate all the schedule risk and cost challenges faced by the recent large light-water reactor projects in Europe and North America. To realise a transformational reduction in costs will require a relentless focus on product design optimisation which:

- Harvests the benefits of alternative and simpler nuclear heat supply systems with coolants that don't boil away and cores that don't melt (noting that molten salt reactors are designed to operate with molten fuel, but with core structures that are intended to remain solid).
- Minimises the scope of the plant subject to bespoke nuclear grade quality requirements, and maximises the scope of the plant which can be delivered through multiple suppliers against standardised equipment specifications.
- Reduces the man hours required in manufacture, deployment, operation and maintenance.

This combination of product development to meet market needs, realise the opportunities presented by advanced nuclear heat supply systems and modern manufacturing methods, and maximise economic value is illustrated in figure 14.

[21]JAEA HTTR Continuous Hydrogen Production for 150 hours. World Nuclear News 28th January 2019 https://wna.informz.ca/informzdataservice/onlineversion/indbWFpbGluZ2luc3RhbmNlaWQ9MTA1MjI2OSZzdWJzY3JpYmVyaWQ9OTEyODQxNjc2

Figure 14
Design Optimisation for Nuclear Products



NEXT STEPS

The following actions should be pursued:

- Development of a better understanding of a potential programmatic approach to a succession of UK large light-water reactors together with the impact of different policy options in driving the rate of potential cost reduction. It is only these designs which can offer significant new nuclear electricity generating capacity between 2025 and 2035. A range of evidence based potential cost reduction curves should be developed to replace the pessimistic assumption shown in figure 11. Given that the ETI NCD database only includes a single reactor constructed in the UK, this requires a specific focus on UK costs and context to better understand the impact of different UK policy options.
- Innovative designs for SMRs and AMRs should be encouraged; it is expected that these will eventually be self-selecting because only the products with a total focus on design optimisation are likely to be ultimately successful. If such designs successfully emerge, then they will offer the multiple benefits of cost-effective UK energy system decarbonisation and economic growth through deployment in energy markets beyond the UK. The earliest of these are unlikely to be operating in significant numbers before 2035. Other than some light-water SMRs, technology demonstrators are likely to be required for advanced nuclear heat supply systems as part of the design optimisation process and to accumulate operation and maintenance experience to support the safety case for a commercial FOAK.
- ESME development to better appraise the value Advanced Modular Reactors; in particular, implementation of the model functionality to recognise the potential for flexible power, heat and hydrogen production from these technologies. Advocates of different advanced reactor systems claim different benefits from these technologies, and it may be necessary to introduce a range of different Gen IV technology lines into ESME including possibly the representation of a generic modular fusion reactor.
- ESME functionality and scenarios to explore and demonstrate:
    - extending system decarbonisation from 80% to 100% (or carbon neutral)
    - achievement of the triple optimisation of cost, decarbonisation, and cities which meet legally binding air quality standards
    - the system impacts if nuclear is excluded from contributing to future energy system decarbonisation scenarios

CONCLUSIONS

- The NCD project established the following 8 nuclear cost drivers and associated owners:

Table 2
ETI Nuclear Cost Driver Categories and Associated Owners

Cost Driver	Owner
Supply Chain	Vendors
Labour	EPC
Project Governance and Project Development	Government
Construction Execution	EPC
Political and Regulatory Context	Government
Equipment and Materials	EPC/Vendor
Vendor Plant Design	Vendor
Operations	Operator

- The NCD project report concluded that there was strong evidence of applicable cost reduction in the UK, but collective action is required against all cost drivers by all project stakeholders, including government, to bring about the integrated programme of activities necessary to realise this potential. The benefits of such collective action are largely realised through productivity improvements in direct labour and indirect services during construction, giving shorter, more predictable schedules and repeatable engineering.
- Contemporary giga-watt scale reactors are the only designs ready to be deployed in the UK in numbers between 2025 and 2035. The conservative and pessimistic application of learner effects from a potential UK programmatic approach, using data derived from the ETI NCD project and applied in limited ESME scenario sensitivity testing, indicates that deployment of such reactors continues to be part of a UK lowest cost low carbon energy solution.
- Further evaluation of a potential UK programmatic approach is needed to better understand the range of potential UK policy options and the associated impact on the shape of the technology cost reduction curve.
- Through SMRs and AMRs, nuclear energy has the potential to offer a greater range of products and services beyond the well-established supply of baseload electricity by contemporary giga-watt scale reactors.
- A range of innovations are applicable to nuclear in manufacture, assembly and construction which can reduce cost and risk, and create projects which are viable, attractive and investible. These innovations can be applicable to SMR, AMR and fusion designs currently in development.
- Innovations in the nuclear heat supply system (Gen IV advanced reactors and fusion) are yet to be proven technically and commercially, but some FOAK commercial plants could be operating in numbers from 2035. Such commercial plants could offer further transformational reductions in cost and consequential growth in economic opportunity through deployment in the UK and elsewhere. Successful deployment of these innovations as low carbon energy products is expected to depend on the exploitation of the advantages of simpler nuclear heat supply systems combined with delivery through factory based modular manufacture and assembly to reduce costs.
- Future nuclear plants designs developed without a singular focus on cost, and the associated necessities of minimising labour content and application of nuclear grade quality requirements, are unlikely to be commercially successful.
- Updated and continued energy system scenario modelling is necessary to avoid a singular focus on LCOE which can be misleading. Such whole system modelling analysis should encompass the uncertainties in decarbonising heat and transport and be extended to consider carbon neutral scenarios which enable UK cities to achieve minimum

legal requirements for air quality. Nuclear can support these goals and, with the right policy framework, can be a cost competitive technology within a UK low carbon energy mix.

- Nuclear remains a valuable technology in the mix in an affordable UK transition to a low carbon economy as identified in the Clockwise scenario of Options, Choices, Actions [updated 2018].

Through SMRs and AMRs, nuclear energy has the potential to offer a greater range of products and services beyond the well-established supply of baseload electricity.

Photo courtesy of EDF Energy

Glossary

ABWR Advanced Boiling Water Reactor

AMR Advanced Modular Reactor

CCS Carbon Capture and Storage

EEDB Energy Economic Database Programme

ESC Energy Systems Catapult

ESME Energy Systems Modelling Environment

EPC Engineer, Procure and Construct

ETI Energy Technologies Institute

FOAK First of a Kind

GWe Giga Watt electricity

HTGR High Temperature Gas Reactor

LCOE Levelised Cost O f Electricity

NA/WE North America/Western Europe

NCD Nuclear Cost Drivers

NOAK Nth of a Kind

NPV Net Present Value

ORNL Oak Ridge National Laboratory

PWR Pressurised Water Reactor

ROW Rest of the World

SMR Small Modular Reactor

QC Quality Control

QA Quality Assurance

WACC Weighted Average Cost of Capital

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Mike Middleton joined the ETI in April 2013. His diverse experience in nuclear operations, projects and services includes waterfront submarine support; liquid and solid waste processing; construction projects; nuclear facility decommissioning; and new nuclear power. Mike is now Practice Manager for Nuclear at the Energy Systems Catapult.

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