energy technologies institute

The ETI Nuclear Cost Drivers Project

Full Technical Report

LUCID CATALYST

CATAPULT Energy Systems

Acknowledgements

The ETI Nuclear Cost Drivers Project:

Full Technical Report

September 2020

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The Project Team wishes to express deep appreciation to the many people who helped this study reach successful completion. First and foremost, we thank the Project Manager at the Energy Technologies Institute (ETI), Mike Middleton, currently Practice Manager Nuclear, UK Energy Systems Catapult for his exceptional guidance and steady support throughout. We also thank three officials at the UK Department for Business, Energy & Industrial Strategy (BEIS) who provided insights during our discussions: Craig Lucas (Director of Science and Innovation), Craig Lester (Deputy Director of Nuclear Strategy), and Prof John Loughhead (Chief Scientific Adviser). We are very grateful to the 50+ interviewees around the world who shared their experience and expertise in nuclear power plant design, construction, ownership, and operation. Finally, many thanks to our independent expert reviewer, Dr Tim Stone; to expert advisors – Dr Ken Petrunik, Charles Peterson, Esq., Prof Jacopo Buongiorno, and Dr Ben Britton; and to Bill Carruthers and Richard Waite – who were pivotal members of this collaboration.

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List of Abbreviations & Acronyms

ALARP	As Low as Reasonably Practicable
AMR	Advanced Modular Reactor
BEIS	UK Department for Business, Energy, and Industrial Strategy
CAPEX	Capitalised Expenditures
C&C	Coordination and Control
CAD	Computer Aided Design
CTC	CleanTech Catalyst Ltd
CfD	Contract for Differences
COD	Commissioning Operation Date
DECC	Department of Energy and Climate Change (UK)
ENEC	Emirates Nuclear Energy Corporation
EPC	Engineering, Procurement, and Construction
ETI	Energy Technologies Institute LLP
EXIM	Export-Import Bank
FIT	Feed-in-Tariff
FME	Foreign Material Exclusion
FOAK	First-of-a-kind
Gen-IV	Generation-IV International Forum
GPC	Georgia Power Company
HTGR	High Temperature Gas Reactor
HTTR	High Temperature Engineering Test Reactor
IAEA	International Atomic Energy Agency
IDC	Interest During Construction
JAEA	Japan Atomic Energy Agency
LCOE	Levelised Cost of Electricity
LMFR	Liquid-Metal Cooled Fast Reactors
KAIST	Korean Advanced Institute of Science & Technology
KEPCO	Korea Electric Power Corporation
KEXIM	Export-Import Bank of Korea
KHNP	Korea Hydro & Nuclear Power
MSR	Molten Salt Reactor
MWh	Megawatt Hour
NE	Nuclear Electric (purchased by EDF Energy in 2010)
NOAK	Nth-of-a-kind
NRA	Nuclear Regulation Authority (Japan)
NRC	Nuclear Regulatory Commission (US)
OPEX	Operating Expenditures
PPA	Power Purchase Agreement
PPG	PWR Project Group (Sizewell B)
PSC	Georgia Public Service Commission (US)
PWR	Pressurized Water Reactor
QA	Quality Assurance

QC	Quality Control
RAE	The Royal Academy of Engineering (UK)
RMB	Chinese Renminbi
ROW	Rest of World
SMART	Specific, Measurable, Attainable, Realistic, and Timely
SMR	Small Modular Reactor
SNUPPS	Standard Nuclear Unit Power Plant System
SSR	Stable Salt Reactor
TMI	Three Mile Island
TPI	Third Party Inspector
UAE	United Arab Emirates
USD	United States Dollar
WACC	Weighted Average Cost of Capital
WANO	World Association of Nuclear Operators

Preface

The summary report to the Energy Technologies Institute (ETI) Nuclear Cost Drivers (NCD) project was released in April 2018. This preface is the only additional text to the original project technical report which was submitted by LucidCatalyst to the ETI on 20th April 2018. This was accompanied by a statement concluding the independent review of the project outputs including the costs database, cost model and project reports. This preface provides context for this new version of the project technical report, and why the Energy Systems Catapult (ESC) has decided to release it in September 2020.

The ETI operated from 2007 to 2019 and is now closed. The ETI was a public-private partnership between global energy and engineering companies and the UK Government which worked as a conduit between academia, industry and the UK government to accelerate the development of low carbon technologies. The organisation working with its supply chain delivered engineering projects to support the development of affordable, secure and sustainable technologies to help the UK address its long term emissions reductions targets.

As part of its nuclear programme between 2013 and 2019, the ETI launched an open competitive procurement process in June 2017 for the delivery of a knowledge gathering project to provide an evidence based understanding of the range of factors influencing the cost of energy from new nuclear plants. CleanTechCatalyst (CTC) Ltd. working with LucidStrategy Inc. was selected to deliver this project and the legal entity CTC has subsequently developed into the organisation now known as LucidCatalyst led by Kirsty Gogan and Eric Ingersoll. The project, together with the independent review, was delivered to scope, schedule and budget and the project outputs made available to ETI members in April 2018. A summary report was released on the ETI's website 30th April 2018.

The NCD summary report was subsequently cited as a reference in the UK Nuclear Sector deal agreed between the Nuclear Industries Association and UK Government in June 2018. The NCD project approach and findings have also been used as inputs to reports including: MIT's *The Future of Nuclear in a Carbon-Constrained World*; the OECD NEA's *Unlocking Reductions in the Construction Costs of Nuclear: A Practical Guide for Stakeholders*; the Nuclear Innovation Research Advisory Board *Annual Report* (2020); and Energy System Catapult's *Nuclear for Net Zero*.

The ETI closed in December 2019 and its intellectual property rights regarding the outputs from the NCD project were assigned to Energy Systems Catapult. One of the ETI's guiding principles was to allow private sector ETI members to extract value from their investment in the ETI whilst publishing the learning from the projects consistent with matched funding investment from the taxpayer through UK Government. Two years on, the time is right to publish this version of the project technical report to allow more of the NCD learning to be available in the public domain. This version of the technical report provides more detail on the case studies than the summary report, and much more detail on the range of opportunities with potential to reduce nuclear costs.

Apart from this preface, this version of the full project technical report contains no new content. It has been updated with minor editorial amendments to improve flow and brevity for the reader. It has been rebranded by the authors at LucidCatalyst for consistency. It has also been checked by Energy Systems Catapult to ensure that these minor updates do not impact on the scope, contents and evidence presentation that were subject to independent review.

Executive Summary

Executive Summary

Nuclear energy has been identified in the UK Industrial Strategy and Clean Growth Strategy as having the potential to play a significant role in the UK transition to a low carbon economy, provided it is cost competitive and there is a market need. Recent nuclear projects in North America and Europe have been vulnerable to schedule delays and cost increases.[1] By contrast, plants built elsewhere during the same period have not suffered from such schedule and budget issues but instead demonstrated that nuclear energy can be highly cost competitive.

In the UK, a significant challenge for projects initiated over the next 10 years will be to complete construction and commissioning within acceptable norms of schedule and budget variation. A further challenge will be to deliver meaningful cost reduction for follow-on plants, to meet the expectations of investors, government, and consumers. This first challenge requires strategies for mitigating "first-of-a-kind" (FOAK) schedule risk (especially where designs are not FOAK), and the second requires strategies for programmatic reduction of construction duration and total capital costs.

The project team identified and verified the most significant drivers of delivered plant cost within different regions around the world, leading to a series of recommendations for principal actors in the sector that are transferable to the UK new build context. Instead of predicting specific commercial project costs, or Contract for Differences, or strike price, this project focused on potential trends impacting levelised cost of electricity (LCOE).

Cost reduction inherently requires increasing schedule and budget certainty. In doing so, there is less project risk and higher overall confidence in successful project delivery, which benefits all stakeholders, including the public and project developer. Reducing risk lowers overall construction financing costs, both in terms of leading to a shorter construction period, but also a lowering in the risk premium. Engaging in the right kind of collective action and demonstrating risk reduction by all project stakeholders can therefore yield lower electricity costs for the consumer, allow for the vendor to realise its desired risk-adjusted rate of return, and expand market potential.

1 Recent analysis of published historic cost breakdowns of LWRs in the US shows that the main cost driver is not the nuclear technology itself; rather, it is the cost of a large-scale construction project that is regulated by strict nuclear standards. (Dawson et al., 2017)

Evidence gathered and analysed during this project suggests that UK nuclear new build has very significant cost reduction potential. Sections 1 and 2 describe how the documented experience with successful multi-unit builds and new build programmes in other countries indicates the range of cost savings that could be achievable in the UK context. Key characteristics of low-cost and high-cost new build programmes (described in Section 2) are strongly supported by evidence from multiple sources and documented experience. Section 3 describes the key differences between high-cost and low-cost nuclear construction, identifying important and consistent themes in each, including the importance of detailed design completion before construction starts. This evidence is further supported by a series of Case Studies in Section 4, underpinning the summary of findings in Section 5 and a series of cost reduction opportunities transferable to the UK context in Section 6, discussion of the reliability of report contents in Section 7, conclusions in Section 8, and recommendations for next steps in Section 9.

The report concludes that a carefully designed programme that engages all of the key stakeholders with a shared vision and focus on the key characteristics of low-cost, high quality construction can start the UK down the path to affordable nuclear power.

The project also identified the potential for a step-reduction in the cost of advanced reactor technologies and small modular reactors (SMRs). Whilst such technologies are not yet licensed, nor construction ready, this project provided further evidence in support of early testing of design claims by regulators, and the examination of cost reduction strategies by potential investors.

From within 35 cost reduction opportunities identified in this study, the following smaller group of actions should be prioritised for reducing project cost and risk in the UK.

Finding	Cost Driver Category
Complete detailed plant design prior to starting construction	Vendor Plant Design
Follow contracting best practices	Project Dev. and Governance
Project owner should develop multiple units at a single site	Project Dev. and Governance
Innovate new methods for developing alignment with labour around nuclear projects	Labour
Government support should be contingent on systematic application of best practices and cost reduction measures	Political and Regulatory Context
Design a UK programme to maximise and incentivise learning, potentially led by a newly-created entity	Political and Regulatory Context
Government must play a role in supporting financing process	Political and Regulatory Context
Transform regulatory interaction to focus on cost-effective safety	Political and Regulatory Context

Main Report

1 Introduction

"The nuclear sector is integral to increasing productivity and driving growth across the country. Nuclear is a vital part of our energy mix, providing low carbon power now and into the future."

1.1 Motivation: Cost reduction will be necessary if nuclear energy is to play a significant role in meeting the UK decarbonisation targets

Nuclear can play a significant role in the UK transition to a low-carbon economy provided it is cost competitive and there is a market need.[1] The amount of new nuclear capacity deployed by 2030, 2050, and beyond will depend on a number of factors but cost competitiveness will be critical. The Government's *Clean Growth Strategy* highlights the importance of cost reduction in the low carbon energy transition:

> *"The UK will need to nurture low carbon technologies, processes and systems that are as cheap as possible. We need to do this for several reasons. First, we need to protect our businesses and households from high energy costs. Second, if we can develop low cost, low carbon technologies in the UK, we can secure the most industrial and economic advantage from the global transition to a low carbon economy. Third, if we want to see other countries, particularly developing countries, follow our example, we need low carbon technologies to be cheaper and to offer more value than high carbon ones."* [2]

Recent nuclear new build projects, particularly in North America and Europe, have been vulnerable to schedule delays and cost increases.[3] By contrast, nuclear projects in other parts of the world are performing far better on cost and schedule. In the UK, a significant challenge for projects initiated in the next 10 years will be to complete construction and commissioning within acceptable norms of schedule and budget variation. A further challenge will be to deliver meaningful cost reduction for follow-on plants to meet the expectations of investors, government, and consumers. This first challenge requires strategies for mitigating "first-of-a-kind" (FOAK) schedule risk (especially if designs have already been built in another country), and the second requires strategies for

1 The quotation above is from Industrial Strategy: *Building a Britain Fit for the Future*, November 2017. This white paper sets out a long-term plan to boost the productivity and earning power of people throughout the UK.

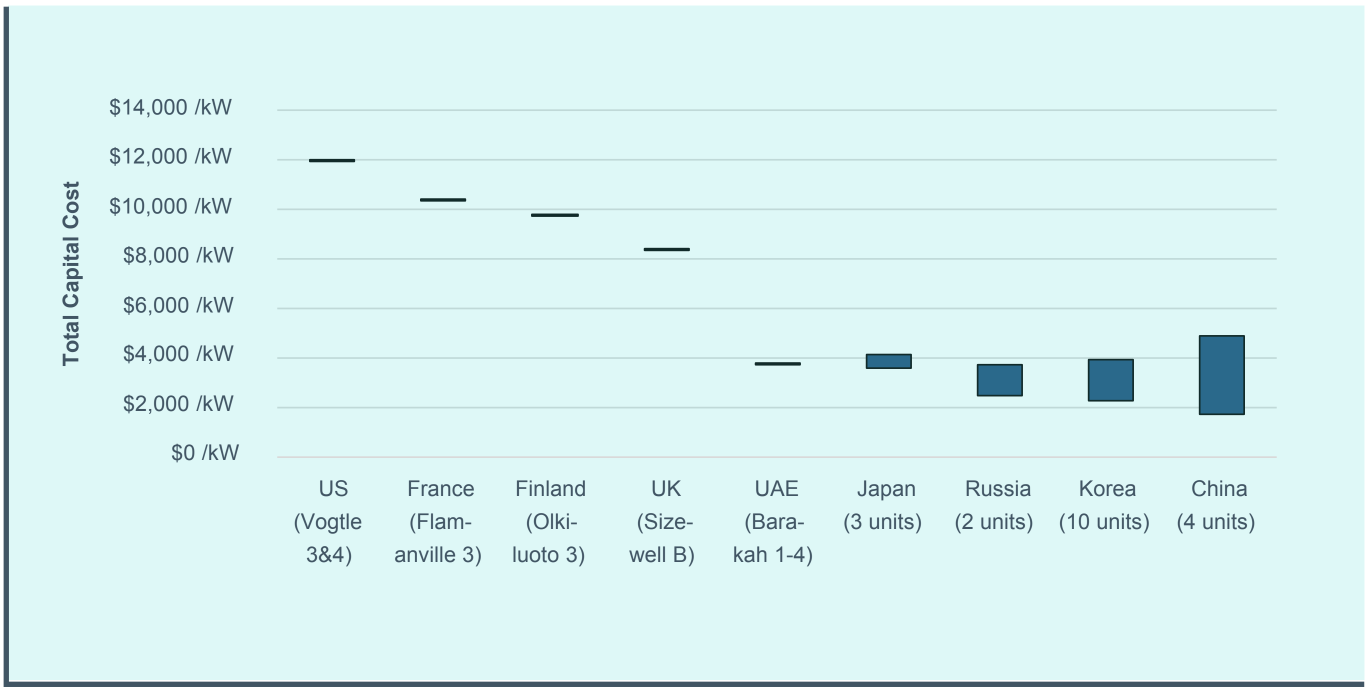
2 *Clean Growth Strategy*, October 2017.

3 Recent analysis of published historical cost breakdowns of light water reactors (LWRs) in the US shows that the main cost driver is not the nuclear technology itself; rather, it is the cost of a large-scale construction project that is regulated by strict nuclear standards. (Dawson et al., 2017)

programmatic reduction of construction duration and total capital costs.

A brief examination of the costs of recently completed plants from around the world indicates that there is a wide range – a factor of four. As shown in Figure 1 below, national programmes in China, Japan, and South Korea have demonstrated positive learning curve effects (a recent example being the Korean nuclear industry's ongoing delivery of four nuclear power units at Barakah in the UAE). These recent successful national programmes have repeat designs and strongly prioritised cost reduction strategies for large Generation III+ designs, such as those currently envisaged for construction in the UK. This suggests that even if the UK cannot re-create all the conditions in countries achieving the lowest cost in nuclear construction, there may still be significant potential to lower the cost of nuclear energy in the UK.

Figure 1. **Total Capital Costs for Historical and Ongoing Nuclear Projects in Database**



Further nuclear new build may be considered beyond the 16 GWe currently planned by developers and encouraged by government. Within the context of an internationally cost-competitive UK energy system, additional nuclear capacity will also need to be competitive with other low-carbon sources. For instance, the cost of renewables is expected to continue to fall, as will the cost of new plants using Carbon Capture and Storage (CCS) technology as additional capacity is added. Finding credible routes to the long-term reduction of levelised cost of electricity (LCOE) from nuclear plants is an important goal to be achieved through innovation, combined with a concerted emphasis on cost reduction in design, delivery, and operation.

Private sector activity in innovative nuclear plant design is currently strong across a range of technologies: from Small Modular Reactors (SMRs) to Advanced Modular Reactors (AMRs), including High Temperature Gas Reactors (HTGRs), Liquid-Metal Cooled Fast Reactors (LMFRs) and Molten Salt Reactors (MSRs). The Generation IV technology programme has been inspired by the goals of enhancing safety, proliferation resistance, and future waste reduction. These factors remain important, but for such technologies to be commercially deployed in significant numbers, they must also offer economic advantages compared with contemporary Generation III/III+ designs. Typically, advanced designs have relatively smaller power ratings, which make capturing economies of scale difficult. Therefore, innovations that reduce capital costs are paramount.

There are frequent claims of transformational costs from vendors promoting a variety of Generation IV designs. However, these designs are neither “construction ready” nor have they been approved by regulators. Therefore, the current evidence base must also be further substantiated regarding the strategies and prospects for “Nth-of-a-kind” (NOAK) Generation IV reactors to deliver a step change in cost reduction compared with Generation III+.

1.2 Objectives

In response to the lack of evidence regarding a positive learning effect for conventional nuclear and prospects for Gen-IV plants, the ETI carried out an open and competitive solicitation to commission a project entitled “Low Carbon Electricity Generation Technologies: Nuclear Cost Drivers Project.” The project employed a data-led approach, informed by the cost base of water cooled power reactors, to identify cost drivers within historical, contemporary, and advanced reactor designs. Knowledge gained from this investigation supported the identification of important trends related to project costs in nuclear power stations. It also supported the corresponding pursuit of identifying potential opportunities for achieving cost reductions. Three principal goals of the project were improved understanding of:

- the cost drivers within contemporary UK nuclear new build projects and identifying areas of potential technical or delivery innovation which can support cost reduction;
- the cost drivers within advanced reactor technologies and identifying 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.

Developing a comprehensive cost database of historic, contemporary, and advanced nuclear projects was pivotal to successful delivery of the project. The database followed a standardised cost coding structure to enable meaningful comparisons between nuclear projects. Where necessary, data was anonymised to protect confidentiality and the provenance for all entries was clear, recognising differing level of detail between projects. In addition to the database, an associated cost model with supporting dashboard metrics was created to interact with the database.

To maintain focus, certain known cost drivers were determined to be outside the scope of the current study, including:

- approaches to nuclear new build project financing;
- rates of interest during construction and during operations; and
- decommissioning strategies including fuel disposition.[4]

Therefore, the project objectives were to:

- assemble and apply:
  - a credible cost database across a global sample of historic, contemporary and advanced nuclear reactor projects; and
  - an associated credible cost model;
- perform and report on an analysis of the principal cost drivers for contemporary designs, SMRs and advanced reactor technologies;

4 This third item is excluded also because it has essentially zero impact on project cost.

- identify, analyse, and provide an improved understanding of:
  - the cost drivers within and across 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; and
- identify areas of nuclear power plant design, construction and operation with potential to deliver cost reduction relevant to contemporary designs, advanced reactor technologies and SMRs.

Through a competitive procurement process, the ETI awarded the project to CleanTech Catalyst Ltd (CTC), which, along with its subcontractor, Lucid Strategy (now LucidCatalyst and hereinafter the "project team"), developed work products to support the outcomes listed above. The project team received support from an Independent Reviewer, Dr Tim Stone CBE, as well as four project advisors: Dr Ken Petrunik, Charles Petersen Esq, Dr Jacopo Buongiorno, and Dr Ben Britton. In carrying out the project in its entirety, the project team developed a Scope of Work in coordination with the ETI that included the following summarised tasks:

- Task 1. Develop a tailored Cost Database and Cost Model schema that enables delivery of the Project Objectives
- Task 2. Conduct the Early Results Meeting with the ETI and ETI Members and meet with UK stakeholders
- Task 3. Develop and deliver the Draft ETI Cost Model and ETI Cost Database Report
- Task 4. Conduct the cost drivers analysis and deliver corresponding Draft Cost Drivers Analysis Report
- Task 5. Develop and deliver the Draft Project Summary Report
- Task 6. Deliver final 2-hour presentation to the ETI and the ETI Members
- Task 7. Prepare and submit to the ETI the final ETI Cost Model, associated final ETI Cost Database and final Reports

1.2.1 Cost reduction need not result in "winners" and "losers"

While the principal charge of this project is to reveal the major cost drivers for nuclear projects, a concurrent goal is to identify cost reduction strategies. In practice, reducing cost requires reducing project risk by increasing schedule and budget certainty. Less risk and higher overall confidence benefit all stakeholders, including the public and project developer. Cost reduction should therefore not be considered a zero-sum game that comes solely at the expense of vendors' or EPC profit margins. Reducing project risk – whether related to project development, construction, or supply chain – is a "win-win" that benefits all parties.

Risk reduction results from improvements in the supply chain, construction practices, labour productivity, the size of the market, or increased certainty or direct support from government, legislators, or the regulator. In turn, reducing risk can lower financing costs which is an important element within the proposed nuclear sector deal as part of the UK Government's industrial strategy. Engaging in the right kind of collective action and demonstrating risk reduction by all project stakeholders yields lower electricity costs for the consumer, allows for the vendor to realise its desired margin, and expands the market potential for new build projects.

1.3 Contents

The remainder of this report is divided as follows:

- **Section 2** explains the methodology by which the team identified a wide range of cost drivers and down-selected to a final group to analyse. It includes the team's approach to capturing the influence of each cost driver on overall cost using publicly available data.
- **Section 3** describes the ETI Cost Database and associated ETI Cost Model, and a supporting report provides additional detail (listed as Deliverable #2 above).
- **Section 4** uses narrative case studies to illustrate how each cost driver relates to total cost. The case studies include past projects as well as innovative concepts under development
- **Section 5** describes how the team grouped plants into categories of like technology and geography to develop "genre"-representative plants. These plants served as a basis for the ETI Cost Model and approach for anonymising confidential information
- **Section 6** focuses on cost reduction opportunities based on numerous discussions with project construction managers and other senior-level personnel (with direct project experience) who shared lessons learned and best practices, many of which are identified as transferable to the UK context
- **Section 7** lists several factors that support the ETI's ability to rely on the report contents.
- **Section 8** summarizes the report's conclusions, which are informed by the weight of evidence of the collected data, interviews, and case studies.
- **Section 9** provides recommendations for follow-on work.

2 Cost Driver Analysis

Identifying primary cost drivers for nuclear construction projects is challenging for several reasons. First, most cost and project delivery information is confidential. Little relevant data exists in the public domain. Second, while establishing a quantitative link between certain cost drivers and final project cost is straightforward (e.g. cost and quantity of raw materials, financing interest rate, number of staff, etc.), there are many other drivers for which this linkage is less direct. Many costs are the result of design decisions, approaches to project planning and project management, labour productivity, contracting and procurement methods, or supply chain readiness, for example. These may influence cost increases (or decreases) in different ways. Third, some cost drivers are outside the control of the project delivery consortium (e.g. extent of regulatory interaction/ intervention, labour rates, political climate, etc.).

With these constraints and complexities in mind, the project team developed a methodology to capture numerical and qualitative information on the most significant cost drivers for dozens of individual reactors.

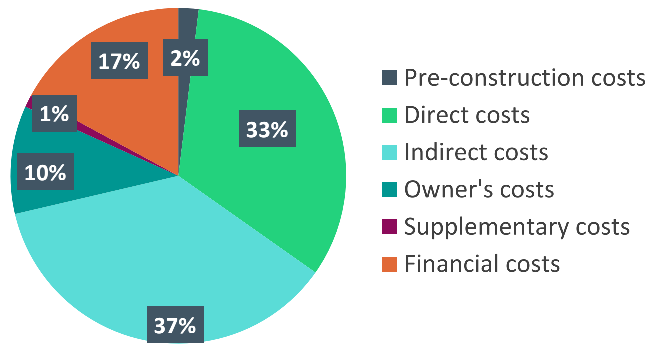
To adequately explain this methodology, this section is divided into three parts. The first part introduces a benchmark nuclear plant, which serves an important role in the project's methodology (as well as in the ETI Cost Model, explained in Section 3.1). The benchmark plant highlights major cost centres for nuclear plants and introduces important concepts, such as interest during construction (IDC) and levelised cost of electricity (LCOE). The second part describes the methods by which the project team selected a final group of cost drivers and how it used the benchmark plant in its approach to engage companies and experts to capture desired information. The third part explains how the data was used to statistically evaluate the relative influence of each driver on total cost.

2.1 Benchmark Plant

A benchmark plant provides a single reference point on which plants can be evaluated and enables an apples-to-apples comparison across all plants in the ETI Cost Database. The project team selected a US PWR from a 1986 Oak Ridge National Laboratory cost study as the benchmark plant (ORNL 1986). This plant reflects a 22-year effort by the US government to annually update the detailed cost estimates for a PWR, with information “representative of current experience and practice” and “reflect(ive of the) impact of changing regulations and technology” (ORNL 1986). The 1986 study presents costs in terms of a “best” and “median” industry experience. To align more closely with post-Chernobyl and post-Three Mile Island (TMI) costs, the project team selected the “median” experience and escalated the 1986 costs to 2017 USD and escalation assumptions are in Section 3.1.4. Table 1 presents a cost breakdown of the PWR benchmark using the Generation-IV International Forum’s (Gen-IV) cost accounting framework.

Table 1. **Cost Breakdown of PWR Benchmark**

Capitalised Costs	Gen IV Acct Codes	Cost
Pre-construction costs	10s	$133 /kW
Direct costs	20s	$2,255 /kW
Indirect costs	30s	$2,512 /kW
Owner’s costs	40s	$715 /kW
Supplementary costs	50s	$79 /kW
Financial costs	60s	$1,175 /kW
Capitalised Costs Total		**$6,780 /kW**



Gen-IV Cost Accounting Categories (1-digit level)*	Description of High-Level Cost Category Contents (2-digit Categories)
Pre-construction costs	Land and Land Rights; Site Permits; Plant Licensing; Plant Permits; Plant Studies; Plant Reports; Other Pre-Construction Costs; Contingency on Pre-Construction Costs
Direct costs	Structures and Improvements; Reactor Equipment; Turbine Generator Equipment; Electrical Equipment; Heat Rejection System; Miscellaneous Equipment; Special Materials; Simulator; Contingency on Direct Costs
Indirect costs	Field Indirect Costs; Construction Supervision; Commissioning and Startup Costs; Demonstration Test Run; Design Services Offsite; Project Mgmt/Construction Mgmt Services Offsite; Design Services Onsite; Project Mgmt/Construction Mgmt Services Onsite; Contingency on Indirect Services Cost
Owner’s costs	Staff Recruitment and Training; Staff Housing; Staff Salary-Related Costs; Other Owner’s Costs; Contingency on Owner’s Costs
Supplementary costs	Shipping and Transportation Costs; Spare Parts; Taxes; Insurance; Initial Fuel Core Load; Decommissioning Costs; Contingency on Supplementary Costs
Financial costs	Escalation; Fees; Interest During Construction; Contingency on Financial Costs

* The left-hand column above lists the Gen-IV “1-digit” code of accounts for a nuclear plant. The right-hand column lists the constituent “2-digit” categories, each of which has its own costs. The 2-digit categories for direct costs are further disaggregated into “3-digit” costs. The 1986 PWR cost study includes nearly 150 cost entries in total.

2.1.1 Overnight vs. Total Cost

Table 1, above, presents total capitalised cost for the benchmark PWR, broken out into six separate cost categories. Together, these represent a plant's total or "all in" delivery cost. Another term used to express plant delivery cost is "overnight cost." Overnight cost reflects a company's detailed cost estimates for delivering the project but excludes financing costs, which vary from project to project and are only known for certain once a plant is completed (because they reflect the elapse of time as interest compounds). For consistency in reporting values (including the ETI Cost Database and Model), the project team converted all overnight costs to total costs by applying a uniform financing assumption across all plants for which costs were converted. The process for this conversion is explained in greater detail in Section 3.1.4 and Appendix D.

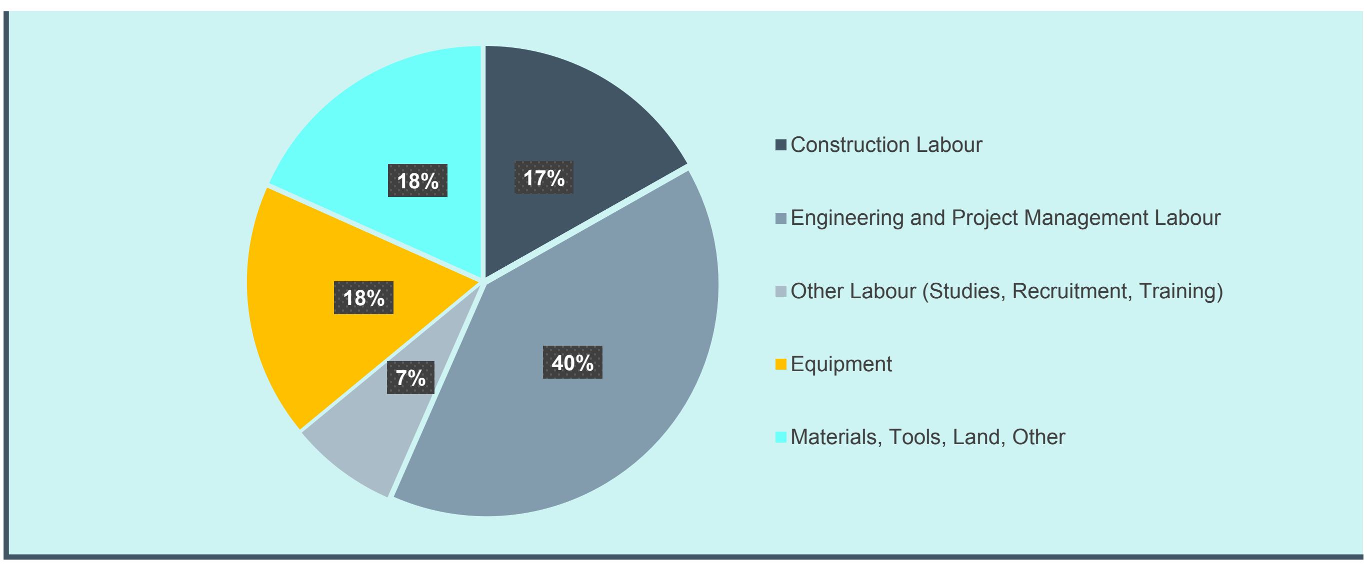
2.1.2 Major Cost Components in the PWR Benchmark

As shown in the pie chart on the previous page, direct costs and indirect costs and, to a lesser extent, financing costs dominate a plant's total cost. While financing costs are important and a function of perceived risk (reflected as the financing interest rate) and construction duration, the ETI has explicitly removed it from consideration as a cost driver (although it is included as a dynamic variable in the ETI Cost Model). In excluding financing costs, direct and indirect cost make up an even larger share of total cost and labour makes up approximately 40% and 80% of these categories, respectively. This demonstrates how the quantity of labour (and hourly rates, productivity, etc.) can explain much of the cost variation across projects.

2.1.3 Labour Components of Overnight Capital Costs

Figure 2 below shows labour and other components of overnight capital costs for the US PWR Benchmark plant. The three labour components reflect (1) construction labour within the direct construction category [20s]; (2) engineering and project management labour within the indirect services category [30s]; and (3) studies, recruitment, training, and other labour within the pre-construction [10s] and owner's costs [40s] categories. Together these three labour components represent 64% of the overnight cost of the US PWR Benchmark plant. The breakdown of labour and other overnight cost components derives from ORNL (1986, Table 5-3). The source specifies man-hours and labour costs within the direct construction and indirect services categories. In the absence of labour cost details for the other cost categories in the source, labour costs are assumed to constitute approximately 50% of pre-construction and owner's costs (and a negligible percentage of supplementary costs).

Figure 2. **Labour and Other Components of US PWR Benchmark Overnight Costs**



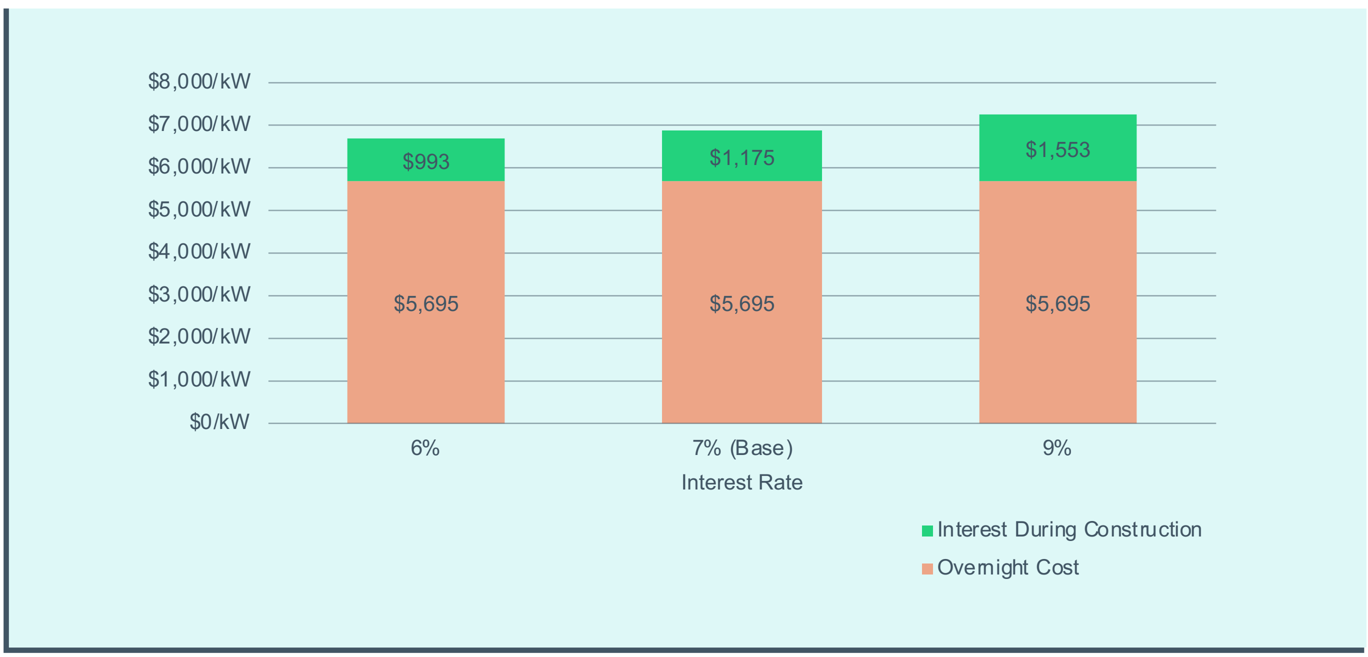
2.1.4 Interest During Construction

As discussed above, this study examines capital costs in a comprehensive manner by including the interest that accrues on debt or other capital resources during construction. This subsection provides further detail on the four drivers of interest during construction (IDC): (1) overnight capital cost, (2) interest rate, (3) construction duration, and (4) expenditure profile. This subsection uses parameters for the US PWR Benchmark Plant to illustrate the impacts of alternative scenarios. In base case calculations, the overnight cost for the Benchmark Plant is $5,695/kW, the interest rate is 7%[1], the construction duration is 5 years following 2 years of preconstruction activities, and the expenditure profile allocates most of the equipment costs to early years while spreading labour and other costs evenly. Provenance for these assumptions is discussed in Appendix D.

IDC is a percentage of overnight capital cost when the other three drivers are held constant. As shown in Table 1, IDC for the Benchmark Plant in base case calculations is $1,175/kW, or 21% of overnight cost. In light of this proportionality, the most straightforward strategy to minimise IDC is to minimise overnight cost.

To illustrate the second driver, the Figure 3 below shows total capital costs, consisting of overnight cost and IDC, for the Benchmark Plant with interest rates of 6%, 7%, or 9%. The various interest rate scenarios all use the same parameters listed above for overnight cost, construction duration, and expenditure profile. A 6% interest rate would lower IDC to $993/kW (15% reduction), while a 9% interest rate would raise IDC to $1,553/kW (32% increase).

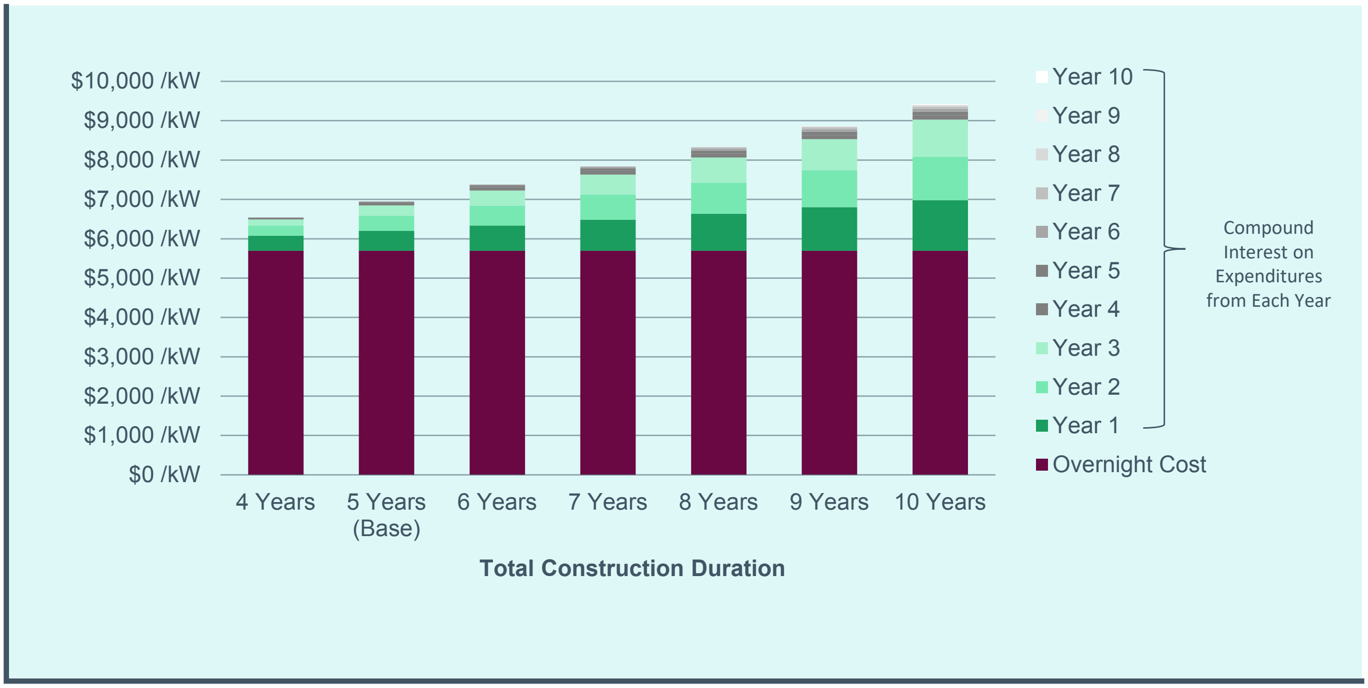
Figure 3. **Interest Rate Impacts on Interest During Construction**



1 Interest and discount rates in this analysis are expressed in real terms (controlling for inflation).

To illustrate the third driver, Figure 4 below shows interest during construction with various scenarios for construction duration. The scenarios all use the same overnight cost as above and an interest rate of 7%, but they make different assumptions for duration and expenditure profile. The analysis reflects an initial expectation of a 4-year construction duration in which one quarter of the overnight cost ($1,424/kW) is spent in each of the first 3 years. The remaining quarter of the overnight cost is then spread evenly over the remaining years in the actual construction duration, which ranges from 4 to 10 years. If the project finishes in 4 years, the IDC due upon completion is small ($844/kW). Through continuous compounding, IDC due upon completion is much larger if the project takes longer, reaching $3,729/kW (65% of overnight cost) if construction lasts 10 years.

Figure 4. **Construction Duration Impacts on Interest During Construction**



The fourth driver of IDC relates to the expenditure profile within the construction period. The example above shows that large expenditures in early years, such as costly equipment orders, can lead to significant accumulation of IDC if the project takes many years. Lower expenditures during early project phases mitigate this effect. For example, if the project takes 10 years but the overnight cost is spread evenly ($570/kW in each year), IDC upon completion is $2,444/kW (34% less than the IDC shown above with high initial spending).

In summary, the four strategies to reduce IDC are (1) minimise overnight cost, (2) minimise the interest rate, (3) minimise construction duration, and (4) push large expenditures later into the project schedule to the extent feasible.

2.1.5 Levelised Cost of Electricity

In addition to total capital cost estimates per kW (combining overnight cost and IDC), this study estimates levelised cost of electricity (LCOE) by calculating capital recovery per MWh and adding operating expenditures per MWh. This analysis uses relatively simple formulas to estimate LCOE rather than modelling cash flows by year. Operating expenditures are assumed to remain constant throughout the operating period, and LCOE is expressed on a pre-tax basis. LCOE may differ significantly from actual prices for nuclear power because of numerous plant-specific factors, such as pricing structure (market, contract, or government supply), financial parameters for the plant owner (such as capital payback period and tax rates), and pricing adjustments (such as tax credits, nuclear insurance or waste disposal adders, or price guarantees through a contract for differences).

Calculation of capital recovery per MWh uses a standard formula (shown in Appendix D) with inputs for total capital cost per kW, capitalisation period, discount rate, and capacity factor. Note that the discount rate for spreading capital costs over power production is a subtly different concept from the interest rate for IDC. This study uses the following assumptions to calculate capital recovery per MWh for all plants and genres: capitalisation period of 60 years, discount rate of 7%, and capacity factor of 95%. Provenance for these assumptions is discussed in Appendix D.

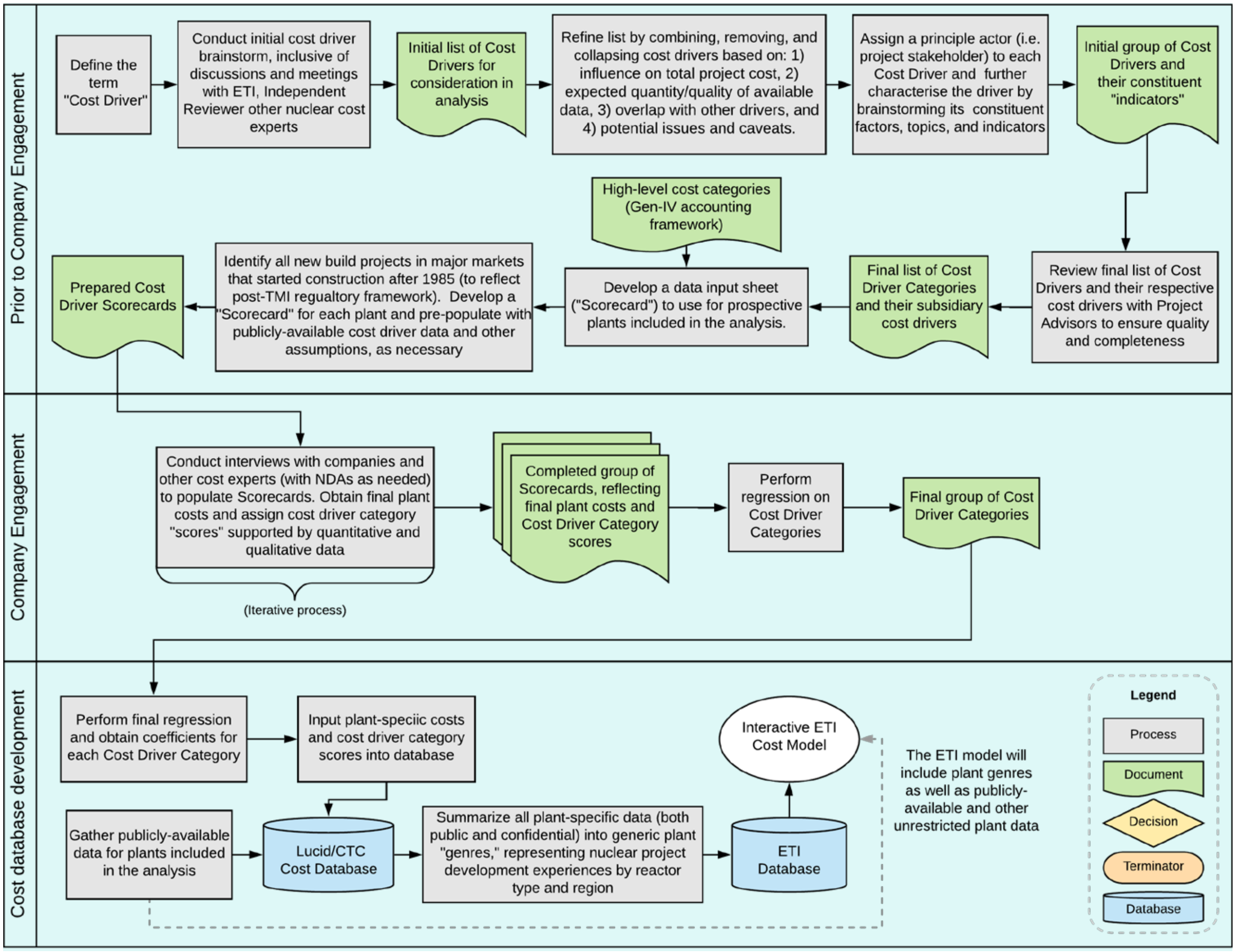
With these standard assumptions, the Benchmark Plant's total capital cost of $6,870/kW requires capital recovery of $59/MWh. Capital recovery moves in the same direction as changes in discount rate but in the opposite direction as changes in capitalisation period. For example, a discount rate of 9% would increase the capital recovery to $75/MWh, and a discount rate of 6% would decrease it to $51/MWh. With the discount rate back at 7%, a shorter capitalisation period of 25 years would increase the capital recovery to $71/MWh.

The O&M cost for the Benchmark Plant is $20/MWh, and the fuel cost is $7/MWh. Summing the capital recovery with these operating costs, the LCOE for the Benchmark Plant is $87/MWh (with rounding). The ETI Cost Database calculates LCOE for individual plants, the ETI Cost Model calculates it for genres, and Section 5 of this report shows LCOE results by genre (with markers for alternative interest and discount rates).

2.2 Methodology for Deciding on Cost Drivers and Data Collection

The flow diagram in Figure 5 on the following page summarises the project team's approach for identifying, prioritising, vetting, quantifying, validating, and subsequently analysing a final set of nuclear cost drivers. The figure divides this process into three phases from top to bottom: (1) prior to company engagement, (2) company engagement, and (3) ETI Cost Database and ETI Cost Model development. The subsections below provide details on the first two of these three phases. The last phase – Development of the ETI Cost Database and associated ETI Cost Model – is described in detail in the next section.

Figure 5. **Process Flow Diagram for Data Collection**



2.3 Prior to Company Engagement

Prior to engaging with companies, the following items were prepared:

- **Definition of the term "Cost Driver."** The project team conducted several internal collaborative workshops as well as extensive consultations with the ETI, the Independent Reviewer, project advisors, and other nuclear cost experts to generate an exhaustive list of cost drivers to potentially consider for the project. The team settled on a definition for cost drivers as:
  - Increasing or decreasing the cost of the project;
  - Representing one of the processes critical to plant completion or "realisation;"
  - Having factual and/or measurable indicators;
  - Associated with at least one of the principal actors in plant completion or "realisation;" and
  - Collectively explaining most of the cost variation among plants.

Using this definition, the team developed an exhaustive list of qualitative and quantitative cost drivers.

- **Refine and finalise exhaustive cost driver list.** The project team carefully evaluated each of the initial cost drivers and used the following down-selection criteria to arrive at a final group of drivers for consideration: (1) influence on total project cost, (2) expected quantity/quality of available data, (3) overlap with other drivers, and (4) potential issues and caveats. Where appropriate, specific cost drivers were removed or combined.
- **Assign cost drivers to their principal actors and contextual factors.** The project team attributed each cost driver with its "principal actor" or project delivery stakeholder (e.g. EPC, vendor, government, etc.) who plays a critical, functional role in project delivery. In many cases, roles may be combined, as in the case of a single entity playing the roles of Vendor and EPC, or shared among parties, such as when there are multiple owners for a project. These stakeholders are largely responsible for implementing cost reduction strategies related to the cost driver for which they are assigned.

  The Team also designated several contextual factors or "indicators" to each driver. These indicators included numerous quantitative factors and metrics but also qualitative, driver-specific topics, which served as prompts during discussions with experts regarding how a project performed against each driver.

  The project team settled on a final group of eight cost drivers. From a semantics perspective, these eight drivers describe broad cost categories and therefore are often referred to as "Cost Driver Categories," for which there are several constituent cost driver "indicators." The eight Cost Driver Categories and their corresponding actors are listed in Table 2 below. A list of category-specific indicators can be found in Appendix A. As the Cost Driver Categories covered all major project cost centres, experts were allowed to speak freely and the project team to definitively assign responses to an individual driver category. The project team acknowledges that there may be alternatives for defining and grouping the range of cost drivers. However, there was strong alignment across the range of project advisors and construction experts for the drivers as defined (and the intent was to identify the principal trends rather than forecast individual project costs).

Table 2. **Final Eight Cost Drivers and Associated Principal Actors**

Cost Driver Category	Principal Actor	Description
Vendor Plant Design	Reactor Vendor	Includes all pre-construction efforts related to plant design, including detailed design decisions, detailed 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	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, weighted average cost of capital (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.); proactive maintenance; daily, weekly, monthly, and annual checklist adherence; scheduled incident training exercises and documentation; third-party operation audits and board reporting.

- **Review final list of Cost Driver Categories and their constituent indicators.** Assisted by the project advisors, the project team conducted a final review of the Cost Driver Categories and their respective cost drivers. Discussions with advisors resulted in eliminating measures that were deemed to overlap with others and adding a small number of cost indicators. Appendix A provides a complete list of cost drivers for each category.
- **Develop a Cost Driver Category "Scorecard".** Based on the finalised list of Cost Driver Categories, the project team prepared a data input form (or "Scorecard") in Microsoft Excel that served to capture a qualitative score for each cost driver category as well as underlying rationale that supports the assigned score. A simple scoring methodology was chosen to allow respondents to score each category using a range of -2 to 2. The range was set around the US PWR benchmark, which defined the score of zero. As shown in Table 3, a score of less than zero indicates that the category reduced the overall plant cost against the benchmark PWR. Similarly, a score above zero indicates that the respective category contributed to higher cost in that area.[2]

  Assigning scores for each category required a clear definition what is included in the "zero" PWR benchmark score. Therefore, on the scorecard itself, the project team included several indicators for a "zero" score (as presented in Table 4 on the following page).

Table 3. **Possible Cost Driver Category Scores**

Category	Score
Significantly Reduces Cost	-2
Somewhat Reduces Cost	-1
Neither Increases nor Decreases Cost	0
Somewhat Increases Costs	1
Significantly Increases Cost	2

- **Identify all plants in target markets that started construction past 1985 and prepare related scorecards with public data (as available).** To only include plants that had been subject to a post-Three Mile Island regulatory regime, an eligibility cut-off date was set for plants that started construction past 1985. In practice, however, priority was given to plants that have been most recently commissioned (including those that will be commissioned relatively soon).

2 Table 5 on study results presents a summary of plant characteristics from the database for each score across the cost driver categories.

Table 4. **Indicative Cost Driver Values by Category for US PWR Benchmark Plant**

Cost Driver Category	Indicative Cost Driver Characteristics
Vendor Plant Design	• ~1,000 MWe plant capacity • Multiple units in same country • Few or no units elsewhere in the world • Standard design includes 1 reactor unit • 33% thermal efficiency • Seismic design does not deviate from industry norm (i.e. no innovation) • ~9 million man-hours spent on design
Equipment and Materials	• US equipment prices • 30-40 US tons of steel/MW • ~300 cubic yards of concrete/MW • Equipment requires significant on-site labour to finish and install
Construction Execution	• 60-72 month build schedule • <12 months of delay from original construction schedule • Relatively minimal cost for construction rework • ~$860M spent on design work prior to and during construction • Very little construction cost allocated to offsite assembly
Labour	• ~20 million man-hours for direct construction • ~9 million man-hours for indirect services • ~9 million man-hours for plant design • $50-55/hour avg. construction wage (fully loaded) • 8 hours per day; American construction productivity • Modest cost of worker training and preparation • Majority of workers have at least some nuclear construction experience
Project Governance and Project Development	• ~7-8% weighted average cost of capital (WACC) • Few discretionary changes to design • 1 unit at the plant site • Well organised project structure from owner's perspective • Defined limits to the number of prime and subcontractors • Clear assignment of liability and customer exercises diligent oversight
Political and Regulatory Context	• No significant political or public opposition to project • Relatively few changes required by the regulator • No challenges financing plant • $265/hour for regulator billing rate • Regulator has experience vis-a-vis overseeing nuclear construction • Site licensing process takes no more than 2 years • Pace of regulatory interactions do not influence the project schedule • Few changes required by the regulator during construction
Supply Chain	• Local supply chain is capable and has nuclear experience • Modest cost to prepare supply chain, including costs related to obtaining nuclear qualifications • Low cost of ensuring supply chain readiness/availability • Nuclear-grade concrete and steel prices are 2-5x higher than non-nuclear
Operation	• Stable fuel price for enriched uranium • ~750 operating staff • Average annual staff salary of $75,000 • 90% capacity factor • Few unplanned outages

With a clear understanding of the "zero score," the project team conducted semi-structured interviews with each interviewee, guided by the cost driver indicators. Through the interviewees' own direct knowledge of the project delivery experience, interviewees assigned each cost driver with a score that reflected how it "did not" ('0'), "somewhat" (-1,+1) or "significantly" (-2,+2) influenced the overall plant cost (or savings).

The Scorecard also included two dynamic sliders (shown in Figure 6 below) that changed positions as total plant cost and average cost driver scores were adjusted. This constrained the participant into assigning scores such that the average score aligned with the final plant cost. For example, a final plant cost of $4,500/kW would have an average of the eight cost driver scores close to -0.8.

Figure 6. **Dynamic Cost and Cost Driver Sliders on the plant "Scorecard"**

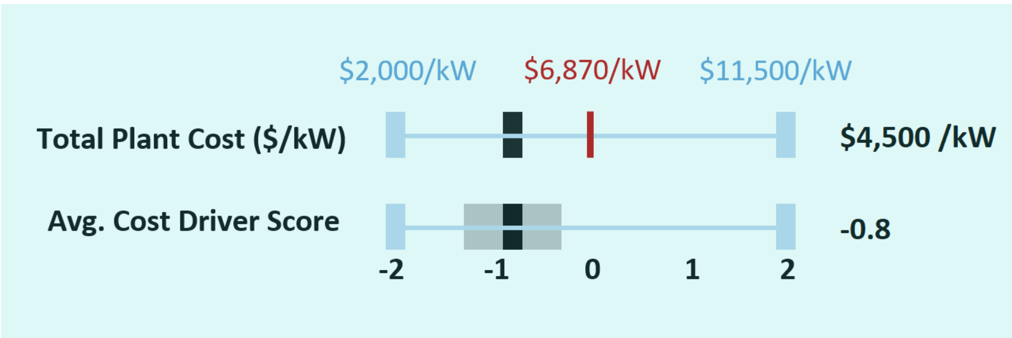
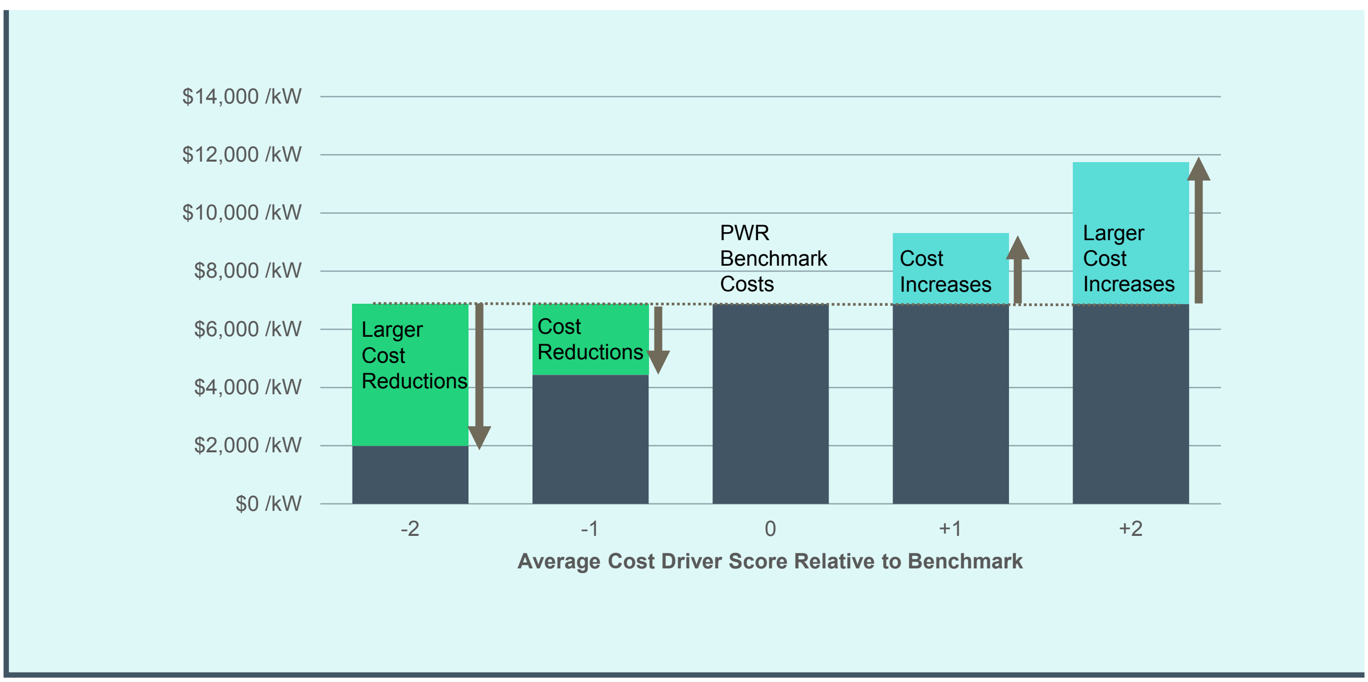


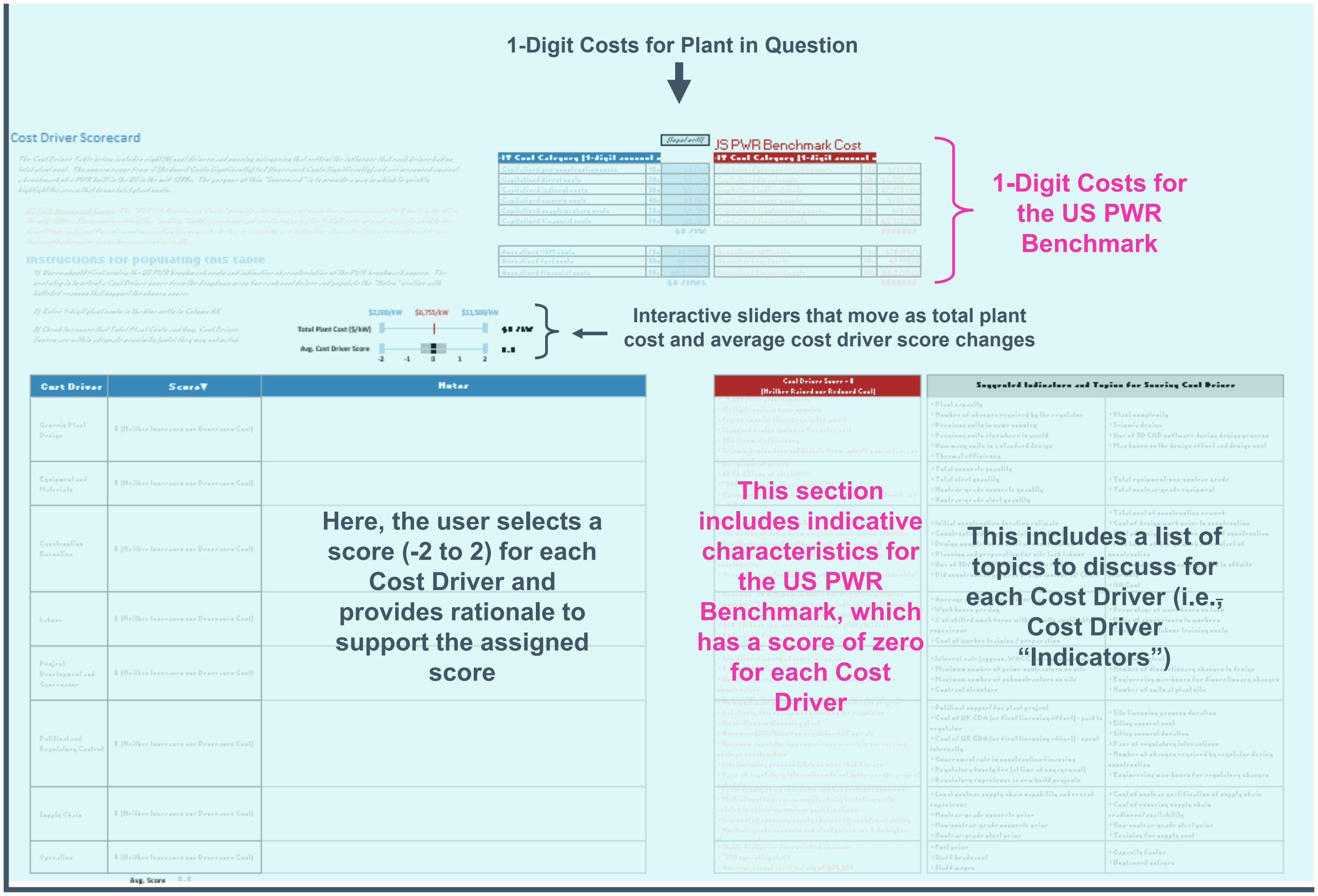
Figure 7 below shows the relationship between total capital costs and average driver scores for nuclear plants included in the study. The figure shows that the Benchmark plant with driver scores of zero has total capital cost of $6,870/kW, while plants with average scores above zero have higher costs (up to about $12,000/kW) and plants with average scores below zero have lower costs (down to about $2,000/kW).

Figure 7. **Relationship Between Total Capital Costs and Average Driver Scores**



The Scorecard, shown annotated in Figure 8 below, also provided a place for respondents to enter "one-digit" plant costs according to the Gen-IV cost accounting framework. The project team anticipated that a full set of one-digit cost detail would be less onerous on the participating companies (than requesting 2- and 3-digit level cost data) and therefore more likely to be achieved and sufficient to enable confidence in conclusions and recommendations about the importance and influence of each driver. As discussed below regarding cost sources, however, a number of companies were unable to provide cost information within the time constraints for this study.

Figure 8. **Annotated Cost Driver Scorecard**



2.4 Company Engagement

The second phase consisted of the following items related to company engagement:

1. Non-disclosure agreements. The project team executed non-disclosure agreements (NDAs) before requesting or discussing confidential information.[3] NDAs allowed participants to assign plant information to three categories: (1) public information from our research and their non-confidential additions for presentation in our public reports and our transferral to the ETI, (2) confidential information that does not allow explicit presentation in our public reports but does allow transferral to ETI, and (3) confidential information that does not allow explicit presentation in our public reports or transferral to ETI. The methodology for masking confidential information in this report is described below in Section 3.1 and Appendix C and was rigorously adhered to throughout every aspect of this study.

2. Interviews with experts. Following an initial conversation about the objectives and methods of the project and executing NDAs as necessary, the team carried out semi-structured interviews largely guided by the eight cost drivers and their associated indicators. Interviews took place over the phone and in person in the UK, France, USA, Korea, and Japan. A primary outcome of the interviews was a populated "scorecard," which was then added to the LucidCatalyst Cost Database (described below). Where possible, the project team checked plant cost entries and cost driver rationale against publicly-available information.

The project team conducted more than 150 hours of expert interviews for this project. All interviews were conducted with a minimum of three people in the meeting to ensure accurate recording of information and consistency in note taking. The expertise of the interviewers ensured a level of peer-to-peer understanding. Any unclear statements were immediately clarified.

Interviewees included experts with the following backgrounds:

- Board-level directors, major infrastructure projects
- Construction managers, global nuclear new build
- Project directors, global nuclear new build
- Quality assurance experts
- Contract law, finance and major transactions
- Senior policy directors, government
- Senior management, global nuclear industry
- Academia
- Regulators
- Investors

In total, the project team obtained scorecards for 39 units that have been built or are currently under construction (33 conventional and 6 SMRs or advanced concepts).

Discussions sometimes evolved beyond these topics and often included details on best practices, lessons learned, or specific cost reduction strategies that drove the final cost.

3 Some companies would only grant interviews on a non-confidential basis.

3. Regression analysis of cost drivers. The project team performed a regression analysis to quantitatively estimate the influence of each cost driver on total plant cost. A regression is a commonly used statistical measure for estimating relationships among different variables. It is particularly useful in determining which independent variables (i.e. cost drivers) are significant predictors of the dependent variable (i.e. total plant cost). It also estimates the rate of change in the dependent variable as a function of changes to the independent variable(s). Our regression confirmed that three of the eight cost drivers had a statistically significant influence on total plant cost: Supply Chain, Labour, and Project Development & Governance.

> **Limitations of the Regression Analysis:** Precision (or "sensitivity") of the coefficient values is largely a function of sample size. While the project team was successful in obtaining cost driver score for over 30 plants in a very short period of time, it is a relatively small sample size for 8 independent variables. More data points can provide greater precision; however, the regression results should be treated as indicative and considered alongside the results from the structured interviews, plant costs, and case studies. The plant data reflects two vastly different environments – one where the nuclear industry is attempting to restart (i.e. building the supply chain, training labour, a regulator with little project experience, etc.) and another where all project stakeholders are experienced and competent due to continuous projects. The overarching purpose of this regression analysis is to understand the most significant cost drivers for planning nuclear projects in the UK and elsewhere. The purpose is not to predict the cost of a new project with high precision, because costs in the UK or elsewhere will depend on several project-based and market-based factors (among others).

The third phase, "Cost Database Development," consisted of inputting plant costs, cost driver scores, and regression outputs (i.e. cost driver coefficients) into the LucidCatalyst database and anonymising the data for transfer to the ETI Cost Database and ETI Cost Model without violating confidentiality agreements.

3 ETI Cost Model and Associated Database

The project team's methodology for storing, organising, synthesising, and distilling value from the confidential data made it "actionable" to the ETI. Described in this section is the development, structure, and function of the ETI Cost Database and associated ETI Cost Model. The database and model provided the ETI with an evidence base to better understand the main cost drivers for different nuclear technologies in different markets and where to focus support for cost reductions on UK new build projects.

In building the ETI Cost Database and ETI Cost Model, the project team developed the concept of a plant "genre." A "genre" simply refers to a representative plant that characterises the cost and delivery experience of a group of plants of a given technology (i.e. conventional vs. advanced nuclear technology) from a defined region in a non-confidential manner.

For the purposes of the project, plants were grouped into seven genres:

Conventional (Generation II/III/III+)

1) Reference US PWR
2) Conventional Plants – Europe / North America
3) Conventional Plants – Rest of World

Advanced (Generation IV)

4) Light Water SMRs
5) High Temperature Gas Reactors
6) Liquid Metal Cooled Fast Reactors
7) Molten Salt Reactors

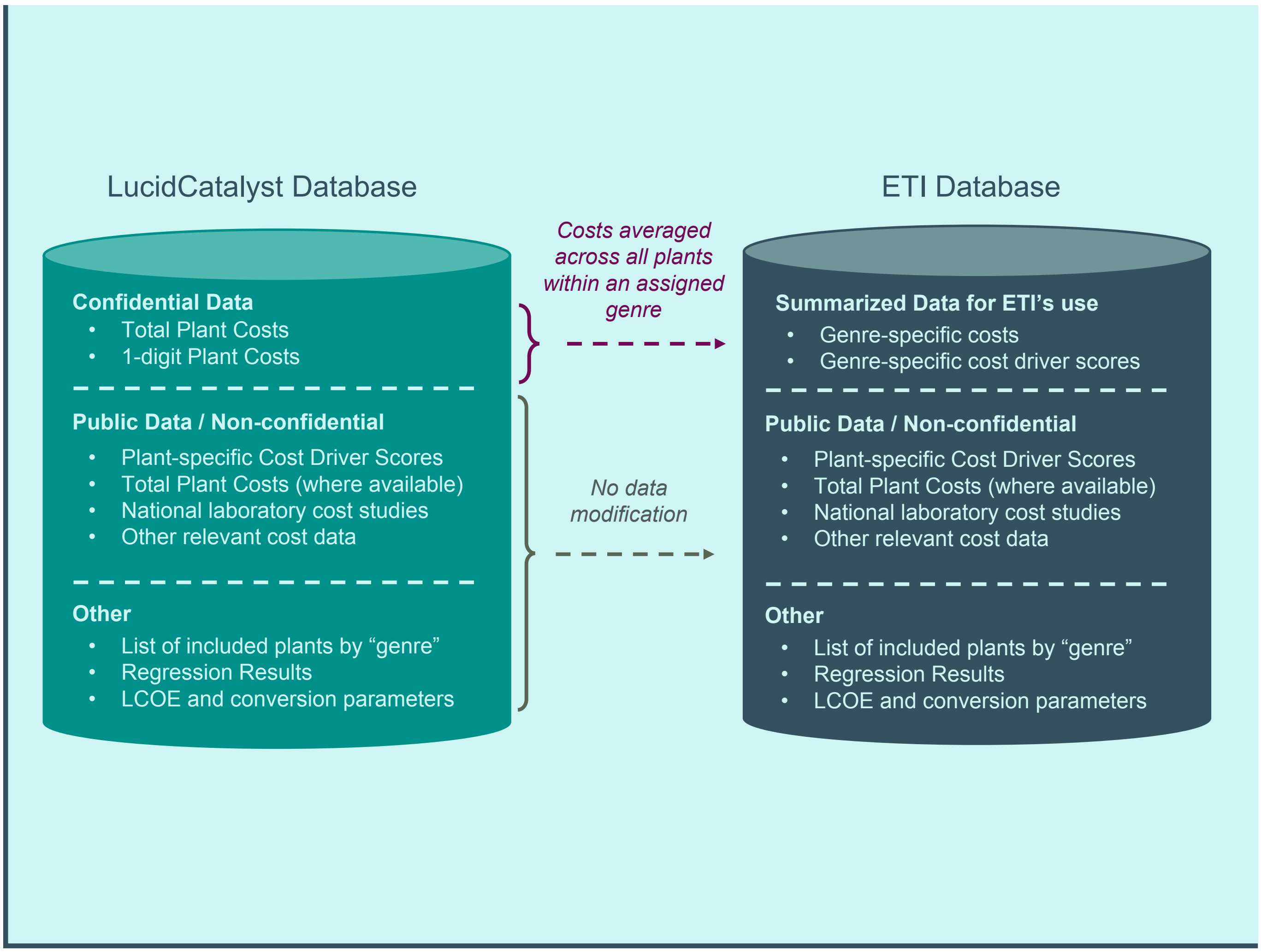
The "genre" concept serves two purposes. First, genres are fundamental features of the cost model (described in further detail in Section 3.5). Second, by reflecting averages across multiple plants, confidential data is transformed and effectively anonymised while the common characteristics and experience of a subgroup of plants are preserved.

3.1 ETI Cost Database

3.1.1 Overview

To prevent unauthorised disclosure of confidential proprietary information, there is a "LucidCatalyst" version of the database and an "ETI" version. The "LucidCatalyst" version contains the confidential information received from interviewees on individual plants and is encrypted with a password. The "ETI" version excludes all confidential information by removing plant-specific tabs and using watermarks in relevant cells of summary tables. The two versions contain full information on genres, which is non-confidential. Each database is a Microsoft Excel spreadsheet with effectively the same structure. The "LucidCatalyst" database, including confidential data, is only accessible by the project team. A subset of the database, excluding confidential data but including genre summaries, constitutes the "ETI" database, as shown in Figure 9 below.

Figure 9. **Overview of Stored Data in the LucidCatalyst and ETI Databases**



3.1.2 Data Collection for Existing and Ongoing Nuclear Projects

The project team entered costs and driver scores from expert interviews for each conventional nuclear project in the Cost Database. Each plant has an individual tab containing its cost data, plant indicator details underlying the cost driver scores, and the source(s) of this information. The tab labelled "Plant Data" provides a summary matrix of all information from the individual plant tabs. The process for converting conventional nuclear plant information into genre summaries is described below.

If company participants were unable to provide cost information within the time constraints for this study, the project team relied on public cost information from Lovering et al. (2016).[1] This source provides overnight costs for nuclear plants in various countries based on Lovering et al.'s interactions with power plant companies and corroboration with government information. The project team added IDC to the overnight costs in this source using the methodology described above.

All cost information in the Cost Database for conventional projects is non-confidential because it comes either from public sources, interviewees who granted use to the ETI through signed agreements, or Lovering et al. (2016) and the Breakthrough Institute who also granted use to the ETI. The cost driver scores for conventional nuclear projects are also non-confidential because the project team developed them in consultation with company interviewees and the expert advisors for this study. Thus, all cost and driver information on conventional nuclear projects is non-confidential and is included in the ETI Cost Database.

3.1.3 Data Collection for SMRs and Advanced Concepts

The project team captured estimated costs and cost driver scores for SMRs and advanced nuclear concepts based on in-depth interactions with developers. Confidentiality is particularly critical for these SMR and advanced nuclear developers as they move toward commercial projects. Several of the developers granted use of their information to the ETI through signed agreements, but others chose to withhold information. Some cost information is therefore excluded from the ETI version of the Cost Database. Cost driver scores for SMRs and advanced concepts, are non-confidential (as with conventional nuclear projects) because the project team developed them in consultation with company interviewees and the expert advisors for this study.

Advanced Reactor and SMR Costs vs. Historic Costs from Operational Plants

It is important to note that costs and scores for advanced reactor concepts and SMRs reflect projects that have not yet been built. Aside from the Japanese HTTR, these costs are projected estimates for NOAK plants, which assume a relatively standardised design that reflects learnings from multiple, previous builds. Providing NOAK estimates is useful in understanding whether these concepts are likely to be cost competitive. However, today, most of these reactor designs are unlicensed and no company has gone through the process of building a commercial demonstration or FOAK plant. In the ETI database, it is important to distinguish between these forecasted costs and actual costs obtained from completed and operational plants (most, of which, have been refuelled multiple times).

1 The organisation with ownership of this cost information, Breakthrough Institute, affirmatively granted permission to the Project Team to use the data and include it in the ETI Cost Database.

3.1.4 Consistent Currency Values

Cost information sources using US dollars from previous years were inflated to 2017 dollars using the historical Consumer Price Index (US Bureau of Labor Statistics, 2018). The cost sources using historical dollars were Lovering et al. (2016) and US national energy laboratory reports on nuclear plant designs: Oak Ridge National Laboratory (1980, 1986) and Idaho National Laboratory (2012).

Three cost sources used a different currency than the US dollar. Cost information for Sizewell B and Nuclear Electric's proposal for Sizewell C was expressed in 1992 British pounds. These costs were converted to 2017 US dollars by first converting pounds to dollars at the 1992 exchange rate (1.77 US dollars per pound using Bank of England data) and then inflating from 1992 dollars to 2017 dollars. Cost information for the SMR genre (Atkins, 2016) was expressed in 2015 pounds. These were converted to dollars at the 2015 exchange rate of 1.47 and then inflated to 2017 dollars. Cost information for the High Temperature Experimental Test Reactor in Japan was expressed in 2017 yen. These costs were converted to 2017 US dollars at the 2017 exchange rate (117 yen per dollar using US Government data).

3.2 Summary Table of Cost Driver Findings

Table 5 below summarises study findings by cost driver. The columns show unit characteristics for each score from -2 to +2 based on the expert interviews. They also show the distribution of units assigned each score for each cost driver. As the table demonstrates, each of the eight cost drivers fully captured a wide range of unit characteristics, and virtually every "bin" (possible score for each driver) contained at least one unit.

Table 5. **Summary of Cost Driver Findings**

SCORE >>	-2	-1	0	+1	+2
Vendor Plant Design	15 units	8	1	4	5
	Simpler design, NOAK in that country, high degree of design reuse, minimal site-specific design required (nth unit on same site)	Some design reuse, some site-specific design required	NOAK, low degree of design reuse, 5 million man hours ($850M) for design	FOAK in that country	Complex plant, FOAK, >10 million man hours (~$1.5B) for design
Equipment and Materials	11 units	15	2	1	4
	Low cost materials environment AND highly cost Optimised use of materials	Low cost materials environment	US materials costs and benchmark level of materials and equipment use	More complex equipment and or higher materials use than the benchmark	Expensive materials environment, High nuclear cost premium, high percentage of 'nuclear grade' materials and equipment

SCORE >>	-2	-1	0	+1	+2
Construction Execution	18 units	9	1	1	4
	No rework, short construction schedule (40 month), experienced construction management, balancing of labour between multiple projects	50-month schedule	Medium construction schedule (60 months), no delays to final delivery	Longer (72+ months) construction schedule but on time delivery (<12 months delay)	Long construction schedule (84+ months) significant rework, significant schedule delays (> 12 months)
Labour	12 units	15	0	4	2
	Low cost AND highly productive labour	Low cost OR highly productive labour	$50/hour, 20 million man hours for direct construction, 10 million man hours for indirect	Higher rates OR lower productivity (more man hours)	Higher labour rates than benchmark AND more man hours
Project Dev. and Governance	17 units	8	2	3	3
	Experienced developer/ owner, well-designed and proven contracting structure, no lawsuits, strong project oversight, Efficient decision making, strong leadership	Some, but not all of the -2 drivers	No major problems caused by the Project Developer and Project Governance	Some, but not all of the +2 drivers.	Inexperienced developer/owner, problematic contract structure, lawsuits between project participants
Political & Regulatory Context	14 units	10	0	9	0
	Regulator experienced with design and construction of that plant, no delays due to regulator intervention	Some, but not all of the -2 drivers	Not applicable – no units	Some changes required by regulator after construction starts, political ambivalence towards project	Not applicable – no units
Supply Chain	17 units	10	1	1	4
	Efficient supply chain, experienced with the plant design and meeting quality and regulatory requirements	Some, but not all of the -2 drivers	No significant delays caused by supply chain	Some, but not all of the +2 drivers.	Significant delays and rework required due to supply chain, failure to meet regulatory and quality requirements

3.3 Regression Results

The project team performed the regression on completed plants and those that are planning to commission relatively soon (note that the regression excludes SMRs and advanced concepts because their costs remain uncertain until actual plants are built). Table 6 below presents coefficient values for each cost driver as they relate to Capitalised costs sorted by impact. These values represent the expected increase in Capitalised cost per kW for a one-unit increase in the cost driver score. The implications of these regression results are discussed in Section 6 and in the Conclusions and Recommendations sections.

Table 6. **Coefficients for Cost Drivers related to Capitalised Costs**

Cost Driver	Coefficient Value
Supply Chain	669*
Labour	550*
Project Governance and Project Development	527*
Construction Execution	345
Political and Regulatory Context	136
Equipment and Materials	116
Vendor Plant Design	98
Constant	6,660

* Denotes statistical significance

3.4 Plant Genres

As discussed above, plant-specific information in the Cost Database, including confidential information in some cases for SMR and advanced concepts, was converted to non-confidential summary information by genre for the Cost Model. In the Cost Model, each genre has capital expenditure (CAPEX) and operating expenditure (OPEX) components at the 1-digit level as well as an average score for each cost driver category. This summary information, in combination with the regression coefficients, enables users of the Cost Model to estimate costs for any genre based on alternative values for cost driver scores, as described further below.

This section describes the methodology for developing genre summary information for conventional nuclear plants, SMRs, and advanced concepts. Additional details are provided in Appendix C.

3.4.1 Conventional Nuclear Plants

To convert plant information for conventional nuclear plants into genre summaries (divided into Europe/ North America or Rest of World) for the Cost Model, the project team calculated average costs and average driver scores among the plants. Average cost results for conventional nuclear projects appear in Section 5, with additional cost and driver score details in Appendix C.

3.4.2 SMRs and Advanced Concepts

For SMRs and advanced nuclear concepts, it was especially important to develop representative and realistic information by genre without revealing confidential data. The project team first reviewed CAPEX and OPEX estimates from US and UK government-supported reports on SMR and advanced nuclear concepts. The Team then adjusted the CAPEX and OPEX estimates from the government reports for alignment with the average of cost estimates from advanced nuclear developers. The tab labelled "Generic Cost Summary" in the Cost Database shows the scaling of advanced genre cost components for approximate alignment with company information. Driver scores for the SMR and advanced genres reflect averages among the relevant concepts. Appendices to this report provide details on the SMR and advanced nuclear concepts comprising each genre and the methodology for developing genre summary values. Average cost results for SMR and advanced nuclear genres appear in Section 5, with additional cost and driver score details in Appendix C.

3.5 ETI Cost Model

To make the captured data more useful to the ETI, the project team built an ETI Nuclear Cost Drivers Model. The model allows ETI Members and other authorised users to understand the cost impacts of cost driver settings for hypothetical plants. The model holds no confidential information and like the database, was built in Microsoft Excel.

The main model feature is an interactive "Dashboard" (shown in Figure 10 on the following page), which allows users to load plant genres and adjust cost driver assumptions to see how they affect overall cost.

Figure 10. **Screenshot of Interactive ETI Cost Model Dashboard**

Cost Model Dashboard

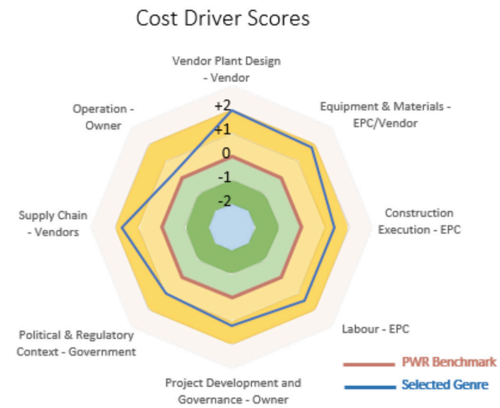
Select genre --> Conventional in Europe / North Am

Scenario name --> Example scenario name

Save Scenario to Archive

Cost Estimates Based on Cost Driver Settings (Below) and Regression Coefficients

			Reference US PWR	Conventional in Europe / North Am		
				Representative Cost	Change from Represent. Cost	Updated Cost With Change
Capital	10s	Preconstruction Costs	$133 /kW	$178 /kW	-	$178 /kW
Capital	20s E	Direct Construction Costs: Equipment	$1,006 /kW	$1,345 /kW	-	$1,345 /kW
Capital	20s M	Direct Construction Costs: Materials	$292 /kW	$391 /kW	-	$391 /kW
Capital	20s L	Direct Construction Costs: Labour	$957 /kW	$1,279 /kW	-	$1,279 /kW
Capital	30s	Indirect Services Costs	$2,512 /kW	$3,357 /kW	-	$3,357 /kW
Capital	40s	Owner's Costs	$715 /kW	$956 /kW	-	$956 /kW
Capital	50s	Supplementary Costs	$79 /kW	$105 /kW	-	$105 /kW
Capital	60s	Financing During Construction	$1,175 /kW	$2,776 /kW	-	$2,776 /kW
Capital		**Total Construction Costs**	$6,870 /kW	**$10,387 /kW**	-	**$10,387 /kW**
Capital		**Levelised Construction Costs**	$59 /MWh	**$89 /MWh**	-	**$89 /MWh**
Operating	70s	O&M Costs	$21 /MWh	$14 /MWh	-	$14 /MWh
Operating	80s	Fuel Costs	$7 /MWh	$10 /MWh	-	$10 /MWh
Operating	90s	Financing During Operation	$0 /MWh	$0 /MWh	-	$0 /MWh
Operating		**Total Operating Costs**	$28 /MWh	**$25 /MWh**	-	**$25 /MWh**
		Levelised Cost of Electricity	$87 /MWh	**$114 /MWh**	-	**$114 /MWh**



Cost Driver Settings

	Reference US PWR	Conventional in Europe / North Am		
		Representative Value	Cost Driver Sliders	User's Updated Value
Vendor Plant Design - Vendor	0.0	+2.0		+2.0
Equipment and Materials - EPC/Vendor	0.0	+1.8		+1.8
Construction Execution - EPC	0.0	+1.4		+1.4
Labour - EPC	0.0	+1.4		+1.4
Project Development and Governance - Owner	0.0	+1.2		+1.2
Political and Regulatory Context - Government	0.0	+1.0		+1.0
Supply Chain - Vendors	0.0	+1.7		+1.7
Operation - Owner	0.0	+0.4		+0.4
Average	0.0	**+1.4**		+1.4

Cost driver settings can range from -2 (significant cost reduction) to +2 (significant cost increase); 0 corresponds to PWR Reference

Click on scroll bar arrows to adjust cost driver settings

3.5.1 Using the Dashboard

The dashboard has five primary components – genres, cost values, cost driver sliders, a radar chart, and a scenario archive button. Users first select their genre of interest from the seven genres outlined above. This immediately prompts other cells on the dashboard to repopulate with information for the selected genre.

Cost values on the dashboard reflect each genre's default costs from averaging the relevant plants in the database file. Costs are presented at the one-digit level with separation between capital costs and operating costs. The first column of cost values relates to the PWR Reference plant as a benchmark for comparison. Subsequent columns relate to the selected genre's default cost values and then the updated cost values based on the user's adjustments to individual cost driver settings. The underlying formulas for updating cost values from driver settings rely on the regression coefficients on a later tab.

The lower half of the dashboard shows cost driver settings for the PWR Reference plant and the selected genre. When users select a new genre at the top, the cost driver settings at the bottom refresh automatically. Each cost driver has an adjustable slider, which changes the cost driver score in intervals of 0.1 within the range from -2 to +2. These sliders allow users to set custom driver scores for their hypothetical plant within the selected genre. The cost formulas in the upper panel of the dashboard multiply these customised cost driver settings by the regression coefficients to update cost estimates for the hypothetical plant under consideration.

The radar chart in the upper right of the dashboard compares cost driver settings for the PWR Reference plant and the selected genre by referring to the updated driver settings in the lower right of the tab. The radar chart contains eight spokes, each corresponding to a cost driver. Concentric rings correspond to the -2 to +2 scoring range, with the PWR benchmark denoted as a red ring with all cost driver settings at 0. The blue ring changes position as the user adjusts the cost driver scores. The user sees from the radar chart that cost driver settings within the red ring (with scores below 0) tend to reduce costs relative to the PWR Reference plant, while settings outside the red ring (with scores above 0) tend to increase costs relative to it.

The scenario archive button at the top of the dashboard allows the user to save the inputs and results from a genre analysis on a separate tab labelled “Scenarios Archive”. Users can enter a scenario name in the cell to the left of the scenario archive button to designate different runs on the archive tab.

4 Case Studies

This section presents short case studies on nuclear plants and concepts that illustrate key relationships between costs and drivers (Appendix B includes unabridged versions of these case studies). The case studies provide illuminating details on the reasons for wide variation in nuclear cost values around the world, and offer important lessons on potential strategies to pursue, as well as pitfalls to avoid, for new nuclear build in the UK or elsewhere. The project team worked closely with company executives and other knowledgeable experts to develop a complete picture of each plant or concept among the case studies, identify the principal causes behind their high or low costs, and highlight the most useful implications for future contexts. The case studies include historical nuclear projects, a previously planned project, ongoing projects, and innovative concepts in development.

Table 7 on the following page presents an overview of the nuclear projects and concepts discussed in the case studies. The project team selected them from the many projects and concepts in the ETI Cost Database because they span a wide range of technologies, costs, driver scores, experiences, and lessons. Green circles in the table's cost driver columns denote positive factors associated with low costs, while maroon circles denote negative factors associated with high costs.

Following Table 7 are subsections showing the costs and driver scores for the various case studies, along with brief summaries of experiences and lessons for each. Additional details on each case study, with source citations, are provided in Appendix B.

Table 7. **Case Study Overview**

Case Study	Country	Vendor Plant Design	Equip. and Materials	Constr. Execution	Labour	Project Dev. and Gov.	Pol. and Reg. Context	Supply Chain	Oper-ation
Sizewell B and Nuclear Electric's Proposal for Sizewell C	UK	●	○	●	○	●	●	●	○
Barakah	UAE	●	○	○	●	●	○	○	○
Vogtle	US	● (−)	○	○	○	● (−)	○	● (−)	○
Rolls Royce SMR	UK	●	○	●	●	○	○	○	○
JAEA HTTR	Japan	●	○	○	●	●	○	○	○
Generic MSR	Various	●	●	●	○	○	○	●	●
Offshore Wind	UK	●	●	●	○	○	○	●	●

● – Positively influences Driver ● (−) – Negatively influences Driver ○ – Less Relative Significance

4.1 Sizewell B and Nuclear Electric's proposal for Sizewell C (Operational; Proposed)

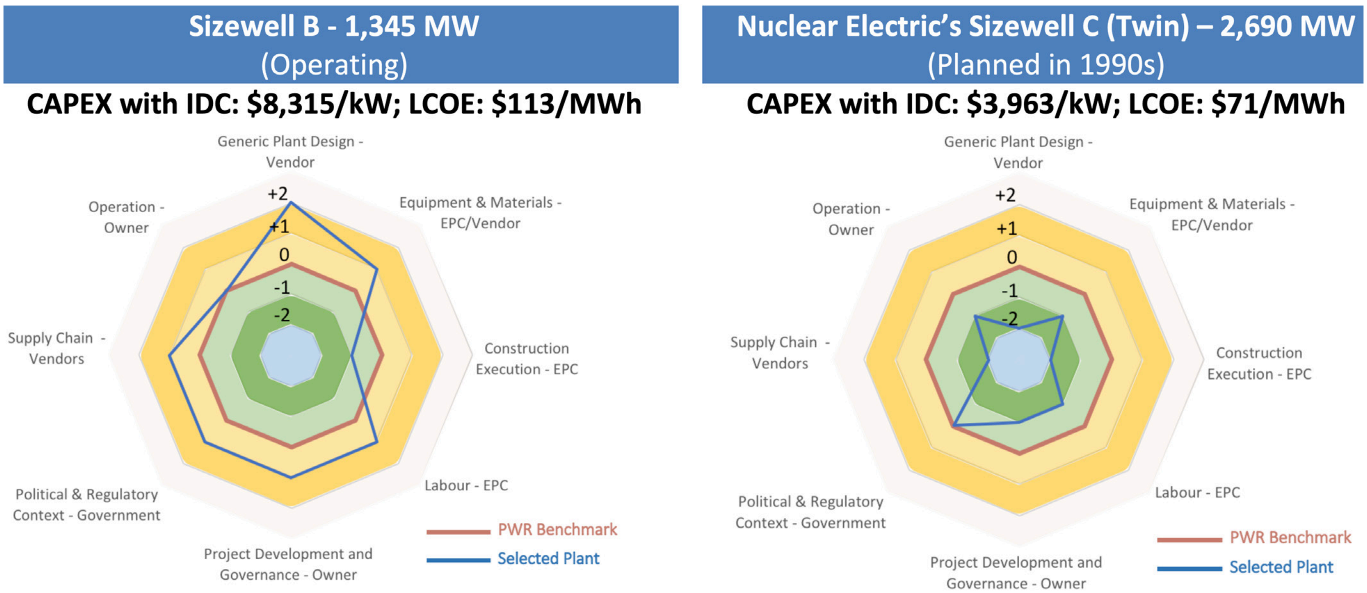
Important Finding: All low-cost projects have built multiple units on a single site enabling maximum learning for cost reduction, shared use of infrastructure, shared operational facilities, and more organised and efficiently-timed construction to optimise the use of labour and project management resources.[1] The factors that make a project expensive can all be improved during a second project. The Sizewell case study clearly demonstrates how much cost reduction is possible by improving multiple drivers.

Sizewell B was the first power generation PWR in the UK and the most recent nuclear plant built in the country (1989-1995). It was a successful FOAK project and avoided significant schedule delays and cost overruns. The developer/owner, Nuclear Electric, planned a subsequent unit Sizewell C ("NE's Sizewell C") in the 1990s, but it was not built. Costs for Sizewell B includes some very high first-of-a-kind expenses for the project, such as plant design, software, and interest during construction.[2] NE's Sizewell C shows potential cost reductions from a coordinated and planning multi-unit construction. Reusing the design, primary contractors, and suppliers from Sizewell B for NE's Sizewell C, planned in both single and twin configurations, would have lowered costs significantly for software (over $1,000/kW savings), nuclear steam supply system (over $750/kW savings), civil works (over $250/kW savings), and controls

1 Reflecting the high cost of working capital, construction of a second unit is sometimes deferred to allow revenues from the first unit (when operational) to defray some of the working capital needs for the second unit.

2 Although the owner of the plant did not explicitly borrow money for the construction of the plant, the team used our proxy for 7% to make the conditions and reported costs similar to current practice in the UK.

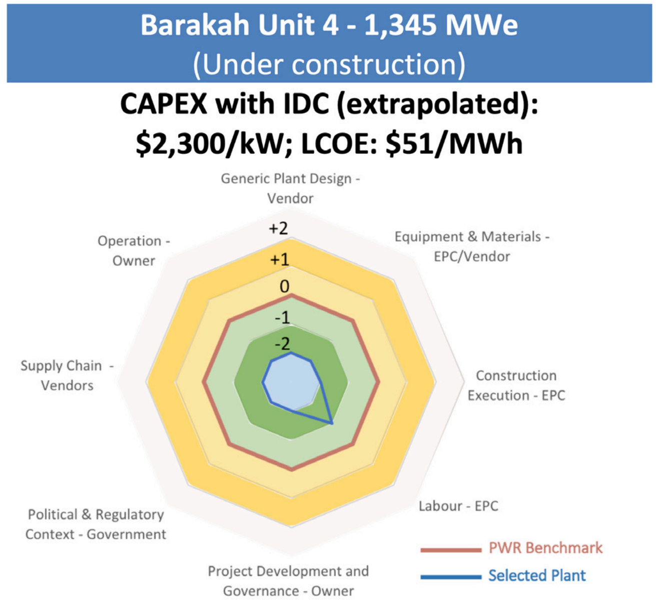
and instrumentation (over $180/kW savings). In addition, there were significant learnings that enabled a much shorter construction schedule. By building two units in 51 months vs. one unit in 76 months for Sizewell B, the twin configuration would have cost less than $4,000/kW, according to detailed estimates from the planning process in the 1990s, by sharing designs, buildings, systems, and staff across the units.



Cost Driver	Experience
● Vendor Plant Design	Sizewell B uses a basic PWR design from two previous plants in the United States with additional safety features for licensing in the UK. NE's Sizewell C would have largely reused the blueprints for Sizewell B, but with 25% reductions achieved in concrete and steel quantities due to structural and site efficiencies.
● Construction Execution	Sizewell B's construction period of 78 months was only 4 months beyond the planned timeline. The planning team for NE's Sizewell C developed a detailed construction schedule with total duration of 54 months, a 31% reduction from Sizewell B.
● Project Governance and Project Development	Sizewell B's PWR Project Group was an integrated delivery organisation that supported every aspect of the project, from the project management office to the engineering, licensing, quality control, quality assurance, and commissioning. Consolidating all these functions, responsibilities, and authorities under one organisation streamlined many processes and enabled short lines of communication.
● Political & Regulatory Context	Sizewell B received substantial attention and support from the UK government as the first PWR in the country and sole nuclear plant under construction at that time. Nuclear Electric managers made timely submissions to the regulators and worked with them to resolve problems quickly.
● Supply Chain	Sizewell B has a slightly worse score than the benchmark for supply chain because the switch from gas-cooled reactors to a PWR required many adaptations among vendors.

4.2 Barakah 1-4 (Partially Complete)[3]

Important Finding: The benefits of Barakah's multi-unit project include (but are not limited to) shared site infrastructure, one mobilisation effort (not separate or requiring of stop/start mobilisation), bulk purchasing, and having the same contracts and overhead. Multiple learning effects enabled continual improvements in efficiency and productivity from unit to unit. The project also reinforces the need to have an effective owner in addition to a proven strong vendor.



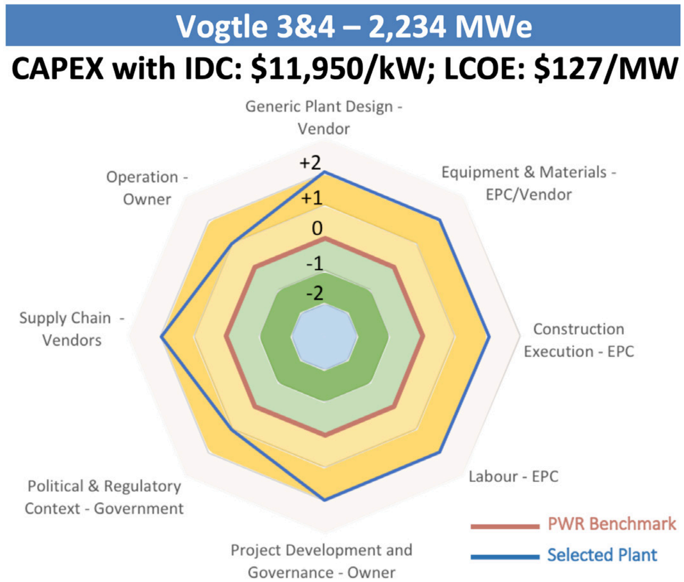
Emirates Nuclear Energy Corporation (ENEC) signed a contract in December 2009 with Korean Electric Power Corporation (KEPCO) as the head of a Korean consortium to build four APR-1400 units at the Barakah site in the UAE. KEPCO has extensive experience in nuclear construction along with its consortium partners through Korea's fleet programme, building 17 plants since the 1990s. The turnkey contract for the Barakah project had a total price of $20.4 billion, including funding for construction of a port facility and other project infrastructure. The total price indicates an average cost across the four units of $3,700/kW. Early units have higher costs and later units have lower costs through both multi-unit efficiencies and learning effects. (The figure shown here relates to Unit 4.).

Cost Driver	Experience
● Vendor Plant Design	The UAE selected the KEPCO consortium partly because of successful recent projects in Korea. The UAE did not want to experiment with an unproven design or one with a less successful track record.
● Labour	KEPCO management was very committed to winning the UAE contract. There is a focus on key goals and incremental improvement among KEPCO's top executives. The consortium has adjusted shift systems to enhance efficiency.
● Project Governance and Project Development	Barakah's success is tied directly to the way the RfP was structured and carried out. The bidding process was intentionally designed to avoid as many of the past mistakes as possible. The KEPCO consortium shows the value of clear responsibility and authority under the prime contractor.

3 As of March 26, 2018, Unit 1 was complete; Unit 2 was 92% complete; Unit 3 was 81% complete, and Unit 4 was 67% complete (World Nuclear News, 2018).

4.3 Vogtle 3 & 4 (Under Construction)

Important Finding: Vogtle 3 & 4 reflects how cost can quickly escalate when cost drivers are poorly managed or reflect contextual factors (e.g. lack of readied supply chain, slow pace of the regulatory interactions, expensive regulator billing rate, etc.) that can present intractable burdens on the project.



Georgia Power Company (GPC) is currently building two additional reactors at the Vogtle plant. Vogtle 3 & 4 are the first Westinghouse AP1000 PWRs in the United States and the country's first new nuclear projects in three decades (the recently completed Watts Bar 2 project began construction in the 1980s). Partly because of their FOAK status, the units have suffered numerous setbacks in the ten years since GPC requested approval from the Georgia Public Service Commission and the US Nuclear Regulatory Commission. The expected cost in the initial plans from 2008 was $6,400/kW, and the expected completion year for Unit 3 was 2016 (about 5 years after pouring the first nuclear concrete), followed by Unit 4 in 2017. The approval process and initial site work went slower than expected, significant regulatory interventions delayed the project, notably requiring redesign of the aircraft impact protection structure and further problems arose with construction of the large concrete structures. The latest estimates put the cost at $11,950/kW and completion in 2021-2022. As the two most costly projects in the ETI Cost Database, the Vogtle units have scores of +2 in six cost driver categories.

Cost Driver	Experience
● Vendor Plant Design	NRC design approval was delayed by 11 months and the construction licence was delayed by 8 months. The construction team has submitted more than 60 license amendment requests to the NRC since receiving the licence in 2012.
● Project Governance and Project Development	Georgia Public Service Commission staff concluded in a draft order that "the Project has not been effectively managed, and it is apparent that there has never been a realistic, and therefore achievable, fully integrated schedule for the Project." Governance problems at Vogtle stem largely from the complex contract in 2008 between GPC and a consortium led by Westinghouse. As costs mounted for the project and major lawsuits loomed over the contract parties, Westinghouse acquired one of the consortium members (CB&I) but continued to face financial hardship, ultimately declaring bankruptcy in 2017.
● Supply Chain	Although the AP1000 design incorporates modularity and simplified systems, off-site submodule fabrication also pointed up significant supply chain issues. These supply chain problems show the obstacles to successful FOAK projects, particularly when the country lacks experienced nuclear construction workers and equipment vendors after a long period of inactivity.

4.4 Rolls-Royce SMR (Unbuilt; Design in Commercial Development)

Important Finding: Rolls-Royce's SMR design demonstrates that many of the risk and cost centres of conventional nuclear can be "designed out" during the plant design phase and radical evolutions in the delivery process are possible.

Rolls-Royce is continuing to develop its design for a small, modular, Gen III+ PWR with a power rating between 400 – 450 MWe. The design includes multiple, advanced passive safety systems and reflects a comprehensive understanding of the broad range of risks and challenges faced by conventional approaches to nuclear plant delivery. In addition to their primary focus of reducing LCOE, the company has intentionally incorporated several "down-stream" considerations into the design process such as: ease of plant licensing, manufacturability, design reuse, reduced construction scope, optimised inspection and QA, operation, and decommissioning, and ease of accessing commercial financing. The SMR design significantly reduces or avoids major cost and risk centres associated with stick-built construction approaches.

Cost Driver	Experience
● Vendor Plant Design	Rolls-Royce is "productising" a nuclear power station (i.e., designing something that can be produced repeatedly with little to no modification), which represents a dramatic departure from the traditional "project-based" approach. Their plant design reflects every effort to "design out" or minimise major cost and risk centres whilst Optimising for LCOE. Every plant component (including the reactor itself) is small enough to enable standardisation and modularisation across the entire power station. Modules can be transported to the site by road, rail, or sea, which supports the company's aspirational target of a 500-day build schedule.
● Construction Execution	Rolls-Royce's plant delivery approach includes two, distinct work phases. The first phase includes all the required civil works and construction of a foundation slab equipped with an aseismic bearing pad. The aseismic bearing pad "neutralises" the seismic and thermal loads of the region. Solving for the local geologic and geographic constraints enables the plant (sitting atop this foundation) to be highly standardised. The second work phase includes all other construction activities through COD and is performed under a purpose-built, site construction canopy that provides protection from the environment (and vice versa). The controlled and protected working area allows for 24/7 working conditions (such as those achieved in China) and dedicated teams that can bring learning from one power station to another.
● Labour	In replacing onsite labour with offsite module manufacturing, Rolls-Royce allows for much greater overall productivity, controlled environments for higher and more consistent quality, greater opportunities for learninf effects by dedicated teams, cost control, as well as the avoidance of expensive, one-off components. Members of Rolls-Royce's project consortium have reported man hour reductions >40% on actual, albeit non-nuclear, construction projects through modularisation and offsite manufacturing.

4.5 Japan Atomic Energy Agency's High Temperature Engineering Test Reactor (Test Reactor; Design in Commercial Development)

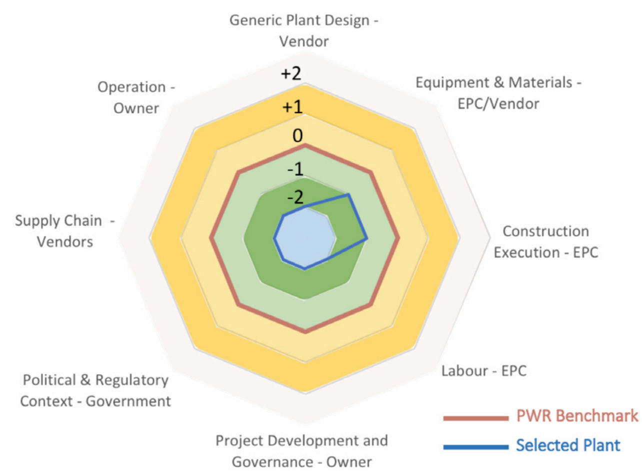
Important Finding: Japan's HTTR, a prismatic high temperature gas reactor, shows the near-term viability of an advanced nuclear concept, which is projected to be low cost due to a comprehensive, multi-year focus on cost reduction.

The Japan Atomic Energy Agency (JAEA) has been developing high temperature gas reactor technology. To that end, it built a 30MWt High Temperature Engineering Test Reactor (HTTR) in 1998 and have been performing tests and developing technology ever since. Concurrent R&D work has demonstrated key components of a complimentary helium-based gas turbine technology that allows a more efficient and lower cost Direct Cycle power generation system and other cogeneration applications such as desalination, high-grade industrial heat, and a highly efficient thermal energy to hydrogen production process based on the Sulphur-Iodine process. It should be noted that the 275 MW reactor (assumed here) has not been built yet and the HTTR's costs and driver scores are less certain than the costs and scores for historical and ongoing plant projects.

JAEA HTTR – 1,100 MWe (4 x 275 MWe) (Under Development)

CAPEX with IDC: $2,687/kW

LCOE: $41/MWh

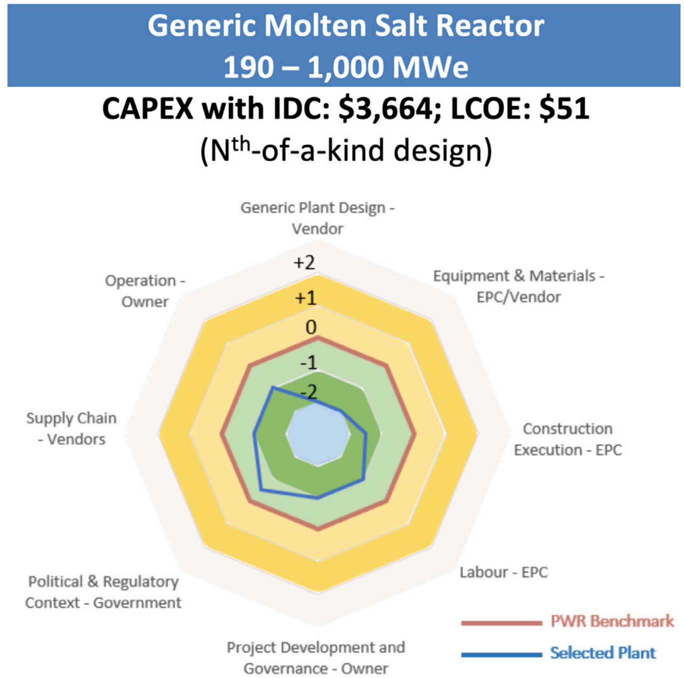


Cost Driver	Experience
● Vendor Plant Design	JAEA's HTTR technology is estimated to be more cost-competitive than most other commercially-available nuclear technologies. These economics can be further improved by the cogeneration applications being pursued by JAEA.
● Equipment and Materials	The HTTR technology platform has validated key aspects of its complementary, helium Direct Cycle gas turbine power generation system, which is significantly simpler and cheaper than a comparable steam turbine power cycle. This also increases efficiency from a typical rating of 33% typical of Light Water designs to 45-50%. This has the effect of lowers CAPEX/kW by increasing output by approximately 40%. OPEX is also reduced by increasing the output per unit of operating expense.

4.6 Generic Molten Salt Reactor (Unbuilt; Multiple Designs in Commercial Development)

Important Finding: The inherent benefits of using molten salt as the primary coolant (or combination of fuel and coolant) enables several transformative cost reduction opportunities.

Molten salt reactors are a class of advanced reactors that use molten fluoride or chloride salts as the primary reactor coolant and, often, the fuel itself. The high operating temperatures, low operating pressure, inherent safety, load following capabilities, and relatively low waste production offer several advantages over typical, light water reactors. As of spring 2018, there are at least 13 different companies and organisations developing molten salt reactor designs. While the safety and operating characteristics enable significant cost reduction opportunities, the reactor technology has not been licensed (although several companies are pursuing the licensing process in Canada.)



Cost Driver	Experience
● Vendor Plant Design	The reactor operates near atmospheric pressure, which dramatically reduces both the quantity of engineered safety systems as well as their specification (or classification). Such low operating pressures make an expensive pressure vessel unnecessary and the containment building can be held to much less strict design specification. Many MSR plant designs locate the reactor below the ground level. Without high pressure steam in the nuclear island, there is no need for the related equipment or engineering, which reduces overall construction complexity and cost. Many MSR designs have orders of magnitude smaller footprints than conventional reactors of the same power rating.
● Equipment and Materials	MSR plant designs are physically much smaller (and more power dense) than conventional plants and require less safety-grade materials (and components). This means that materials are not only less expensive, but the training, qualification, documentation, supply chain QA (and onsite component QA) is drastically reduced.
● Construction Execution	Most MSR designs are based on having a relatively high degree of factory – or shipyard-based production. This is intended to limit on-site construction and shorten construction schedules. Shortening the design and construction period leads to lower borrowing costs overall, and lower financing costs on the borrowed amount.
● Operations	Continuous refueling capability, fewer required reactivity controls, fewer components and moving parts that require servicing, simpler reactor control systems, and conventional power generation system (less onerous and costly to operate and maintain) lowers operating costs.

4.7 Offshore Wind

The offshore wind industry recently smashed expectations with astonishingly low prices: £57.50 per MWh for new build projects starting in 2022/23. This represents a halving of costs achieved in a five-year period, illustrating the power of innovation, collaboration, and drive. By identifying and demonstrating cost reduction across key areas including foundations, high voltage cables, electrical systems, access in high seas and wind measurement, the sector has transformed its overall performance on cost and delivery.

Technical routes to increase reliability and size have been examined and achieved. Nine MW turbines are already 190m high and need to get even higher. The optimum size will be as tall as the Shard and 15MW. In order to meet the required fleet size (30GW by 2035), offshore wind deployment must increase significantly from current levels: from one to two turbines per day, whilst moving towards higher power density. Current projects to 2023 / 2025 aim for 10GW installed capacity by 2022, equivalent to 110 turbines per year, at one per day. Future build aims for 30GW by 2035, delivering two per day.

Cost reduction efforts have been identified and achieved across design, delivery and deployment:

- **Design:** Economy of scale: 1600 turbines now delivered. Standardisation of design enabling non-recurring engineering costs to be absorbed by a much larger number of units.
- **Delivery:** Standardisation of components, including using existing kit from wider supply chain. Modularisation – capital cost to start manufacture is one tenth of the cost. Cost of operation and maintenance reduced. Lifetime extended from 20 years to 25 years.
- **Deployment:** With a range of fixed and floating foundations, the UK can optimise the offshore fleet.

Conclusion: The rising tide that lifts all boats. Learning from the success of the offshore wind industry suggests that in addition to design and delivery improvements, innovation through collaboration; cost and risk sharing across the public sector, supply chains and developers will be critical in realising strategic priorities for the nuclear sector. Such priorities include the need to tackle construction delay; cost over-runs; slow build rate; and high financing costs. A key feature of the off-shore wind sector transformation was a transition to modular build and factory-based assembly of mass-produced units that can be manufactured and shipped to sites for installation rather than custom-built, thereby speeding up delivery times and lowering direct and financing costs. Investment in engineering solutions that are subsequently standardised and deployed at scale enables non-recurring engineering costs to be absorbed across a higher number of units. Technological innovation has been coupled with a laser-like focus on accelerating commercialisation of new products, at scale, within rapid timescales.

5 Findings

A relatively small number of understandable factors drives the cost of nuclear plants. This finding reflects a high degree of consensus among the experts consulted.

This section describes the key differences between high cost and low cost nuclear construction, identifies important and consistent themes in both of these. This evidence is further supported by a series of Case Studies in Section 4, underpinning a series of recommendations for cost reduction opportunities transferable to the UK context in Section 6.

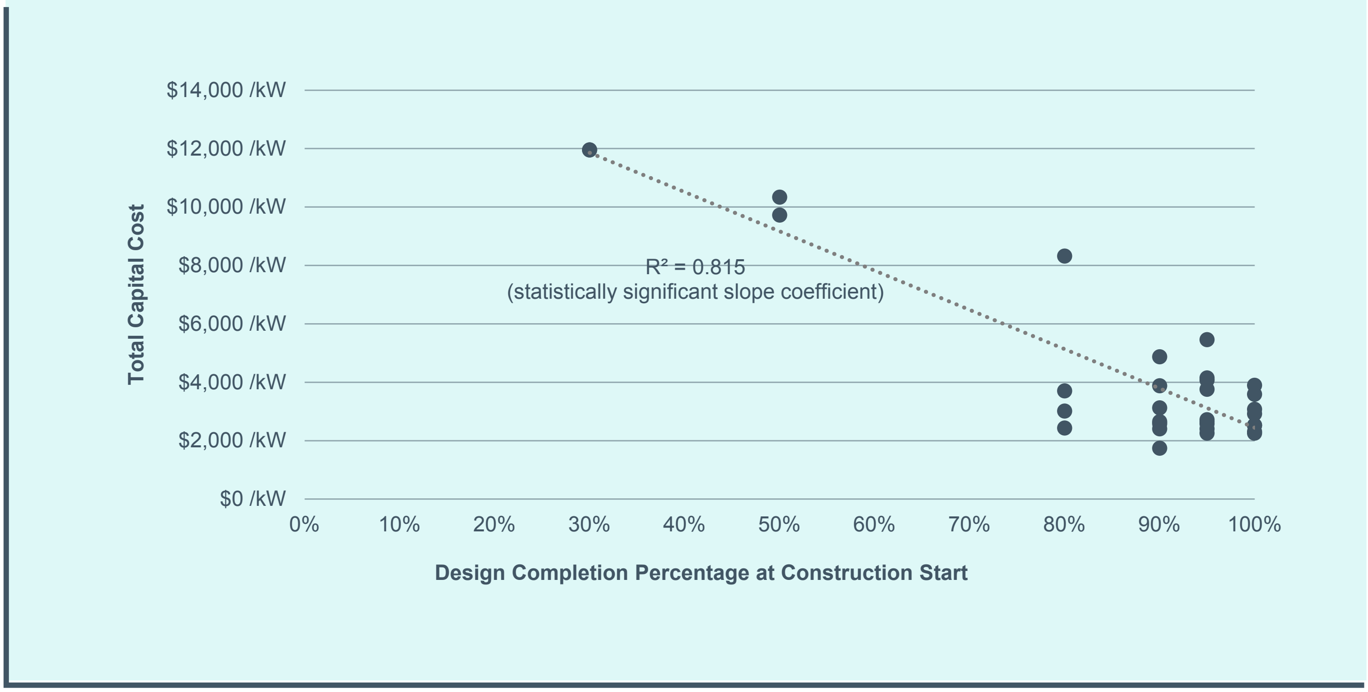
5.1 Detailed Design Completion as an Important Factor

Interviews with nuclear plant experts revealed that the degree of detailed design completion when construction began was one of the most important drivers of total capital cost.[1] As the project team conducted interviews and prepared case studies, a strong pattern emerged that high-cost projects had started with incomplete detailed designs, while low-cost projects had started after managers had finalised the full plant design and planned the construction project in detail.

The percentage of detailed design completion prior to construction is an indictor under the Construction Execution cost driver. As the study progressed, however, several interviewees and expert reviewers suggested giving more prominence to detailed design completion among the cost drivers and drawing out the implications for future nuclear construction in the UK or elsewhere. The project team therefore used information from the database to estimate detailed design completion at construction start for each unit. In Figure 11 on the following page, each unit is a dot showing detailed design completion and total capital cost, with a tight correlation across the dataset.

1 The level of plant design detail required by the regulator during the licensing/certification process is qualitatively different than the design detail required for actual construction. It is the latter that is so important to complete prior to starting construction.

Figure 11. **Detailed Design Completion Percentage and Total Capital Cost**



5.2 Genre Summary Results

As described in Section 3.4, genres represent reactors of a given technology and market: two for conventional reactor technologies (in Europe/North America or Rest of World), one for SMRs, and three for advanced reactor technologies. The included plants span a wide range of global nuclear project experiences. According to the World Nuclear Association (2018), 135 nuclear units have been built since 1990 in 19 countries. Some of these countries, such as Iran and Pakistan, are outside the practicable geographic scope for this study. Some others, such as Bulgaria and Argentina, are more open to UK/US researchers but have built only one unit in the relevant period, so they are also excluded. The three countries that have built the most units in recent decades – China, Japan, and South Korea – are well represented in the study's database. Other included countries are the UK, US, France, Finland, Russia, and UAE. Therefore, the 33 nuclear projects are well representative of the breadth of cost outcomes and are well-suited for identifying the most important drivers and lessons from historical and ongoing experiences. This section describes each genre, its cost provenance and distinguishing characteristics, first presenting conventional reactors and then SMRs and advanced concepts.

5.3 Conventional Plants

A total of 33 conventional nuclear plants are included in the ETI Cost Database – 25 pressurised water reactors (PWRs), 5 heavy water reactors, and 3 boiling water reactors (BWRs). The plants were categorised by those in "Europe/North America" and those projects in the "Rest of World" (ROW). A comparison of genre-specific CAPEX and LCOE (combining CAPEX per MWh and OPEX) are provided in the following figures. In the LCOE figure, base case results reflect an interest rate and discount rate of 7%, while the lower marker reflects rates of 6% and the upper marker reflects rates of 9%. The methodological assumptions used to calculate the cost breakdowns and a full presentation of the list of genre-specific plants, cost driver category scores, averaged Conventional plants in Europe and North America have an average driver score of +1.4, while conventional plants in ROW have an average of -1.4. Genre average scores for each driver are shown in Appendix C.

Figure 12. **Capitalised Cost Breakdown of Conventional Reactor Genres**

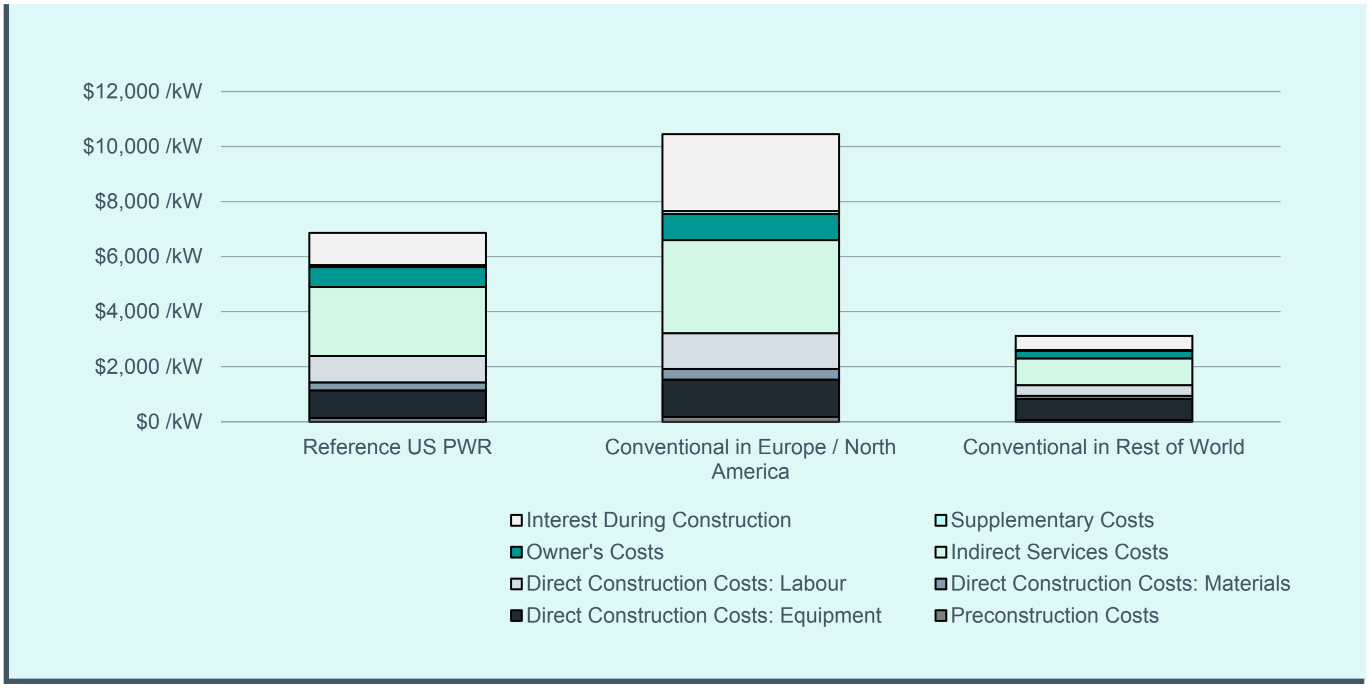
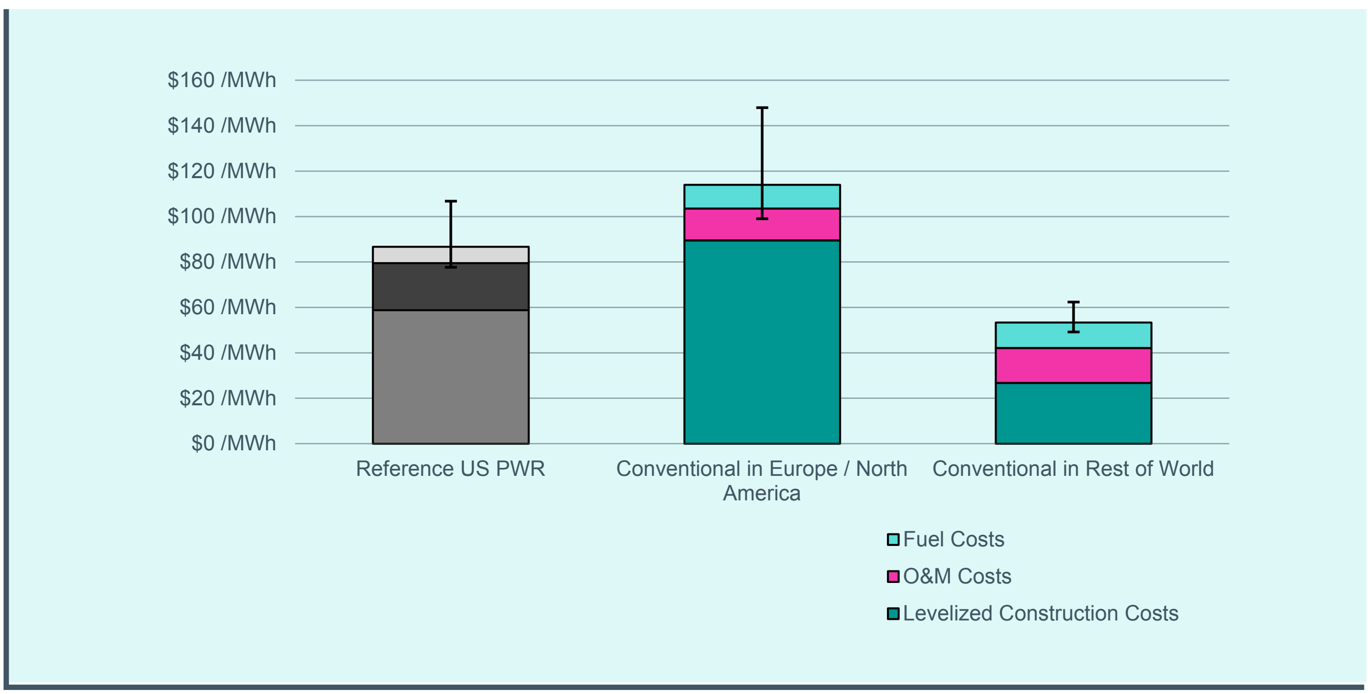


Figure 13. **LCOE for Conventional Reactor Genres**



Note: For the three LCOE figures in this section, base case results reflect an interest rate and discount rate of 7%; the lower marker reflects rates of 6%, and the upper marker reflects rates of 9%.

Several factors drive the cost differences between the Europe/North America and ROW genres. These are summarised by cost category in Table 8 below.

Table 8. **Factors Leading to Lower ROW Costs**

Cost Category		Rationale for Lower ROW Costs
	General Observations	National nuclear programmes have enabled sustained "learning effects"
10s	Preconstruction Costs	Significantly owner permitting costs; fewer regulations related to public interaction and compensation Less expensive land acquisition
20s	Direct Construction Costs	Equipment costs are very similar between genres Lower materials costs (much cheaper domestic concrete and steel) Dramatically lower construction labour wages and higher percentage of working hours on task Detailed construction planning process and ongoing QA reduces rework Less worker training required (with continuous construction from national programme) Experienced suppliers National programme develops and retains expertise
30s	Indirect Services Costs	Significantly lower labour wages for offsite/onsite plant design work and construction supervision Less overall design work as plants are much closer to detailed design completion at the start of construction Lower design costs (lower cost designers and more design reuse)
40s	Owner's Costs	Lower staff wages Significantly lower staffing levels for operation Less expensive staff housing and salary-related costs
50s	Supplementary Costs	Lower decommissioning costs Preferential tax policies and cheaper liability insurance due to state policy that dilutes owner liability among all nuclear projects, with the state as a back stop Less contingency required
60s	Financing During Construction	Much quicker build schedule (reducing interest during construction) Cheaper financing due to less perceived risk. Reducing risk perception results from a more predictable construction schedule and potentially state-backed financing or state-run EXIM banks (that typically have lower interest rates).

5.4 Alternative Cost Scenarios for Conventional Plant in Europe/North America

Table 9 below shows indicative cost estimates for a nuclear project in Europe or North America under various driver score and discount rate assumptions. The first row reflects the average driver score of +1.4 for this genre among European and North American plants in the database. In addition to the base case assumption of 7% interest and discount rate, the table shows levelised CAPEX and LCOE with 6% (leading to lower costs) or 9% (leading to higher costs). The second, third, and fourth rows of the table reflect improvements in project delivery that lower all driver scores to 0, -1, or -2. The table shows that reducing driver scores to -1 or -2 could reduce costs for a European or North American project significantly, especially when combined with low interest and discount rates.

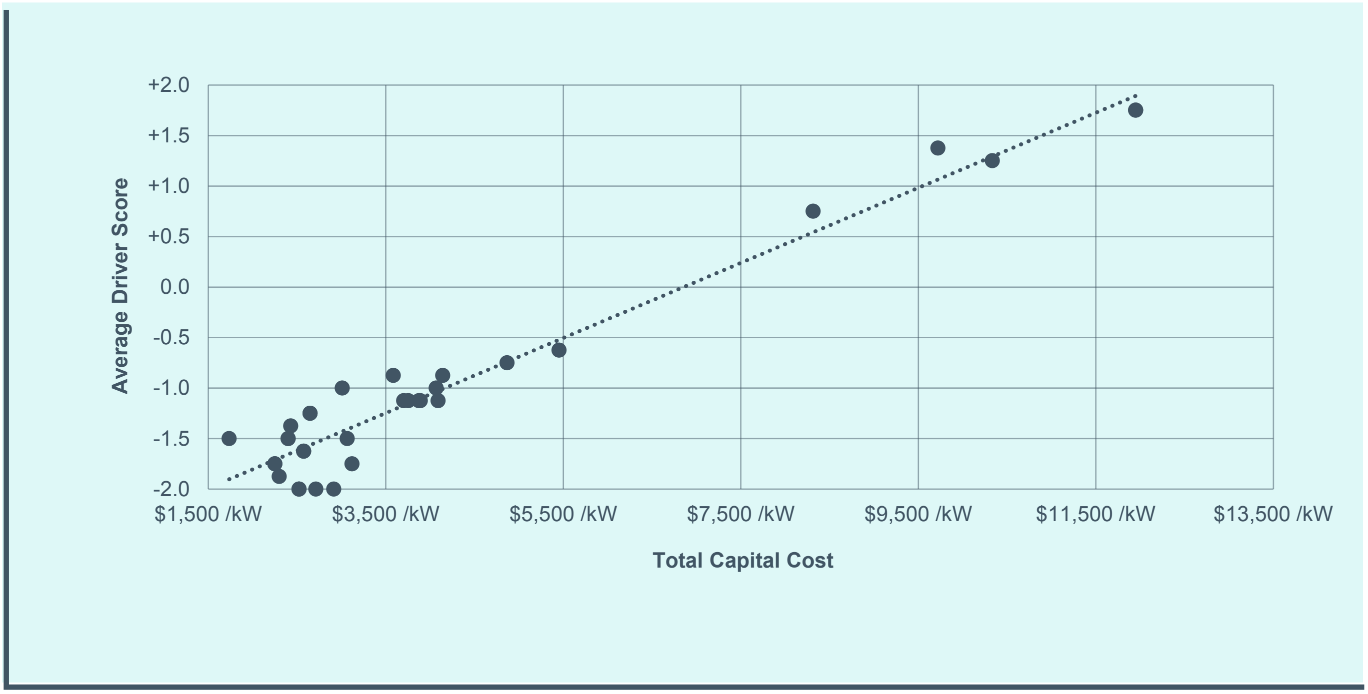
Table 9. **Alternative Cost Scenarios for Conventional Nuclear in Europe/North America**

Avg. Score	Capex/kW	Opex	7%		6%		9%	
			Capex	LCOE	Capex	LCOE	Capex	LCOE
+1.4	$10,387 /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

5.5 Broad Range of Costs and Scores in Completed Nuclear Plants

A cluster of low-cost plants scored well against all cost drivers (as shown in Figure 14 on the following page), demonstrating that low cost is not necessarily only attributable to country or context, but is the result of a concerted effort to drive down costs across all indicators. High cost plants also demonstrated high scores against most cost drivers.

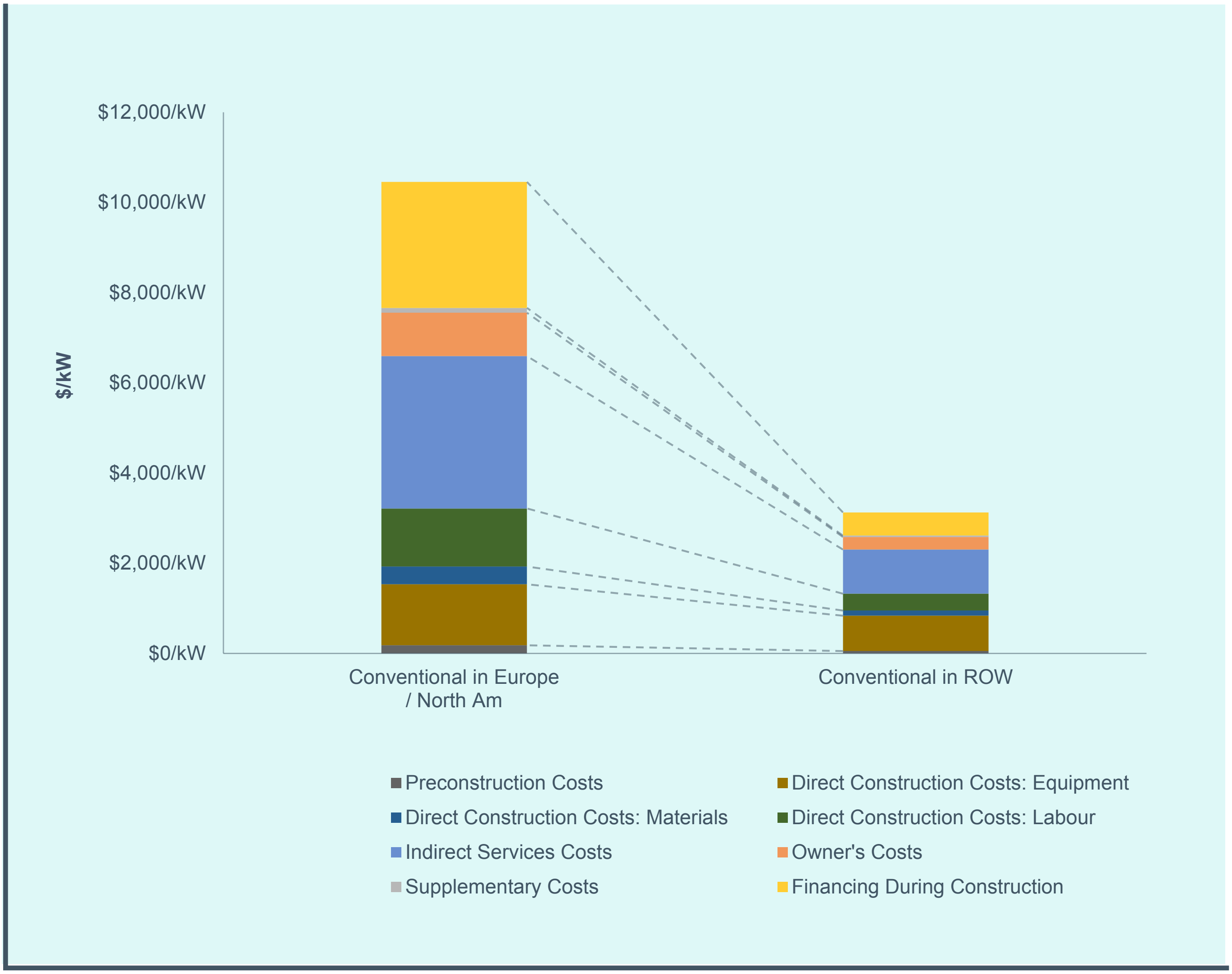
Figure 14. **Average Score for Projects in Database**



5.6 Differences Between High-Cost and Low-Cost Projects

Figure 15 below contrasts the Europe/North American and ROW genres. Evidence suggests the ROW genre is the result of a highly focused, deliberate and intentional programme to drive down costs and drive up performance over time.

Figure 15. **"Genre" Cost Comparison: Europe/North America and ROW Costs**



5.7 Common Characteristics of High-Cost and Low-Cost Projects

The study set out to understand what drives the vast range of costs in nuclear construction around the world. The findings suggest a strong correlation between high costs and high scores against the identified cost drivers. In addition, there was a high degree of consensus amongst experts interviewed for this study about key characteristics within projects that drive costs.

Key characteristics of both high-cost and low-cost projects that were consistently highlighted by multiple sources are summarised in the following table.

Table 10. **Characteristics of Low-Cost and High-Cost Plants**

Low Cost Plants	High Cost Plants
Design at or near complete prior to construction	Lack of completed design before construction started
NOAK design	FOAK design
Intentional new build programme focused on cost reduction and performance improvement	Major regulatory interventions during construction
Experienced construction management	Insufficient oversight by owner
High degree of design reuse	Litigation between project participants
Low cost and highly productive labour	Significant delays and rework required due to supply chain
Experienced EPC consortium	Long construction schedule
Experienced supply chain	Relatively higher labour rates and low productivity
Detailed construction planning prior to starting construction	
Multiple units at a single site	

5.8 SMRs and Advanced Reactor Genres

The project included SMRs and three advanced reactor ("Gen-IV") technologies: High Temperature Gas Reactors (HTGRs), Molten Salt Reactors (MSRs), Liquid-metal cooled fast reactors (LMFRs). All the advanced reactors in commercial development are primarily based upon reactor technologies that have already been designed, built, and tested decades ago at national nuclear laboratories. Companies are combining this experience with more recent scientific and computing breakthroughs to design vastly improved designs that address many of the challenges of the current, conventional nuclear fleet and delivery strategies.

Gen-IV plants are still in relatively early stages of commercial development. All companies are actively engaged (or preparing to engage) in reactor licensing activities. Only after obtaining a reactor license can a company build commercial demonstration or FOAK plant. While advanced reactor companies are projecting much lower costs than conventional plants, these costs will remain inherently uncertain until FOAK plants are delivered. At present, these reactor technologies are not yet deployment ready.

Methodological assumptions for calculating genre-specific CAPEX and OPEX for advanced reactor technologies can be found in Appendix C. The figures below present the average capitalised and annualised operating costs for SMRs and the three types of advanced reactors included in the analysis.

Figure 16. **Capitalised Cost Breakdown for SMRs and Advanced Reactor Technologies**

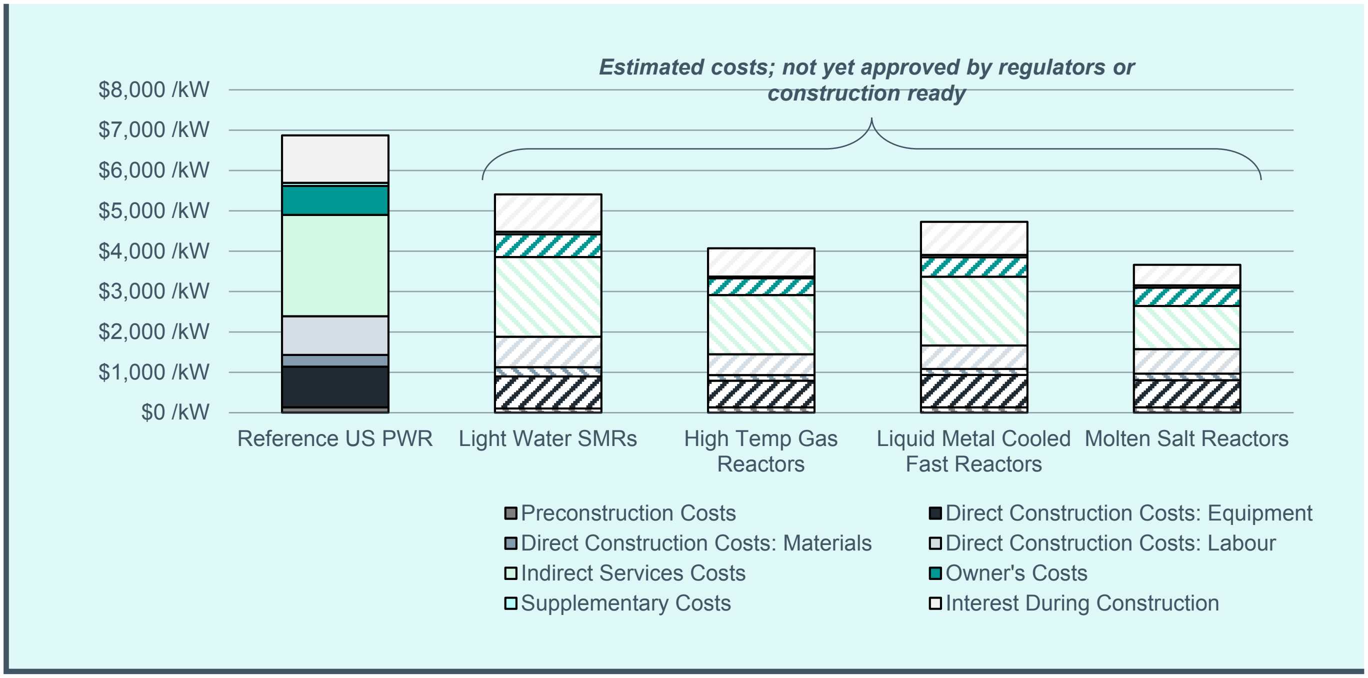
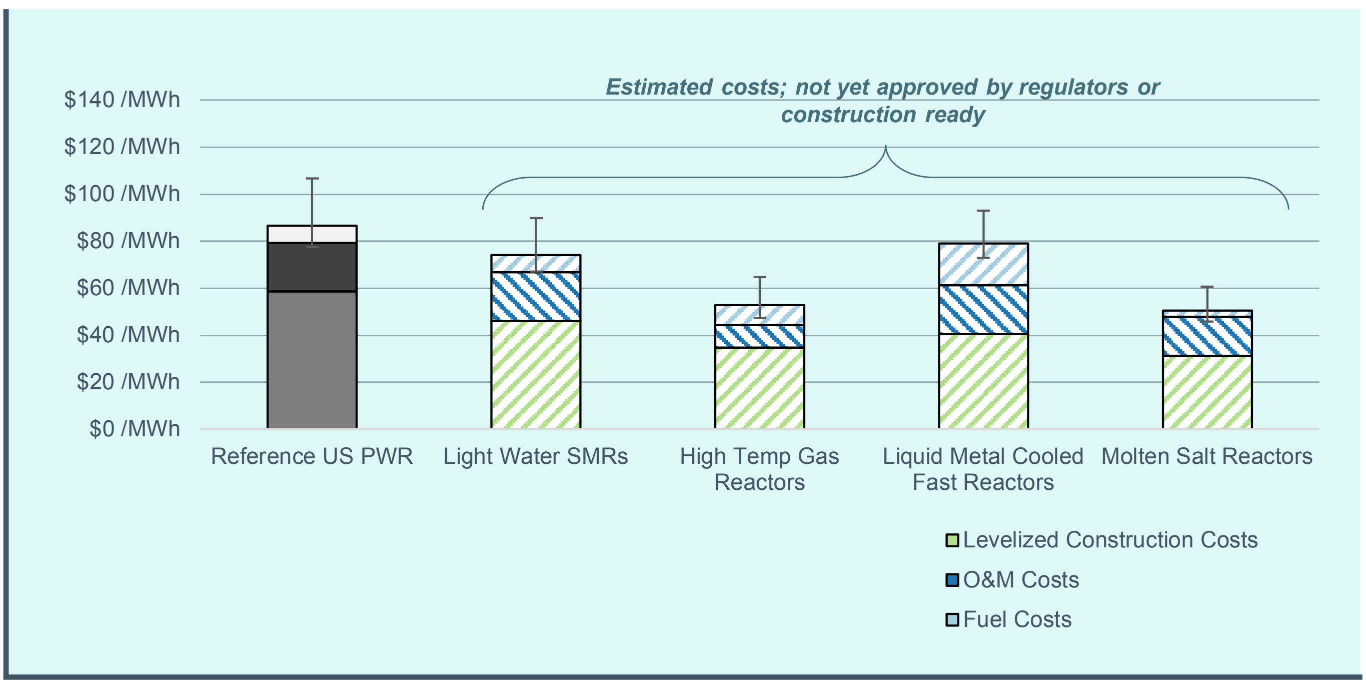


Figure 17. **LCOE for SMRs and Advanced Reactor Technologies**



5.8.1 Cost Reduction Opportunities for SMRs and Advanced Reactors

The project team assumes that the same drivers for conventional plants will be relevant to advanced reactors. As SMR and advanced reactor developers prepare their designs and plans, they have continued opportunity to integrate cost reduction strategies. While this is true, the lack of a detailed design inherently obscures cost and risk. Until the detailed design has been approved by the regulator the design is necessarily incomplete, and until it has been built, the significance of such cost reduction opportunities is harder to assess. Still, advanced reactor vendors are conscious of the shortcomings and risk centres that affect conventional, stick-built construction (as shown in recent Europe/North American projects) and are integrating several cost reduction approaches into their plant design and delivery strategy. Some of these strategies apply understood principles and are being pursued by several industry incumbents as well (see: modularisation, design standardisation, etc.). Other strategies for advanced concepts, however, exploit inherent benefits of non-LWR reactor technology and/or design processes that are relatively unencumbered by conventional thinking, legacy designs, or technologies. Advanced nuclear developers believe this provides a much greater opportunity to realise the theoretical potential of known and novel cost reduction strategies. Typical strategies being pursued by SMR and advanced reactor vendors that may reduce construction costs include:

- Reduced construction scope, duration, and labour, particularly at site due to fewer buildings and fewer safety systems
- Designed to enable a much higher percentage of factory production of key components and assemblies
- Simpler plants designs enabling a less labour-intensive QA & verification process
- Highly-standardised, modular designs:
  - Reduce indirect engineering/labour costs
  - Enable offsite manufacturing of systems and subsystems, which reduce the scope and quantity of onsite labour and enable faster construction schedules (and reduce the risk of schedule exceedance):
    - Manufacturing environment is much more productive than onsite construction and is more conducive to achievement of dependable quality.
    - Leverage common processes, tools, and manufacturing methods
    - Captured learnings from dedicated teams/factories/suppliers
  - Use commercially-available components (limited need for expensive, bespoke parts)
  - Minimise the new engineering activity required between sites
- Design for design reuse and constructability:
  - Designed-in seismic isolation reduces site specific design costs
- Fewer operating staff due to the inherent safety characteristics of the reactor/plant design and fuel type. Some companies are incorporating virtual/remote operation enhancements.

Advanced reactors do present the possibility of a step change in cost reduction – the probability of this, however, is too early to predict. There remains a significant fixed cost in any nuclear generation facility, including site licencing, control systems, the development and planning approval processes, etc. One of the challenges for advanced reactor development is to significantly reduce these fixed costs. Historically, vendors increased plant capacity to spread fixed costs and, as a result, reduce LCOE.[2] However, the

2 Part of the reason why Westinghouse's AP600 was "up-sized" to the AP1000 was to spread fixed costs.

resultant increase in capital intensity and complexity can significantly increase risk unless the project delivery organisation has a proven record of managing such risk.

Figure 18 and Figure 19 below provide a comparison of CAPEX and LCOE for the conventional genres and NOAK estimates from the advanced reactor genres.

Figure 18. **Comparison of Capitalised Costs Across All Genres**

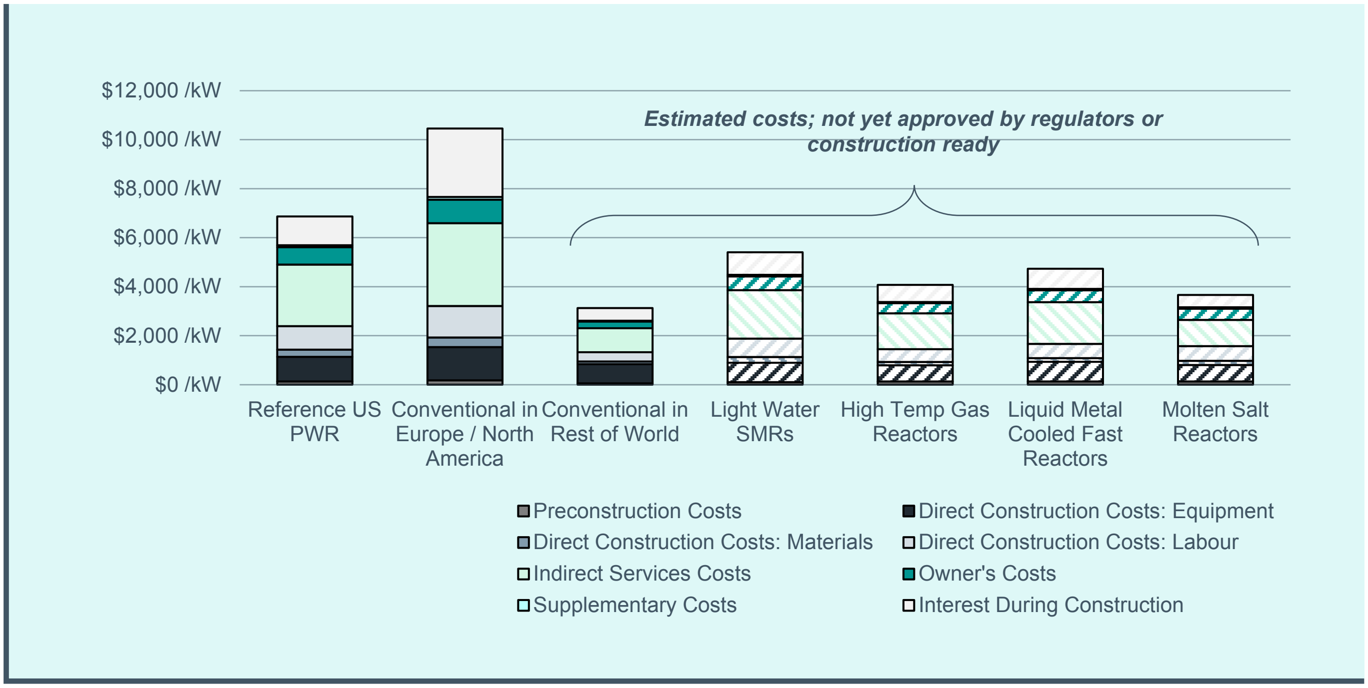
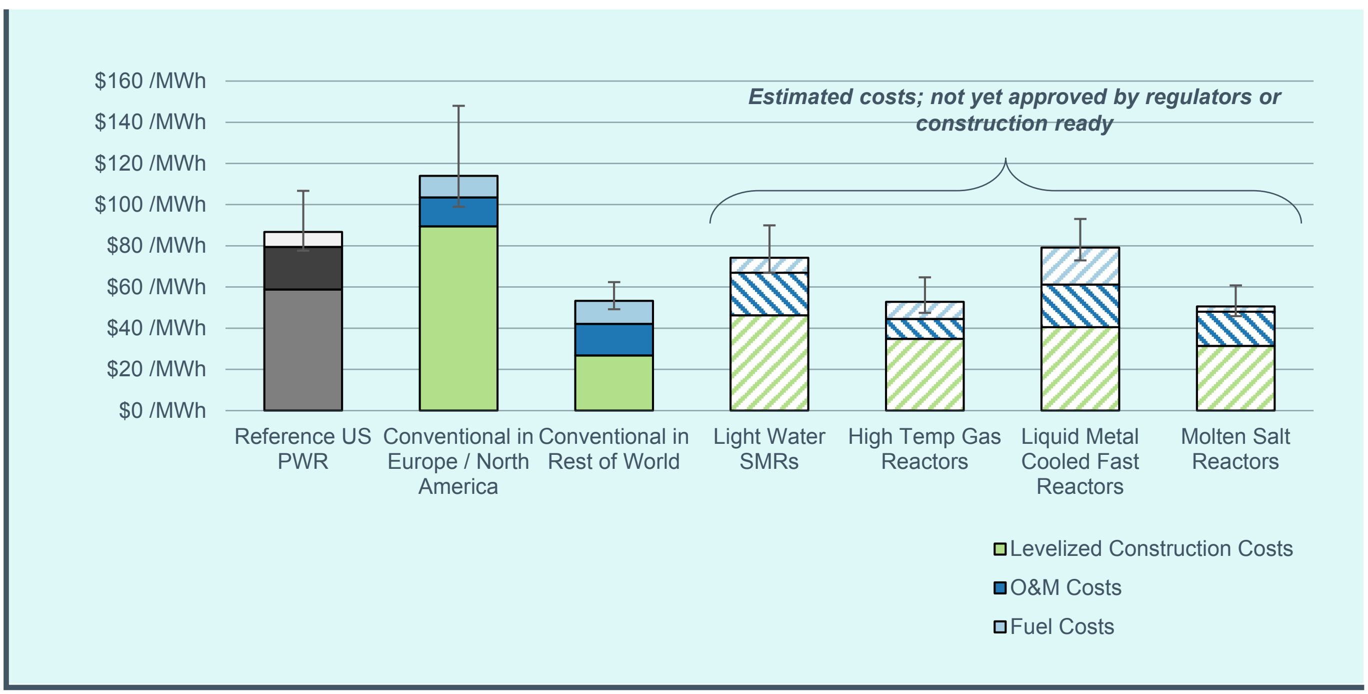


Figure 19. **Comparison of LCOE Costs Across All Genres**



6 Cost Reduction Opportunities

A key component to the ETI Cost Model is the user's ability to modify cost driver scores and view updated costs in real-time. Modifying cost driver scores, however, must be rooted in real-world changes to how a plant is delivered. This section presents several category-specific cost reduction opportunities that track to specific cost drivers and reflect a wide range of evidence collected throughout the project that links to the scorecard data. All listed opportunities have been reviewed and improved with the project advisors and, in many cases, were supported by interviewees (particularly with those providing rationale for low cost plants). There was a high degree of convergence on the opportunities between the scorecards, project advisor reviews, and interviews.

6.1 Provenance of Cost Reduction Opportunities

As the identity of interviewees cannot be revealed for reasons of confidentiality, each cost reduction opportunity below is color-coded by the source type according to the legend in Table 11 below:

Table 11. **Colour Codes for Cost Reduction Opportunity Provenance**

Colour	Source
I	Information obtained from project interviewee
S	Identified or Supported by evidence base within the Scorecards
PA	Suggested by project advisor
PT	Suggested by project team

The remainder of this section describes each cost driver category in order of impact (shown in Table 6 on page 29) and presents associated cost reduction strategies. Readers should note that cost reduction opportunities that originated (or were supported by) multiple sources are not necessarily the most valuable or important. The codes are to signify provenance, not priority.

6.2 Supply Chain

Delivering a nuclear project on time and budget requires a supply chain with the capability, capacity, and experience to meet the developer's demands in a timely manner. Ideally, the supply chain has recent experience in component or materials delivery, has borne the cost of obtaining the required nuclear qualifications, requires little to no training, dutifully follows specifications and documentation requirements (including all quality documentation), and supplies equipment and materials at market-competitive rates. This is not always the case, however. There are many bespoke parts requiring "chain-of-custody"-like documentation (as many parts are sourced from different countries) and investment from the supplier to "tool up" and provide the necessary documentation. Supply chain readiness is a critical requirement to successful project delivery and, depending on reactor technology, plant design, and supply chain experience, can be a major source of direct and indirect costs.

Key Cost Reduction Opportunities	Relative Importance: High

- Embrace a highly proactive approach to supply chain management and qualification
- Increase the percentage of local content over time as part of a programme of multiple units
- Develop incentive programme for suppliers against a schedule of milestones

6.2.1 Embrace a highly proactive approach to supply chain management and qualification

I

S

Nuclear plants have thousands of small equipment packages sourced from all over the globe. Incorrect specifications lead to failures and increases in construction costs. Supply chain management and inspection requires a sophisticated and global organisation that is experienced in inspecting and de-risking supply chains. Organisations like Lloyd's Register have inspectors throughout the world who can survey components and oversee equipment manufacturing to ensure that suppliers – especially those involved in providing nuclear-grade components – are meeting the appropriate standards for quality and documentation. Oftentimes, the further one moves down the supply chain, the probability of meeting specifications decreases.

6.2.2 Increase the percentage of local content over time

I

S

PT

Successful lower cost projects with a higher percentage of imported labour content will enable follow-on projects creating opportunities for increased domestication of content. One or two excessively expensive projects with higher local content are not likely to create an ongoing industry. Building the UK supply chain, particularly for novel reactor designs, will take time. The supply chain should not become unduly influential on cost and schedule. Developing a low-risk domestic content strategy should phase in more local content with each successive build.

6.2.3 Develop incentive programme for suppliers against a schedule of milestones

I

S

Developing an incentive structure for suppliers can help ensure quality standards and delivery schedules are met. This can be particularly valuable for components and equipment that are part of the defined critical path.

6.3 Labour

Labour is one of largest costs in a nuclear plant. For the US PWR benchmark, it represents nearly two-thirds of the total overnight cost. Unfortunately, UK construction productivity is 40% lower than the US (UK Office of National Statistics, 2016). In fact, labour productivity in the UK is the second lowest in all the G7 countries (after Japan), according to the same source. Productivity is just one consideration, however. Included in this "Labour" category are wages, hours worked per day, percentage of work force with direct applicable experience, percentage of hours on task, and the cost of labour training. Every non-labour factor of a nuclear project could be set up to maximise the probability of success (applying best practices and lessons learned to gain significant learning curve effects)and the project could face extreme financial setbacks if labour is unproductive, expensive, inexperienced, or communication with management is poor.

Key Cost Reduction Opportunities **Relative Importance: High**

- Innovate new methods for developing alignment with labour around nuclear projects
- Improve labour productivity
- Invest in the labour force
- Apply principles of the Kaizen system

6.3.1 Innovate new methods for developing alignment with labour around nuclear projects

I

PA

Given the financial implications of construction duration, it is important to align labour with all other stakeholders and avoid disputes and strikes at all costs. This requires establishing and investing in innovative ways to collaborate, cooperate, and develop a team-working relationship with labour unions where there are defined and shared objectives, and maintaining open lines of communication and information transparency. Including labour union representatives into the project planning process builds a sense of "buy-in" and shared responsibility. Labour representatives involved in planning should be contractually committed to remaining onsite during construction to maintain continuity in the cooperation, camaraderie, and shared ownership built during the planning phase. If labour feels included in the process, employees are more likely to embrace predefined quality standards and increase the likelihood of self-policing and self-correction during construction. The project developer will benefit from working with labour to systematise personal accountability and reward quality and innovative ideas. They should hold regular meetings to address issues as they arise and maintain open and clear communication channels.

6.3.2 Improve labour productivity

I

S

PA

Of the G7 countries, UK is among the lowest in terms of output per hour worked. In 2015, it was 16.6% below the G7 average (UK Office of National Statistics, 2017). This is a very material consideration for new build plants in the UK. Several approaches have demonstrably increased labour productivity in the past, many of which have been tried in the UK and discussed above. First, the developer should establish a collective contingency/bonus pool among their contractors. This fund contains additional profit margin upon a successful delivery but also pays for any delays and cost overruns caused by the fund contributors. This was instituted at Sizewell B and contractors were motivated to increase their own profits but were arguably more motivated by not being responsible for reducing profit for the others. Another successful approach is for the owner to tie a percentage of the total project profit to on-time and on-budget delivery.

Other "productivity enablers" include providing open access to information that highlights which contractors are holding up the project, involving labour through representation in the planning process (including board representation), developing a labour agreement that drives productive hours by maximising the number of hours per shift at the workplace, and bonuses for quality work. These approaches (or variations thereof) should be applied to all UK projects going forward. Incentive schemes must also be established at the start of the project and not introduced part way through as a recovery driver. Naturally, incentivising productivity requires establishing detailed metrics for measuring performance.

6.3.3 Invest in the labour force

I

PA

Nuclear plant design in the global west suffers from a generational disconnect between engineers who have project experience but are not technologically savvy and younger engineers who are fluent in the latest design programs but have no actual project experience. At the same time, China is graduating more nuclear engineers than any other country in the world. The UK should invest in UK talent and help fund their training and apprenticeships that includes experience on nuclear construction sites outside the UK – with reputable companies. Such programmes exist at a small scale (Bridgewater Technical College have an apprenticeship program with EDF) but they should be well-funded and expanded beyond the UK borders. Developing project designers, engineers, and builders with experience and exposure to industry best practices and, where necessary, trained in project management and labour supervision, is an excellent long-term investment for the UK.

6.3.4 Apply principles of the Kaizen system

I

S

PA

As demonstrated at the well-known Nissan plant in Sunderland, nuclear contractors should adopt principles of the Kaizen method. Kaizen, the Japanese word for "continuous improvement," is used to describe a company culture where everyone regularly evaluates his or her own work and thinks of ways to improve it. In Sunderland, workers continually propose ideas and innovations to make work more efficient and less physically demanding on the production lines. These same ideas can save a few thousand or millions of pounds in efficiency improvements. The Sunderland work environment is hard-working and pressurized but also positive and supportive. The UK has already successfully adopted Kaizen principles in some industries; applying them to the nuclear industry could lead to significant productivity gains.

6.4 Project Governance and Project Development by the Owner/Developer

Project Governance and Project Development covers the financial, contracting, procurement, quality assurance, and project management components of the project by the owner/developer. According to the regression analysis, these have been shown to have high importance among the cost drivers in nuclear projects.

Key Cost Reduction Opportunities	Relative Importance: High
■ The owner's organisation needs an experienced, multi-disciplinary team ■ Project owner should develop multiple units at a single site ■ Determine and follow Contracting Best Practices ■ Consider an owner-led (not vendor/EPC-led) project delivery model for the UK ■ Establish cooperative partnership between owner and vendor ■ Commission "cradle to grave" inspection by Independent 3rd party	

6.4.1 The owner's organisation needs an experienced, multi-disciplinary team

I

PA

The owner's organisation should have deep experience across a range of disciplines that include nuclear construction supervision, EPC project delivery, and contracting (notably nuclear project contracting). When exercising its responsibility and prerogative, the owner needs to be informed by expert opinion. Construction experts within this organisation may visit and inspect the project site on regular intervals to assess quality and progress (as was done for Sizewell B).

6.4.2 Project owner should develop multiple units at a single site

I

S

PA

Building multiple units enables the project developer and construction team to realise several benefits. These include:

- Economies of scale (i.e. ability to spread fixed costs over all units, lower cost components and materials through bulk ordering, etc.). This lowers the per/kW cost basis for site preparation, licensing, laydown areas, equipment rentals (trucks, cranes, etc.), labour, and all common facilities (e.g. temporary work site, maintenance and administrative buildings, technical buildings, warehouses and workshops, reception and public information buildings, etc.).
  - Use of common access roads, railways, and utility networks
  - Lower per/kW cost basis for services or equipment, such as:
    - Environmental impact and hazard studies
    - Administrative procedures
    - General platform earthworks
    - Water intakes and outfalls
    - On-site fire protection
    - Surveillance facilities

- Productivity gains. Labour and supply chain can leverage lessons learned from one unit to the next.
- Ability to lower/spread FOAK costs. First-of-a-kind (FOAK) project costs can be quite significant and reflect such things as detailed design work from electrical and mechanical contractors, establishing new manufacturing facilities, developing and testing software, equipment qualification, establishing assurance procedures, and setting up special facilities. Spreading these costs across multiple units can significantly lower the cost (and associated risk) with adopting FOAK reactor technologies.

6.4.3 Determine and Follow Contracting Best Practices

I

PA

PT

The prime contract between owner and vendor is the foundation of a project. One of the biggest reasons behind the success of the UAE's Barakah project was the effort that was put into the contract. The project owners instructed their law firm to perform an exhaustive review of dozens of nuclear construction projects and identify, among other things, contracting practices that led to the most expedient results. This led to a well thought out set of contract requirements from a dedicated team with technical, financial, legal, and insurance experts. Identifying goals and risks, performing "red team-blue team" exercises, and memorialising the procurement structure using project management software was key prior to procurement negotiations. Contributors to this study were among those leading the design and implementation of this highly effective innovative approach.

Selecting the Delivery Organisation: A well-designed bidding process is key to maximising the probability of project success. While government-to-government agreements are important (and almost always necessary) for securing project financing, the bidding process should prevent any other external political influences. Unless the owner is willing and, importantly, practically able to take on FOAK risks, all eligible plants should be based on a licensed and previously constructed design.

Setting up a "customer organisation" in the UK: To engage prospective nuclear developers and negotiate procurements more effectively, the UK government should consider establishing a dedicated entity staffed by experienced nuclear personnel. This body would include active and retired public and private sector professionals who advise government and, acting without any financial incentives, review designs and project execution plans to ensure that best practices are being applied. Compliance with entity requests could be eligibility criteria for receiving government support.

Contracting Best Practices:

- **Reduce the number of contract packages** led by the EPC contractor as much as possible. The number of major contract packages could go from >100 to as few as six (OECD, 2000). Achieving this objective with minimum risk requires rigorous vendor assessment to ensure that contractors are sufficiently robust (technically and financially) to be awarded the package.
- **Use incentive-based contracts** which are preferable to punitive contracts in motivating the EPC. Paying a delivery bonus if "substantial completion" (to be defined contractually) is achieved on or before a specified date has been done in the past for projects that ultimately came in a relatively low cost.

- **Identify and define clear fixed price – fixed delivery work packages for subcontractors and vendors**. Assuming the vendor and EPC have adequately completed their detailed plant design and project planning process, then fixed price-fixed delivery contracts are both possible and desirable. Adding bonus provisions for on-time and budget delivery can be helpful in incentivising planning, cooperation, and performance. If plant design and project planning are not sufficiently complete, this contracting structure can be highly problematic.
  - Payments should be made on specific, measurable, attainable, realistic, and timely milestones (SMART).
  - Price escalation should be carefully constrained to very well-defined circumstances.
  - Ensure that all contracts are in stable currency like Euros, USD, or GBP.
  - Include provisions regarding risks that the contractor cannot manage.

Technology Transfer. Bundle any Technology Cooperation Agreement with the EPC contract and transfer IP for purposes of operation, goods and services that can be supplied locally, and regarding any sale of the nuclear power plant to another party.

No Unlimited Indemnities.

Review of existing specimen documents to try to avoid doing the same work a second time.

Appoint a Single Prime Contractor who hires all other contractors and serves as the single point of contact to all contractors and the owner.

Contract for a Turnkey Delivery based on a reference plant – ideally completed in the same country.

Review of EPC Contractor's Books to ensure prices are low but realistic and allow parties to focus on shared objectives like risk management and project delivery performance.

Draft a Requirements Contract with the Prime Contractor that clearly defines the required project outputs as opposed to listing all the specific tasks that need to be completed (i.e. a list of functional requirements and leave the means to the EPC).

Control the Selection of Vendors and take advantage of import-export banks (and other export credit agencies). Also consider tied and untied financing under OECD rules as well as compliance with EU procurement rules.

Control Cost Escalation by starting with a grace period (e.g. three years). It is important to use escalation to compensate the supplier only when the supplier is being affected by an increase in prices. Once the service or equipment is subject to a fixed price, escalation should stop. Owners should also consider requiring contractors to follow an escalation index that reflects actual price changes, and owners should retain the right to require suppliers to purchase goods early in the project to avoid potential price increases later.

Table 12 on the following page highlights the spectrum of contracting terms for the plant owner. Naturally, UK new nuclear developers should ensure that their terms align with the "best" contracting terms.

Table 12. **Contracting Terms**

Best	Worst
Meet all buyer's requirements	Provide specified goods and services
Limit of liability is 100%	Limit of liability is 10%
95% is fixed price	20% of price is fixed
Fixed Commercial Operation date	Target CO date
Warranty of 90% availability	No availability warranty
50% vendor financing	Offers no financing
Vendor takes 15% equity	No equity
Vendor supports operations	No operational support
Parent guaranty	No parent guaranty
Joint and several liability	No joint and several liability
Reference plant near complete	25% of detailed design complete
Sign prime contract in 90 days	Sign prime contract in 11 years

6.4.4 Consider an owner-led (not vendor/EPC-led) project delivery model for the UK

I

S

PA

Delivering nuclear power plants is either led by the vendor/EPC or project owner. The EPC-led delivery model is used where there is a proven, integrated EPC contractor and an owner who desires to place responsibility with a vendor (noting it carries a higher risk and demands a higher cost). Under this structure, several companies come together in a joint venture. Oftentimes, each company adds its own project management structure, which increases the number of players and typical results in slower and less efficient decision making, and notably higher costs. Recent EPC-led projects have highlighted the challenges of this model. Most notably, these include Areva's cost overruns, lawsuits, and schedule delays at its Olkiluoto Project, and Westinghouse's AP1000 projects in the US Southeast (V.C. Summer 2 & 3 and Vogtle 3 & 4), which ultimately led to the company's bankruptcy. Because of these projects, many EPCs are now reluctant to take on substantial project delivery risk.

Owner-led projects offer a relatively simpler structure with less duplication and layering of management and contingencies. Under this structure, an owner acquires the necessary project leadership experience to enable project success and attract financing. Developing an owner's management team starts before hiring contractors and should be augmented with successful architectural engineers and other direct hires as necessary. Today's most successful new build nuclear programs – in China, Korea, Russia, and India – are essentially owner-led projects with experienced and capable local companies.[1] Key factors to project success have been a strong, sustained internal new-build program supporting continuous deployment and the use of proven designs and reference plants, which greatly reduce project risk.

1 The restructuring of Westinghouse's Vogtle 3 & 4 projects included the transition from being EPC-led to owner-led project.

The lack of labour experience and relatively low labour productivity in the UK is a challenge to either delivery model. A strong partnership between UK utilities and the construction industry, coupled with good project management in an owner-led model, can yield lower costs and better results than an EPC-led approach. Also, the UK regulator requires relatively more owner-led project oversight (more so than most countries), which suggests that the owner-led model – in addition to its reduced duplication of management – would be preferable. While the decision on owner-led versus vendor-led will be based on the specific companies and/or vendor countries and their respective policies on nuclear and financial capacities, project success will require cooperative partnerships between governments, vendors, and utilities.

6.4.5 Establish cooperative partnership between owner and vendor

I

S

PA

Delivering a long and complex project requires cooperation and teamwork to address the many issues that are bound to arise. Successful projects do not have fewer problems, instead problems are identified earlier and resolved more quickly. Adversarial relations among stakeholders invariably translate to delays and higher costs. Despite many historical examples of clashes being significantly disruptive (most saliently highlighted in the recent failures at V.C. Summer Units 2 & 3 and Vogtle Units 3 & 4), owners and vendors often do not fully appreciate the benefit of playing for the same team as challenges are inevitable on projects with the complexity and duration as a nuclear power plant (Petrunik, 2015). Developing a cooperative dynamic requires a clear definition of roles and responsibilities for both the owner (licensee) and EPC/vendor and a willingness to compromise and work together when challenges arise. One approach to reducing litigious responses is to include language in contracts that requires parties to meet and make a good faith efforts to attempt to resolve problems before any legal action is taken.

6.4.6 Commission “cradle to grave” inspection by Independent 3rd party

I

S

PA

The project owner should commission “cradle to grave” project inspection – from design through procurement, construction, and commissioning (and potentially operations). A third party inspector (TPI) is highly beneficial in identifying problems or potential issues early in the process, saving money and time for not only the owner and investors but all parties. It requires additional upfront capital; however, this can save significant resources in the long-term (and is especially justified if the developer does not follow an established internal QA process).

Ideally, the TPI should have a reputation and relationship with the regulator and sufficient resources to carry out their duties. It is important that they not be pressured into approving work (which may be the case when the supplier does not know how to comply – or does not want to). In addition to independent auditing, TPIs can also provide clarity on scope to suppliers in advance of production to avoid increased costs or need for re-work. As a critical component to the quality assurance process, TPIs ultimately help to maintain schedules, reduce risk, and increase budget certainty.

6.5 Construction Execution by the EPC

Construction execution is an important driver of nuclear plant costs because projects typically require thousands of labourers over many years, and costs are subject to significant increases if the construction schedule is exceeded. Managing this process requires strict discipline and close alignment of the many involved stakeholders. Below are a series of principles and best practices that, if adhered to, can increase the prospect of a successful on-time and on-budget plant delivery.

Key Cost Reduction Opportunities	Relative Importance: Medium

- Projects must be guided by effective, charismatic, and experienced leaders
- Projects should be guided by an integrated, multidisciplinary project delivery team
- Leverage offsite fabrication
- Sequence multiple projects to maintain labour mobilisation and consistency in delivery teams

6.5.1 Projects must be guided by effective, charismatic, and experienced leaders

I

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Strong and charismatic leaders who have a demonstrated record of success are required for delivering large and complex nuclear projects. These leaders must be up to the task and able to commit for the entirety of the project cycle. Weak and/or inexperienced project management by either the owner of vendor slows down the decision-making needed to drive on time and on budget performance.

6.5.2 Projects should be guided by an integrated, multidisciplinary project delivery team

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The project delivery organisation should oversee a joint planning and construction effort and include members from the project management office as well as a “rainbow” of seconded representatives from the licensing, design, planning, construction, QC, QA, commissioning, and operations teams as well as labour. The team should be bound by commercial arrangements that allow them to stay through construction to provide continuity of the shared vision as well as the ability to focus on project success (i.e. not maximising their respective company profits). Each discipline brings specialised knowledge and having a clear, unified understanding of the critical path and project sequencing (as well as the implications of delays and accelerations) is highly beneficial. Additionally, relatively short lines of communication among a unified group allows for decisions (e.g. responding to design changes) to be made in a swift, integrated, and coordinated fashion.

Leadership development: Irrespective of whether companies formally enact job rotation schemes, they must proactively develop and manage capable and effective leaders. This includes talent development and managed careers, enabling real-world project development experience (seconding personnel to other projects or organisations as necessary) and building the competence and confidence necessary for skilled leadership. This practice is followed in the UK by many large organisations where there is a will to do it.

6.5.3 Leverage offsite fabrication

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Offsite fabrication of components, precast structures, electronics, and various subassemblies and structures can reduce the amount of onsite work. As mentioned previously, the manufacturing environment provides several benefits that can improve quality assurance, reduce site congestions (and related labour and supervision costs), and enable shorter construction schedules. Realising the cost savings of offsite manufacturing requires highly detailed process and interface design.

Labour represents about 42% of the capitalised, overnight direct construction costs for the PWR benchmark. In the UK, it represents well over half of all construction costs (exacerbated by high labour rates and low productivity). Limiting onsite labour costs in the UK will require the adoption of offsite fabrication and potential accompanying updates to relevant codes and standards.

6.5.4 Sequence multiple projects to maintain labour mobilisation and consistency in delivery teams

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A common characteristic in Chinese, Japanese, and Korean new build programmes is the repeated use of proven and experienced contractors and suppliers. Enabled by national nuclear programmes that support well-sequenced continuous new build projects, individuals get better at fulfilling their individual role and collective learning and efficiencies arises among managers, labourers, and suppliers. Personal relationships and camaraderie develop that support alignment and a shared vision as well as quicker and more seamless problem solving (oftentimes pre-empting problems before they arise).

6.6 Political and Regulatory Context (Government)

The political and regulatory context for nuclear project development varies widely across the globe. Country-specific factors influence every phase of the development process, including regulatory interactions, political support (both legislatively and financially), siting considerations, and public support.

Key Cost Reduction Opportunities — **Relative Importance: Medium**

- Government support should be contingent on systematic application of best practices and cost reduction measures
- Government must play a role in supporting the financing process
- Design a UK programme to maximise and incentivise learning, potentially led by a newly-created entity
- Support regulator exposure to projects outside the UK
- Transform regulatory interaction to focus on effective safety
- Engage the Regulator early and agree on a process for resolving licensing is-sues
- Reform and update nuclear safety culture

6.6.1 Government support should be contingent on systematic application of best practices and cost reduction measures

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Government financing, CfD/FIT/PPA offerings, or other state assistance should come with a set of specific, non-negotiable requirements from the state that ensures developers follow best practices and cost/risk reduction measures. To help ensure project success, provide UK consumers with cost competitive generation options, and provide greater certainty to the agencies responsible for securing adequate capacity and resiliency of the UK grid, the government should require many of the cost reduction opportunities discussed here. At one end of the spectrum, this could involve the establishment of a new entity, e.g. a Clean Electricity Generation Authority, staffed and led by highly-experienced nuclear cost, construction, and legal experts, that acts on the nation’s behalf to deliver an “intentional programme of nuclear new build” alongside other clean electricity generation to create a balanced grid that meets security, affordability, and environmental goals. Required best practices include (but are not limited to):

- Completed plant design that sufficiently incorporates UK regulatory requirements
- Completed 4D construction planning and simulation
  - Includes schedule integration and communication between suppliers and owner to confirm "design for constructability"
- Strategic and operational planning by the owner (processes, activities, and milestones)
- Outside auditing of construction project schedule and management
- Competence review for key management
- Clear definition of how all involved parties engage each other (including any cultural and/or language barriers)
  - Ensure timely availability of suitably qualified and experienced staff (both from owners and suppliers)
  - Avoid minor conflicts

6.6.2 Government must play a role in supporting the financing process

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Apart from NOAK SMRs, which are, in part, intended to be solely financed through private capital markets, the capital intensity and risk profile of large nuclear projects (and FOAK SMRs) have traditionally required government-to-government financing arrangements through import-export banks, loan guarantees, and other financial backstops to indirectly help developers secure debt financing. It is important to recognise that until companies can successfully demonstrate an evolution of the stick-built construction delivery model,[2] the government will need to play an active role in supporting project financing. Ideally, if the above recommendations are implemented, project risks will be substantially reduced for all parties and the government's participation in financing will also carry lower risk, and potentially a reduced role.

6.6.3 Design a UK programme to maximise and incentivise learning, potentially led by a newly-created entity

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The government should design a UK programme that incentivises learning between people, companies, and competitors. Several companies are vying to develop nuclear plants in the UK and all should be exercising plant delivery best practices and lessons learned. The programme should provide incentives for discovering and maximising "learning effects" and capture the key lessons in incremental design modifications.

6.6.4 Support regulator exposure to projects outside the UK

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The UK regulator does not need any additional training to maintain its global reputation as a "gold standard" in nuclear licensing and regulation. However, given the dearth of UK new build projects over the past 25 years, it will be beneficial for regulators to actively seek real world project experience. Direct UK experience may be forthcoming with the current suite of projects in early development. However, international collaboration enabling regulatory access and learning to successful projects outside the UK (e.g. in Japan, Korea, and China) can boost confidence and capability, as well as mitigate against any collective loss of experience due to retirements and turnover. There have been issues as vendors

2 Hitachi-GE's ABWR design and delivery model for the Horizon project at Wylfa is expected to be highly modularised as opposed to a typical, stick-built construction project. The AP1000 plants in the southeastern US demonstrably failed in this regard; however, their failure reflects poor project execution as opposed to the potential for modular design and delivery to be successful for large, utility-scale conventional plants.

from other countries fail to fully grasp some of the cultural subtleties relating to interaction with the UK Office of Nuclear Regulation. For example, it might be proactive for a team of regulators to go to Korea and understand from the Korean regulators their perspectives and advice on interacting with KEPCO/KHNP. This might enable 'debugging' some of the cultural miscommunication that might otherwise occur. Another important goal is to move towards international convergence on established designs.

6.6.5 Transform regulatory interaction to focus on effective safety

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Country of origin licensing based on a reputable, operating reference plant is the most cost-effective approach to reactor licensing, but not currently feasible in the UK and other countries. Interim steps can be taken to enable transition from the currently highly bespoke process towards standardisation. For example, proven reactor designs that have been licensed in countries with a mature regulatory capability should only be subject to strongly justified, context specific design changes by the UK regulator. All changes required by the regulator should be subject to cost-benefit analysis to ensure the most cost-effective implementation of changes to achieve measurable and meaningful safety improvements. This is consistent with the World Nuclear Association's (WNA) recommendation of a harmonised regulatory processes that "provide(s) a more internationally consistent, efficient and predictable nuclear licensing regime (that allows) for standardised solutions, to facilitate significant growth of nuclear capacity." (WNA, 2015; WNA, 2010).

6.6.6 Engage the Regulator early and agree on a process for resolving licensing issues

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Given the amount of regulatory involvement during site design and construction, having a resolution process established and agreed upon early by both parties is important. Providing procedural certainty and consistency enables faster resolution and prevents issues being unresolved indefinitely, which can redirect sources and attention otherwise focused on project completion.

6.6.7 Reform and update nuclear safety culture

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Nuclear energy is the safest form of electricity generation (Markandya et al., 2007). While older "Gen-II" and "Gen-III" nuclear plant designs have been successfully licensed and operated (and many decommissioned), companies continue to evolve their designs to enhance their plant's safety profile. While this seems like a natural place to devote resources, it does prompt the question: "how safe is safe enough?" Left unconstrained, the pursuit of increasing levels of safety for its own sake, without due consideration for cost implications or tangible health benefits, not only undercuts cost competitiveness against other, less-constrained energy sources, but results in the perverse outcome that more harmful energy sources gain an advantage.

Several questions can be raised, such as: are the International Atomic Energy Agency's (IAEA) safety definitions for "Gen-III" reactors sufficient? (These define relatively high standards for core damage frequency, radioactive releases, ultimate heat sinks, etc.) If "Gen-II" and "Gen-III" reactors are already considered "safe," why are today's vendors designing beyond these existing standards? Should "Gen-III+" and "Gen-IV" reactors be required to meet higher safety standards? Is conducting an industry-standard Probability Risk Assessment insufficient as a determinant of risk?

In the UK, the term ALARP ("as low as reasonably practicable") is used in nuclear regulation, licensing, and in assessment principles and guidance notes. The ALARP principle guides the occupational risk of radiation exposure, which requires the regulator to make a determination of what is "reasonably practicable" in terms of safety requirements. The regulator's remit is to protect the public good, so it fittingly does not account for the interests of the consumer or taxpayer. However, in determining what is "reasonably practicable" the regulator should endeavour to collaborate with the developer to establish a baseline safety requirement (as opposed to an unending pursuit of safety improvements requiring complex design changes with ever decreasing marginal benefit for public health) and agreement on a cost-effective solution to achieve that. The practical application of the ALARP principles should be reviewed periodically to assess the full impact of cost (and schedule) needs to be considered against value of potential benefits. Regarding US nuclear regulation, a September 2017 report published by Idaho National Laboratories recommended performing "a cost-benefit analysis of the nuclear premium…(because) it is clear that the nuclear premium adds a significant burden to the cost of construction. This burden needs to be justified. If it cannot be justified, then the burden needs to be reduced." (Dawson et al., 2017).

6.7 Equipment and Materials

Reducing cost in the equipment and materials category (i.e. reducing the quantity and cost of nuclear-grade material) requires implementing changes to the plant design during the design phase. The strategies below address reducing equipment and material costs and include ideas from various construction industry and MIT "Future of Nuclear" studies.

Key Cost Reduction Opportunities	**Relative Importance: Medium**
■ Reduce nuclear-grade components as much as possible ■ Substitute concrete with structural steel where possible ■ Follow best practices to reduce material use ■ Develop opportunities to use emerging technologies being used in other sectors	

6.7.1 Reduce quantity of nuclear-grade components as much as possible

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Due to the requirement to meet extensive QA standards, stringent testing requirements, and complete traceability of all items from raw material to the finished product, nuclear grade components are typically over 4-times (oftentimes, well beyond 10x; El-Guebaly, 2009) the cost of the same commercial grade component. Generating the required documentation can oftentimes cost more than the item itself. Suppliers are naturally reluctant to take on the added cost and liability of producing nuclear-grade components, so the cost premium can be quite significant. Optimising the reactor and plant design to minimise the quantity of nuclear-grade components is the most direct way of avoiding the cost premium on nuclear-grade (i.e. "N-stamped") components.

- **Korea's approach to nuclear grade components.** Many Korean suppliers made upfront investment to in safety-grade component documentation, so the required documentation is standardised and readily available when such parts are needed. This has allowed them to produce nuclear grade equipment and components much more cost-effectively.

6.7.2 Substitute structural steel for concrete where possible

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Conventional nuclear power plants use large amounts of concrete and steel (rebar, panelling, structural, etc.). Substituting concrete for steel or reinforced concrete with pre-fabricated modular concrete (e.g. Ultra-High Performance Concrete and steel-plate composites) can reduce the overall materials requirements (and CO2 footprint) and is a method being followed by several advanced reactor companies (particularly those with modular designs).[3]

3 Concrete and steel comprise over 95% of the total energy input into materials used in the construction of nuclear power plants (Peterson et al., 2005).

6.7.3 Develop opportunities to use emerging technologies being used in other sectors

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Emerging technologies and techniques from other sectors have the capacity to benefit the nuclear plant delivery. For example, blockchain/self-documentation could be used to track and verify components within the supply chain (this could have benefits to source verification of nuclear-grade components). Similarly, advanced manufacturing and inspection technology could be used in place of expensive, bespoke forgings and emission spectroscopy could be used for real-time QA of offsite, robotic welding. A larger effort to discover and demonstrate the application of such possibilities should be pursued by public-private partnerships. Westinghouse, Cammell Laird, and the UK Nuclear AMRC are looking at how the latest welding technologies and techniques can accelerate reactor pressure vessel production. More projects like this should be funded by government and affiliate, "catapult" organisations. As evidenced by off-shore wind cost reductions, such efforts can catalyse significant change within an industry.

6.8 Vendor Plant Design

The final plant design sets fundamental guide posts for nuclear power station costs. The design philosophy and collection of small design decisions dictate the quantity of raw materials, bespoke components, construction complexity, and several other considerations that influence cost and construction risk. During the design process, the adage "an ounce of prevention [can be] worth a pound of cure" aptly applies (i.e. prudent investment and design decisions can pay significant dividends during construction execution). The following strategies executed during the plant design/pre-construction phase can dramatically reduce plant cost or construction risk.

Key Cost Reduction Opportunities **Relative Importance: Medium**

- Complete plant design prior to starting construction
- Design for constructability
- Increasing modularity in the design should be Prioritised by its potential to shorten and de-risk the critical path
- Plant design team should be multidisciplinary and include current construction expertise
- Design for plant design reuse
- Consider specific design improvements against full costs and potential benefits of implementation

6.8.1 Complete plant design prior to starting construction

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The importance of having a completed design has been highlighted consistently by nuclear cost experts interviewed for this project and is supported by empirical evidence. History shows that finishing design work prior to construction (even for first-of-a-kind in country designs) saves in the long run (Petrunik, 2015). Starting construction of a nuclear power plant with an incomplete design dramatically increases the risk of rework, redesign, and cascading delays. This has been exemplified by the Westinghouse projects in the south-eastern US, Olkiluoto 3 in Finland, and, to an extent, the AP1000s in China (Royal Academy of Engineering, 2010; Nuclear Intelligence Weekly, 2012). Countries that consistently deliver lower-cost plants – such as Japan, Korea, and China – typically begin construction with >90% completed designs (Buongiorno, 2017). The best-case scenario is to start with a reference plant already in operation, with design details and construction documentation. Designs can be then modified to accommodate engineering codes and standards in a new country/market. The definition of a complete design should include: (1)

licensed and no longer subject to regulatory changes, (2) designed for constructability, and (3) 4D build choreography process design complete.

6.8.2 Design for constructability

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The concept of "design for constructability" describes the process where, prior to starting construction, the interdisciplinary design team (inclusive of engineers experienced in nuclear construction) performs detailed engineering in alignment with the construction planning team. The regular interactivity between the two teams reveals the effects of plant design on construction execution (and vice versa). The design team can redesign parts of the design that are likely to be problematic or increase construction risk.

6.8.3 Spend sufficient resources on site layout, modelling, and planning prior to construction

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Before construction starts for any area or building, the planning team must produce a project "coordination and control" (C & C) schedule (or similar) which clearly sets out all work requirements for all major project activities, including engineering deliverables, procurement, construction and turnovers, and commissioning. This includes having contractually agreed upon schedules (at least a Level 3)[4] that clearly show the sequencing and planned durations for the work. All interfaces should be clearly defined in terms of access and handovers between services and subcontractors and access and all egress routes for equipment and workers should be clearly defined throughout each construction phase. Documents such as an "integrated construction method statements" or similar must also be created, which acts as the agreed work plan to be read alongside the schedules.

For this to occur, the plant design should be near complete (>=70%)[5] and 3D and 4D simulation models used to highlight the timing and location for component installation and construction as well as all preparatory work (e.g. erecting scaffolding) throughout the project. They also help in ensuring that there is sufficient physical space to enable higher quality construction/welds, minor placement changes, planned maintenance, or repairs. The 4D modelling must be developed together with the construction contractors' input and ensure that access for construction will available, including laydown areas and crane positioning/hook coverage. It should also be available for checking minor plant positional changes and define access routes and access for specialist construction equipment.

When the project delivery organisation has confidence in the C & C schedule (particularly as it relates to the critical path) and agreements that facilitates onsite collaborative coordination are signed (for when things do not go as planned), then the planning phase can be considered over and project construction can begin. Quantifying the "sufficient" amount of resources to achieve this level of preparedness and confidence is quite difficult. However, history has demonstrated that whatever it costs is minimal compared to the financial impact of poor planning/modelling causing a significant delay in the completion of the project.

4 "Level 3" is one of five schedule levels used to coordinate work on a project (a project management term of art for construction projects). Levels 3 schedules refer to "Project Coordination Schedules."

5 This is consistent with what the Project Team learned from the interviews with experts and Project Advisors as well as findings by the Construction Industry Institute based on multiple complex construction projects (not just nuclear).

6.8.4 Increasing modularity in the design should be prioritised by its potential to shorten and de-risk the critical path

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Increasing the amount of the plant designed in modules can provide several benefits. When appropriately applied, it enables more of the plant to be built offsite, which reduces the construction scope (and related cost and risk) and utilises the increased productivity inherent to the manufacturing environment (McKinsey Global Institute, 2017). Manufacturing includes opportunities for more automation, significantly higher productivity, higher and more consistent quality, streamlined testing and inspection processes, tight dimensional controls that are automatically enforced, faster delivery, cost controls, parallel fabrication of modules (reducing sequential delay linkages), and a multitude of other benefits. Incorporating modularisation should be done under a strict Quality Assessment regime that includes independent 3rd party assessors[6] to support quality control and ensure that all nuclear codes and standards are met.

Modularity itself, however, does not guarantee cost savings. A vendor's modularity strategy must account for the differences in productivity between factory and construction labours, but also wages (factory worker wages are typically higher than construction labourers). This, along with local content requirements and perceived construction risk for certain components or phases of construction, will guide how much of the plant should be modularised. If ill-conceived or executed, modularisation may increase construction duration and cost (as occurred at Vogtle 3 & 4 and V.C. Summer 2 & 3).

6.8.5 Plant design team should be multidisciplinary

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It is important to include engineers with construction experience on the design team. Therefore, the design team should be multi-disciplinary and include the construction contractor and preferably people with regulatory experience (e.g. ex-inspectors). This can solve problems before they arise (e.g. rebar designs so congested that concrete will not flow into that part of the form), and lead to new, more buildable design solutions.

6.8.6 Design for plant design reuse

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Reusing parts of a design to lower the overall design cost is helpful; however, unless the plant design is specifically designed for reuse, it is can be difficult to avoid redesigning major parts of the plant. Site specific factors such as topography, seismic conditions, and location of cooling water typically demand specific design considerations (especially in the UK but less so in China for example); however, this need not always be the case. Plant designers should identify the most expensive and time-consuming design components and consider if/how they can be automated or designed to be site-agnostic. To this end, they should consider which technologies (software and otherwise) and approaches can enable the most reusable design. All companies that achieved low cost designs focused on reusing as much of the design as possible from plant to plant.

6.8.7 Consider specific design improvements against full costs and potential benefits of implementation

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Irrespective of reactor technology, several decisions can be made by the project owner or design team that can reduce overall cost and construction risk. Many of these decisions require a detailed understanding of the "all in" material costs (i.e. the amount of related engineering and design work, documentation, construction time, specialised equipment and skills, QA, QC, contracting, risk, etc.). A small sample of improvements include:

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6 The most effective way to realise the benefit of 3rd party assessors is to include them at the project outset (i.e. in the design process) and continue their involvement through construction and operations.

- **Seismic Isolation**. Local seismic conditions drive much of the site-specific design work for new build projects. Controlling for seismicity can enable more of the plant design to be standardised and reused.
- **Embedment.** Material costs for the shield building, which houses the reactor pressure vessel, are approximately $200-250/kW. Fully installed, the shield building can be nearly $500/kW. Embedding the reactor below grade and utilising recent innovations in cheaply moving earth could, if properly designed and engineered, offer provide a cost-effective alternative for the shield building.
- **Passive safety features.** Passive safety features enable a safety case to be achieved with simpler design requirements, requiring fewer materials, less regulatory oversight and without the need for complex engineering that can escalate indirect as well as direct costs.

6.9 Operation

The operations phase is integrated with the completion of construction and the delivery of commissioning leading to first commercial operations. Most plants are currently designed for a 60-year life. During this time, operating costs are critically important to the plant's profitability. Plant down-time due to design or construction related factors – or lack of training, experience, or familiarity with the plant – must be minimised.

Key Cost Reduction Opportunities	Relative Importance: Not in regression analysis of CAPEX
■ Involve commissioning staff and operators in project planning and related construction activities ■ Develop excellence in plant operations and maintenance through training and benchmarking such as the World Associated of Nuclear Operators peer review programme	

6.9.1 Involve commissioning staff and operators in project planning and related construction activities

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Operators should be familiar with the plant prior to operations. As soon as they become operationally accountable under nuclear site license, they should be trained, enabled, and confident. Therefore, it is beneficial to include operators on the project planning and commissioning teams and involve them directly in related construction work/decisions. This should be done as early in the process as possible, as avoiding or minimising design changes (leading to schedule delays) is vital. This will lead to a shorter commissioning period as well as a shorter window between the initial fuelling and COD.

6.9.2 Develop excellence in plant operations and maintenance through training and benchmarking such as the World Associated of Nuclear Operators peer review programme

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This enhances safety and performance and has demonstrated to minimise unscheduled outages, which increase a plant's capacity factor (and thereby lower LCOE). This should include early access to the plant simulator.

7 Reliability of Report Contents

Several factors support the ETI's ability to rely on the report contents:

- **Evidence-base and systematic approach.** As directed by the ETI, the project team captured a substantial evidence base of cost drivers for historic, contemporary, and advanced reactor designs. The ETI Cost Database includes recent projects that span the globe and reflect a spectrum of highly successful project deliveries by renowned consortia operating as well as projects that have been plagued by challenges from the start. The methodologies, data collection, and structure of the database and model have been vetted by the ETI, the project advisors, and reviewed and approved by the Independent Reviewer.
- **Large pool of project participants and consultees with direct project experience.** The project team was extremely fortunate to interview several senior directors and construction managers who have been involved in nuclear plant delivery over the past few decades. Interviews were restricted to only those who had direct and intimate knowledge of the delivery for a specific plant. The project team conducted interviews (a majority, of which, were in-person) with companies and senior experts from the UK, France, China, Korea, Japan, Canada, and the United States. Findings and insights from these interviews were corroborated by other interviewees, our project advisors, and other experts within the project team's broad professional network.
- **Guidance from project advisors on approach, analysis, and reporting.** The ETI did not require project advisors. However, the project team's network includes some of the most experienced and knowledgeable professionals in the industry. Dr Ken Petrunik, Professor Jacopo Buongiorno, Charles Peterson Esq, and Dr Ben Britton are highly respected and at the top of their respective fields within the industry and offered invaluable guidance and analysis on the project's methods and deliverables.
- **Multiple Independent Reviewer audits.** The project's Independent Reviewer, Dr Tim Stone CBE, reviewed the methodology, ETI Cost Database and model structure, and treatment of costs and evidence base that informed to the project's conclusions as well as this report. He authored separate, independent statements regarding these areas in parallel to this report.

- **Project QA.** The project team developed and strictly adhered to an internal QA process throughout the entirety of the project. The project's QA Manager, Eric Ingersoll, oversaw several internal assessments and inspections of the ETI Cost Database, associated ETI Cost Model, and all three project reports. This included spot-checking the ETI Cost Model formulas and links and comparing model results against manual calculations. All deliverables were exhaustively reviewed to ensure alignment with contract requirements and the ETI's expectations in terms of scope and quality.

While the project team readily acknowledges the relatively small sample size of plants for the regression analysis, alongside the consistency of expert evidence, plant costs, and relevant case studies, there is high confidence that the identified drivers and associated cost reduction strategies are the right things to pursue. The combined evidence, the rigour of the project approach, and the QA in modelling and reporting provide confidence that the results can be relied upon.

8 Conclusions

The project objectives of assembling a credible cost database and associated model, improving the understanding of cost drivers for contemporary UK new build projects and advanced reactor technologies, and identifying potential cost reduction opportunities have been achieved.

The extent of evidence gathered was limited by the time and resources available for the project. However, there is strong confidence in the importance of the cost drivers selected and the associated cost reduction opportunities. The project's figure of merit for cost was based on cost of energy, calculated as Levelized Cost of Energy (LCOE). This is principally driven by three factors, overnight cost (how CAPEX is defined in this report), cost of capital, and Operating and Maintenance expense. Because the scope of the study excluded financing methods and assumed a constant set of interest rates, and because the CAPEX portion of LCOE is currently expected to dominate the LCOE of UK nuclear new builds, understanding the drivers of CAPEX was a major focus of the study.

The weight of evidence of the collected data, interviews, and case studies support the following conclusions:

- A relatively small number of understandable factors drives the cost of nuclear plants. Whilst building nuclear plants takes place through large, complex projects, the findings of this study are straightforward and there was a high degree of consensus among the experts consulted.
- Strong evidence of applicable cost reduction in the UK. There is strong evidence, particularly demonstrated by projects delivered outside of Europe and the United States, that cost reduction opportunities are applicable to new build projects in the UK. Successful new build programmes have lowered costs by consciously designing in ways to maximise captured learning and incentivise cost reduction from all parties. Table 13 on the following page lists the responsible parties (and corresponding cost drivers) that must align and cooperate to realise low costs.

Table 13. **Principal Actor for Each Cost Driver**

Principal Actor	Cost Driver
Reactor Vendor	Vendor Plant Design
EPC	Equipment and Materials; Construction Execution
Labour	Labour
Owner	Project Governance and Project Development
Government and Regulator	Political & Regulatory Context
Supplier Vendors	Supply Chain
Operator	Operations

- **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 implement and manage a well-designed and intentional programme that incorporates multiple cost reduction opportunities by all principal actors.
- **Relatively significant cost reduction is possible outside reducing the cost of capital during construction.** Averaging costs across large Gen III/III+ reactors in Europe and North America corresponds to a "genre" capital cost of $10,387/kW or $132/MWh (LCOE), assuming a construction interest rate of 7%. In our study's methodology, this cost corresponds to having the highest (worst) score for each of the eight cost drivers. If it were possible to improve to the average of the world performance in each cost driver score, this would result in a cost reduction of at least 35% – without reducing the rate of interest during construction (IDC). It is critical to note that this assumes all project stakeholders are pursuing cost reduction opportunities – not just the project developer and EPC. Collective action is required by all project stakeholders, including government, to bring about the integrated programme of activities necessary to realise this potential.
- **Larger Gen III/III+ reactors and light-water SMRs are more market-ready than advanced reactors.** Large Gen III/III+ reactors have the potential to deliver substantial low carbon UK electricity in the near future. There also appears to be potential for advanced reactors to deliver a step change reduction in LCOE below large Gen III+, and a licensed, commercial-scale high temperature gas reactor will be connected to the grid in China this year. It is highly likely that HTGR's will be under active consideration for nuclear new build projects within the next five years. Due to their ability to provide high temperature process heat, and potential for different siting requirements, these reactors may also play a complementary role to the 1.5GW class LWR's. These advanced designs will need to be approved by the UK regulators.
- **Cost reduction and more predictable delivery can reduce perceived risk and potentially lower the cost of interest during construction (reducing CAPEX even further).** Addressing the drivers identified in this study has the potential to reduce project duration and increase the predictability of project schedules as has been demonstrated by Chinese, Korean, and Japanese consortia. This can lower the actual and perceived risk of nuclear construction and the related cost of capital during construction.

- **The cost reductions in "Rest of World" LWRs are a consequence of national nuclear programmes and the consistent, rational implementation of best practices.** National nuclear programmes with a consistent focus on cost reduction enable multiple learning curve effects. Continuity through on-going construction allows companies to systematically realise learning, keeps supply chains at a level of readiness, enables the same EPC consortium and labourers to work from project to project, and allows for economies of scale for components and materials (both nuclear and non-nuclear grade). Long-term, politically-supported fleet programmes, in Japan, Korea, and China have demonstrated repeatable low costs. These low costs are reflected in our ROW genre. Some of these cost reductions were also experienced in the UK, US, France, and Sweden during the height of new build programmes in the 1960s through 1980s. Such low cost nuclear build programmes require long-term cooperation of all key stakeholders involved in plant deliver and relentless focus on driving efficiency and savings across all key cost drivers.
- **Project delivery organisations in China, Korea, and Japan allocate adequate resources toward maintaining constant efficiency improvements in plant delivery.** Many companies formalise the integration of lessons learned in the field to the design process of the subsequent plant. There is living "post-mortem" documentation of what went well (and what did not) so mistakes are very rarely repeated and EPC consortia are always applying the latest construction technology and methods. China, Korea, and Japan are also highly-experienced in delivering large, complex construction projects. Many of the "soft skills" (e.g. logistics, planning, procurement, site management) transfer well to nuclear construction.

  It is important to note that China, Korea, and Japan also enjoy several "contextual" benefits, especially for in-country projects that may not be transferrable to projects in the UK. For example, they benefit from significantly less expensive and more productive labour (i.e. more hours on task). In those countries, the regulator is paid by the government instead of by the reactor vendor or project developer. In addition, the regulator, while being sufficiently independent, is aligned with other project stakeholders on project completion. China benefits from the ability of state-run enterprises to quickly make large decisions once the political direction has been set – decisions that otherwise require a lengthy board approval process for private companies. All three countries benefit from cultures where litigious responses to problems are extremely rare for on-site issues. Nevertheless, none of the 'contextual' factors discussed in this report suggest that that it would not be possible to implement an effective cost-reduction programme in the UK.
- **Recent challenges in North America and Europe new build projects are partially attributable to local "context."** Domestic industry experience has suffered from decades of inactivity and developers have been unable to leverage or depend on and labour or supply chain experience. Therefore, significant resources must be allocated to train or retrain workers and stand up the supply chain. This is both a reflection and result of a lack of a unified, long-term effort and vision between government and companies.
- **Within the 35 cost reduction opportunities identified in this study, the project team identified a smaller group of actions that present the best opportunities for reducing project cost and risk in the UK. This group of actions is strongly supported by the evidence base, interviews, and regression analysis.** These are included in Table 14 on the following page.

Table 14. **Principal Findings by Cost Driver**

Finding	Cost Driver Category
Complete detailed plant design prior to starting construction	Vendor Plant Design
Follow contracting best practices	Project Dev. and Governance
Project owner should develop multiple units at a single site	Project Dev. and Governance
Innovate new methods for developing alignment with labour around nuclear projects	Labour
Government support should be contingent on systematic application of best practices and cost reduction measures	Political and Regulatory Context
Design a UK programme to maximise and incentivise learning, potentially led by a newly-created entity	Political and Regulatory Context
Government must play a role in supporting financing process	Political and Regulatory Context
Transform regulatory interaction to focus on cost-effective safety	Political and Regulatory Context

9 Recommendations

Evidence gathered and analysed during this project suggests that UK nuclear new build has very significant cost reduction potential. Documented experience with multi-unit builds and intentional new build programmes indicate the range of cost savings achievable. This can be demonstrated with this project's cost database and model. Low-cost nuclear builders reduce all costs over time, starting with the most significant. Interaction between costs and drivers is illustrated in this project's database and model. A carefully designed programme that engages all of the key stakeholders with a shared vision and focus on the key cost drivers can start the UK down the path to affordable nuclear power.

How might the UK implement the findings from this study? Two important points for potential further work include:

1. In-depth analysis of captured knowledge and experience (learning) to deliver meaningful cost reduction in new build over calendar time and over multiple projects.
2. Designing a sequence of optimal near-term and subsequent actions by government, developers, the regulator and other stakeholders. This deeper examination of successful new build programmes, and subsequent translation into actions for the UK context should remain rooted in the documented evidence.

The project also identified the potential for a step-reduction in the cost of advanced reactor technologies and SMRs. While such technologies are not yet licensed, nor construction ready, this project provides further evidence in support of early testing of design claims by regulators and the examination of cost reduction strategies by potential investors.

Appendices

A

Appendix: Cost Driver Indicators

The table below presents the cost driver indicators.

Cost Driver	Cost Driver Indicators	
Vendor Plant Design	Plant capacity Previous units in same country Previous units elsewhere in world How many units in a standard design Thermal efficiency	Plant complexity Seismic design Use of 3D CAD software during design process Man hours on the design effort and design cost
Equipment and Materials	Total concrete quantity Total steel quantity Nuclear-grade concrete quantity	Nuclear-grade steel quantity Total equipment-non-nuclear grade Total nuclear-grade equipment
Construction Execution	Initial construction duration estimate Construction delay from initial estimate Detailed design completion at start of construction Planning and preparation for site task labour Use of 3D/4D CAD software in the field Did construction process design include 4D CAD?	Total cost of construction rework Cost of design work prior to construction Cost of design work after start of construction Man hours of design work after start of construction % of construction cost allocated to offsite assembly QA Cost
Labour	Average construction labour wages Work hours per day % of skilled work force with directly applicable previous experience	Cost of worker training / preparation Percentage of work hours on task Ratio of supervisors to workers Construction labour training costs
Project Governance and Project Development	Cost of capital (approx. weighted average cost of capital (WACC) during construction, and long-term financing) Contract structure and complexity (number of primary contractors and subcontractors) Project control	Number of discretionary design changes by project owner/developer Engineering man-hours for discretionary changes Number of units at plant site

Cost Driver	Cost Driver Indicators	
Political & Regulatory Context	Political support for plant project Government role in construction financing Regulatory hourly fee (at time of engagement) Regulators experience in new build projects Site licensing process duration Siting consent cost	Siting consent duration Pace of regulatory interactions Number of changes required by regulator during construction Engineering man-hours for regulatory changes
Supply Chain	Local nuclear supply chain capability and recent experience Nuclear-grade concrete price Non-nuclear-grade concrete price Nuclear-grade steel price	Cost of nuclear qualification of supply chain Cost of ensuring supply chain readiness/availability Non-nuclear-grade steel price Training for supply chain
Operations	Fuel price Staff headcount	Staff wages Capacity factor Unplanned outages

B

Appendix: Case Studies

This section presents case studies on nuclear plants and concepts that illustrate key relationships between costs and drivers. The case studies provide illuminating reasons for wide variation in nuclear cost values around the world, and offer important lessons on potential strategies, as well as pitfalls to avoid, for new nuclear build in the UK and elsewhere. The project team worked closely with company executives and other knowledgeable experts to develop a complete picture of each plant or concept among the case studies, identify the principal causes behind their high or low costs, and highlight the most useful implications for future contexts. Case studies include both built plants as well as proposed design concepts in commercial development.

Sizewell B and Nuclear Electric's proposal for Sizewell C (Operational; Proposed)

Vendor Plant Design	Equipment and Materials	Construction Execution	Labour	Project Governance and Project Development	Political and Regulatory Context	Supply Chain	Operation
●	○	●	○	●	●	●	○

	Sizewell B	NE – Sizewell C (single)	NE – Sizewell C (twin)
Status	Operating	Proposed in the early 1990s	
Plant Capacity (MWe)	1,345	1,345	2,690
Total Capital Cost ($/kW)	$8,315*	$4,841	$3,963
LCOE ($/MWh)	$96	$66	$59
Vendor reactor design	+2	-1	-2
Equipment and materials	-1	-2	-2
Construction execution	+1	-1	-1
Labour	+1	-1	-1
Project Governance and Project Development	+1	0	0
Political and regulatory context	+1	-1	-1
Supply chain	+1	-2	-2
Operation	0	-1	-1
Average Cost Driver Score	**+0.8**	**-1.1**	**-1.3**

*Sizewell B cost includes expenses for first-of-a-kind project and financing assumptions, as explained below

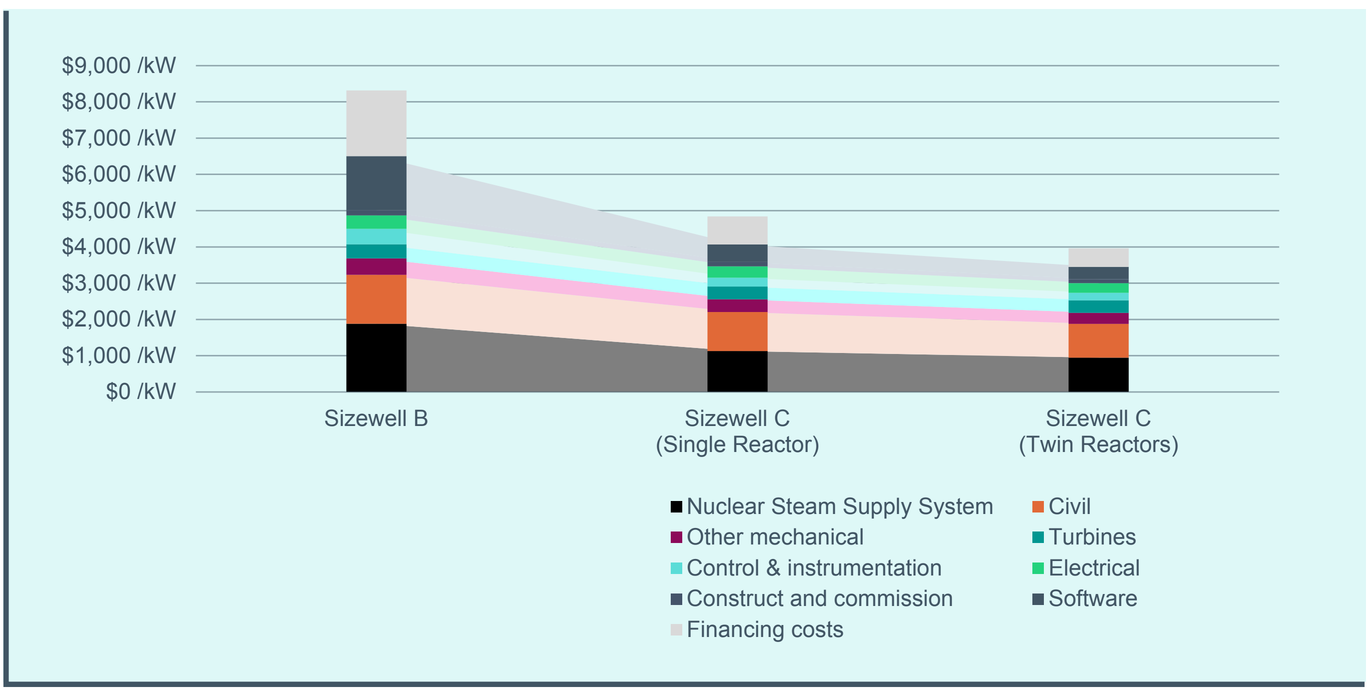
Key Highlights

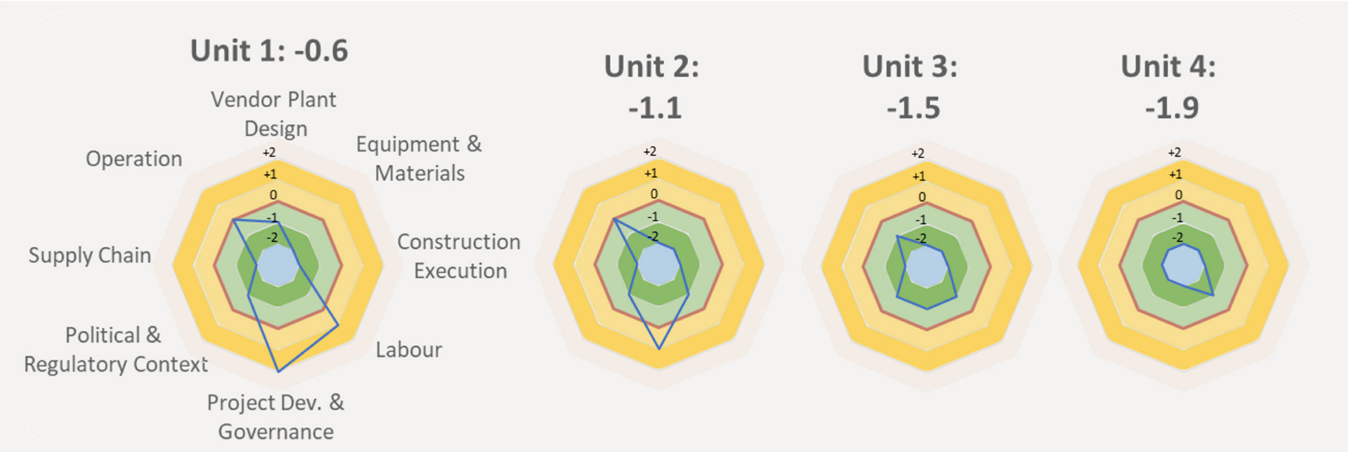
- Feasibility of UK nuclear projects at moderate cost and schedule. In contrast with several subsequent projects in Europe and the United States, Sizewell B demonstrates that successful delivery on time and on budget is achievable in the UK. This was in large part due to effective organisational and operational planning from the outset.
- Large potential cost reductions from learning and fleet effects. The planning documents for Nuclear Electric's (NE) Sizewell C include plausible cost and schedule improvements relative to Sizewell B by recycling proven designs, seizing multi-unit efficiencies at the plant site, and solidifying institutional and supply chain capacity for UK nuclear projects.

The Sizewell nuclear power plant is in Suffolk along the North Sea. Sizewell A, using Magnox technology (graphite moderator and gas cooling), began operation in 1966 and shut down in 2006. Sizewell B was the first PWR in the UK and the most recent nuclear plant built in the country. It began operation in 1995 after a six-year construction period. Although its construction costs are higher than the database average (heavily influenced by many low-cost plants in Asia), Sizewell B stayed within its budget. Developers planned further expansion at the site with similar PWR designs as Sizewell B reached completion but plans for NE's Sizewell C have remained on the shelf since then.

Cost information in the table above for Sizewell B includes expenses for the first-of-a-kind project, such as plant design and software, as well as financing assumptions for consistency with other projects in the ETI Cost Database. NE's Sizewell C shows the specific areas for cost reduction from a multi-unit construction programme (as shown in Figure 20 below). Using essentially the same design from Sizewell B for NE's Sizewell C, whether in a single or twin configuration, would have lowered costs significantly for software (over $1,000/kW savings), nuclear steam supply system (over $750/kW savings), civil works (over $250/kW savings), and controls and instrumentation (over $180/kW savings). The twin configuration would have cost less than $4,000/kW, according to detailed estimates from the planning process in the 1990s, by sharing designs, buildings, systems, and staff across the units.

Figure 20. **Cost Reduction Trajectory between Sizewell B and Nuclear Electric's proposal for Sizewell C**





Vendor Plant Design

Knowledgeable experts have consistently reported that nuclear planners considered their options carefully before building the first UK-based PWR. They decided on the Standard Nuclear Unit Power Plant System (SNUPPS) from Westinghouse, which had already been constructed at two sites in the United States. As noted in The Royal Academy of Engineering (RAE) (2010, p. 17), "the Central Electricity Generating Board, following many years of experience of introducing innovation with almost every new nuclear project, wanted Sizewell B to be based on mature and proven technology with the minimum of innovation necessary consistent with meeting the requirements of safety and performance."

Table 15. **Projected Cost Reductions from Sizewell B to Nuclear Electric's Proposal for Sizewell C (Single & Twin units)**

Capital Costs	**NE Sizewell C Single**	**NE Sizewell C Twin**
Nuclear Steam Supply System	$752 /kW	$935 /kW
Civil	$271 /kW	$419 /kW
Other mechanical	$103 /kW	$147 /kW
Turbines	$38 /kW	$44 /kW
Control & instrumentation	$185 /kW	$224 /kW
Electrical	$53 /kW	$100 /kW
Construct and commission	$23 /kW	$35 /kW
Software	$1,008 /kW	$1,146 /kW
Financing costs	$1,041 /kW	$1,302 /kW
Total Cost Reductions	**$3,475 /kW**	**$4,352 /kW**

Although developers followed a cost-effective strategy by starting from a proven standard design, numerous modifications were made to comply with UK regulatory standards, particularly regarding fire and earthquake risks. Sizewell B went well beyond the safety features in the US reference plant predecessors by doubling the number of separate electrical systems, each with its own back-up generators and structural barriers. The seismic analysis accounted for high pressures and temperatures in a wide range of accident scenarios, leading to an “extremely onerous loading regime for the reactor building making it one of the most complex civil structures then designed” (Royal Academy of Engineering, 2010, p. 18). The vendor plant design score for Sizewell B is slightly above the benchmark for these reasons.

NE’s Sizewell C has a lower score for vendor plant design than the benchmark because it would have largely reused the blueprints for Sizewell B, but with 25% reductions achieved in concrete and steel quantities due to structural and site efficiencies. After first-of-a-kind PWR regulatory review for Sizewell B, less time and effort would have been necessary to install a third unit. Developers for NE’s Sizewell C also prepared plans for adding two units in a twin configuration for further synergies.

Construction Execution

Sizewell B’s construction period of 76 months was only 4 months beyond the planned timeline (Royal Academy of Engineering, 2010, p. 13). Effective execution of the project schedule stemmed primarily from organisational and operational planning. Combining design and construction responsibilities under Nuclear Electric avoided the institutional frictions that often occur in modern megaprojects. The OECD-NEA report *Reduction of Capital Costs of Nuclear Power Plants* (2000, p. 43) notes: “Worldwide experience indicates that a strong customer-vendor relationship, based on mutual competence and supported by the desires for both parties to learn from world operating experience is the best basis for the successful management of a major construction project.”

Careful planning from the earliest stages also contributed to schedule achievement. The Royal Academy of Engineering (2010, p. 16) notes the importance of three-dimensional modelling before and during construction. Nuclear Electric built a large model of Sizewell B in the office and updated it continuously to reflect all design modifications. The Royal Academy of Engineering (2010, p. 16) also highlights the benefits of “involving contractors in the production of detailed integrated schedules to eliminate or de-risk potential interface issues.” Although substantial time was spent on completing designs and planning construction tasks before actual work began, the investment in construction planning paid off in relatively smooth progress through sequencing of overall site activities to achieve project milestones (Royal Academy of Engineering, 2010, p. 19).

NE’s Sizewell C has an even better score than Sizewell B for construction execution because the third unit (or twin units) would have applied institutional capacity and experience from the second unit. The planning team for NE’s Sizewell C developed a detailed construction schedule with total duration of 54 months, a 31% efficiency improvement from Sizewell B.

Project Management and Governance

The Royal Academy of Engineering (2010, p. 20) explains that an important success factor for Sizewell B was the governance structure under the PWR Project Group (PPG). It was carved out of Nuclear Electric plc with its own board. PPG was an integrated delivery organisation that supported every aspect of the project, from the project management office to the engineering, licensing, quality control, quality assurance, and commissioning. Consolidating all these functions, responsibilities, and authorities under one organisation streamlined many processes and enabled short lines of communication. PPG also had clear delegation of duties for external interactions with the regulator, suppliers, and community. The PPG’s success shows the benefits of consolidating project management and governance under a strong central authority.

Political and Regulatory Context

Sizewell B received substantial attention and support from the UK government as the first PWR in the country and sole nuclear plant under construction at that time. A public inquiry led by Sir Frank Layfield gathered information and weighed options from 1983 to 1985, culminating in a 3,000-page report. When the Secretary of State for Energy granted consent for the project early in 1987, he stated in Parliament that "development of a further nuclear station would be a valuable step in achieving greater fuel diversity in our generating system" (UK Parliament, 1987).

Nuclear Electric established an effective system for interacting with the Nuclear Installations Inspectorate (a forerunner of the Office for Nuclear Regulation) throughout construction of Sizewell B. Nuclear Electric managers made timely submissions to the regulators and worked with them to resolve problems quickly (Royal Academy of Engineering, 2010, p. 19). Their mantra to avoid construction delays due to licensing obstacles was "talk to the regulator early and often" (Royal Academy of Engineering, 2010, p. 20).

As with construction execution, NE's Sizewell C has an even better score than Sizewell B for political and regulatory context because the government would presumably have boosted its support in light of the successful experience with the second unit, and managers would have drawn on lessons from the recent interactions. Using similar PWR designs for further expansion at the site would have facilitated regulatory review through fleet effects.

Supply Chain

Sizewell B has a slightly worse score than the benchmark for supply chain because the switch from gas-cooled reactors to a PWR required many adaptations among vendors. The accident at Chernobyl in 1986 also triggered tightening of regulatory standards and quality reviews. Many UK contractors "had to upgrade their facilities and introduce quality assurance programmes that were far more demanding than UK industry had been used to" (Royal Academy of Engineering, 2010, p. 15). The project's success in terms of total cost and schedule demonstrates that the UK nuclear supply chain was ultimately able to meet the various challenges.

NE's Sizewell C has a much better score than Sizewell B for supply chain because of fleet effects, as with other cost driver categories discussed above. It would have benefitted from the fully-fledged UK supply chain for PWR projects that arose for Sizewell B.

Barakah (Units 1-4) (Partially Complete)

Vendor Plant Design	Equipment and Materials	Construction Execution	Labour	Project Governance and Project Development	Political and Regulatory Context	Supply Chain	Operation
●	○	○	●	●	○	○	○

	Unit 1	Unit 2	Unit 3	Unit 4
Status	Commissioning & Testing Phase	>90% Complete	79% Complete	60% Complete
Plant Capacity (MWe)	1,345	1,345	1,345	1,345
Total Capital Cost ($/kW)	$5,452	$4,089	$3,067	$2,300
LCOE ($/MWh)	$74	$62	$53	$47
Vendor reactor design	-1	-2	-2	-2
Equipment and materials	-2	-2	-2	-2
Construction execution	+1	-1	-1	-1
Labour	+2	+1	-1	-2
Project Governance and Project Development	-1	-1	-1	-2
Political and regulatory context	-2	-2	-2	-2
Supply chain	-2	-2	-2	-2
Operation	0	0	-1	-2
Average Cost Driver Score	**-0.6**	**-1.1**	**-1.5**	**-1.9**

Key Highlights

- A consortium led by the Korean Electric Power Corporation (KEPCO) is building four APR-1400 units at the Barakah site in the United Arab Emirates in a fixed fee contract with average cost across the units of $3,700/kW (higher for early units and lower for later units as shown above).
- The project has avoided large schedule delays and cost overruns. Unit 1 completed construction in 2017 and construction completion for Units 2, 3, and 4 are expected to occur in 2018, 2019, and 2020, respectively.
- This case study shows the importance of collaboration and commitment by a broad consortium of experienced companies led by a prime contractor with final responsibility and authority, supported by the highest levels of government.

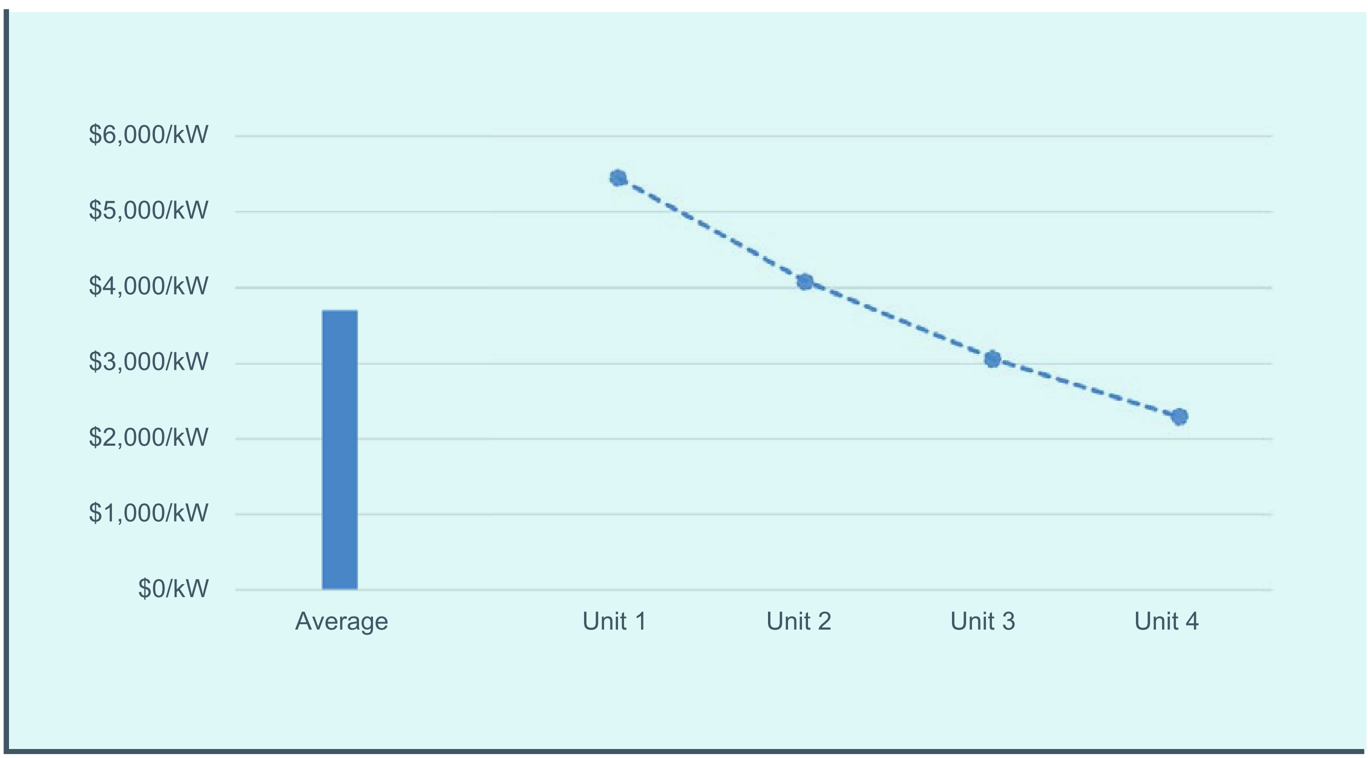
Emirates Nuclear Energy Corporation (ENEC) signed a contract in December 2009 with a Korean consortium to build four APR-1400 units at the Barakah site. The consortium is led by the Korean Electric Power Corporation (KEPCO), which has extensive experience in nuclear construction along with its consortium partners through Korea's fleet programme since the 1990s. The turnkey contract had a total price of $20.4 billion, including funding for construction of a port facility and other project infrastructure

(Kane and Pomper, 2014). The total price indicates an average cost across the four units of $3,700/kW. Early units have higher costs and later units have lower costs through learning effects, which can be seen in the table "Barakah (Units 1-4)(Partially Complete)" above by the particular improvements in construction execution score, and labour score.

Berthelemy and Leveque (2011, p. 2) state that "thanks to an active national programme of nuclear power plant construction, Korea has developed distinct competitive advantages in terms of low cost, high credibility, and high performance." The consortium's success in winning the UAE contract – against French, Japanese, and US rivals – and in making steady progress without major setbacks stems largely from experience earned through Korea's fleet programme, along with support from the Korean president vis-à-vis the UAE. The KEPCO consortium includes its own subsidiaries Korean Hydro & Nuclear Power (KHNP) and KEPCO Engineering & Construction Company (formerly KOPEC) as well as Hyundai, Doosan, Samsung, and the Korean Advanced Institute of Science & Technology (KAIST). The main non-Korean partners are Toshiba and Westinghouse. The Export-Import Bank of Korea (KEXIM) provided $10 billion in project financing, and President Lee Myung-Bak made five visits to the UAE, standing prominently in support of the consortium (Berthelemy and Leveque, 2011, pp. 6-9).

Construction work proceeded slightly late to schedule with delays encountered due to lack of operational readiness. Unit 1 was scheduled into service in early 2017 but will be delayed to early 2020. The reason for delay following construction completion is that the local plant operators need more training (De Clercq and Chung, 2018). Original plans called for unit 1 construction to take 58 months, and the actual duration was only slightly longer at 65 months. This project reinforces the need to have an effective owner in addition to a proven strong vendor. Barakah demonstrates that a stick-built approach to large PWR construction, if done properly, is still very possible without serious delays or cost overruns.

Figure 21. **Extrapolation of Cost Reduction at Barakah Units 1 – 4 ($20.4B)**



Vendor Plant Design

The UAE selected the KEPCO consortium partly because of successful recent projects with the APR-1400 and predecessor designs in Korea (interview with K. Petrunik, 11/18/17). The UAE did not want to experiment with an unproven design or one with a less successful track record. The APR-1400 needed updates for Barakah, however, to thicken the containment building walls by 15 cm to withstand aircraft impact and to account for the higher temperature of intake water (Berthelemy and Leveque, 2011, p. 8).

KEPCO and its Korean partners also developed strategies to minimise construction schedule and cost without compromising safety or performance, based on extensive experience from their domestic programme. Song et al. (2014) note that “to reduce the construction duration of a nuclear power plant, the construction duration of the Reactor Containment Building external wall was cut by placing concrete higher than the conventional level…and by modularising or pre-constructing the equipment hatch.”

Labour

Park and Chevalier (2010, p. 225) describe the focus on key goals and incremental improvement among KEPCO’s top executives. The CEO set up a “war room” in the basement of KEPCO’s headquarters where a large team prepared the UAE bid for seven months surrounded by posters proclaiming, “UAE Nuclear Exports, We Must Do It!” and “Go UAE, Yes We Can!” This shows that managers and corporate commitment are important factors in nuclear projects alongside the productivity and wage measures for engineers, technicians, and manual workers.

KEPCO uses other strategies as well to instil determination and camaraderie among staff. A pioneer of the Korean nuclear industry, Dr Chang Kun Lee (2007, pp. 34-35), describes how KEPCO has sent fresh recruits to a US Marine Corps camp or Buddhist monastery as an initiation. “Even those who were initially reluctant to join the camp later expressed their great satisfaction at having completed the tough training, saying that they are now better prepared for difficult tasks and challenges at work.” Evidently these non-traditional methods, including an initiation for 29 recruits in 2007, helped build and maintain esprit de corps for the massive UAE project.

Many Korean workers are on site at Barakah, but Emirati and third-country workers make up the majority of the workforce (Song et al., 2014, p. 180). The consortium designed and implemented a two-shift system for the rebar work to enhance efficiency.

Project Governance and Project Development

Barakah’s success is tied directly to the way the RfP was structured and carried out. The bidding process was intentionally designed to avoid as many of the past mistakes as possible. In fact, ENEC engaged Pillsbury, an international law firm with directly relevant expertise, to set up the bidding process, analyse recent nuclear transactions to learn what went wrong, and use those lessons learned as guiding principles for the RfP and bidding process (Pillsbury, 2017).

Bidding parties were required to include reactors that had been built and licensed in the country of origin. Therefore, first-of-a-kind reactors were not considered eligible. Political influence was prohibited, although it was expected that the project would be financially “backstopped” by the bidder’s government. Bidders also had to provide separate estimates for each of the four proposed units, demonstrating the economies of scale and type of learning that the vendor expected to realise. In the contract, 50% of the profit was tied to on-time and on-budget delivery.

The KEPCO consortium shows the value of clear responsibility and authority under the prime contractor. Berthelemy and Leveque (2011, p. 9) note that the French bid by Areva, Total, and GDF-Suez, which split the risk among the partners, was less appealing to the UAE because it seemed to make legal battles more likely and dilute the incentives for project success.

Vogtle (Units 3 & 4) (Under Construction)

Vendor Plant Design	Equipment and Materials	Construction Execution	Labour	Project Governance and Project Development	Political and Regulatory Context	Supply Chain	Operation
●	○	○	○	●	○	●	○

	Unit 3	Unit 4
Status	Under Construction	Under Construction
Plant Capacity (MWe)	1,117	1,117
Total Capital Cost ($/kW)	$11,950	$11,950
LCOE ($/MWh)	$127	$127
Vendor reactor design	+2	+2
Equipment and materials	+2	+2
Construction execution	+2	+2
Labour	+2	+2
Project Governance and Project Development	+2	+2
Political and regulatory context	+1	+1
Supply chain	+2	+2
Operation	+1	+1
Average Cost Driver Score	**+1.8**	**+1.8**

Key Highlights

- The expected completion dates for the two Westinghouse AP1000 units at Vogtle in Georgia (US) have been pushed back by over 5 years, leading to total expected construction durations of over 13 years from schedule approval and nearly 9 years from first nuclear concrete pour.
- The expected cost for these units has nearly doubled from the initial estimate of $6,400/kW to the latest estimate of $11,900/kW.
- Although the AP1000 incorporates modularity and simplified systems, numerous setbacks for this first-of-a-kind project in the US have pushed Westinghouse into bankruptcy.
- The plant owner has responded to governance problems and Westinghouse's bankruptcy by hiring Bechtel to complete the project under a cost-plus contract with broader financial risk-sharing between the owner and contractors.
- Supply chain problems have primarily revolved around off-site fabrication of submodules that did not meet specifications for fitting with other plant components.

Georgia Power Company (GPC) is currently building two additional reactors at the Vogtle plant, which already has two units from the 1980s. Vogtle 3 and 4 are the first Westinghouse AP1000 PWRs in the United States and the country's first new nuclear projects in three decades. Partly as a result of their FOAK status, the units have suffered numerous setbacks in the ten years since GPC requested approval from the Georgia Public Service Commission (PSC) and the US Nuclear Regulatory Commission (NRC). The expected cost in the initial plans from 2008 was $6,400/kW, and the expected completion year for Unit 3 was 2016 (about 5 years after pouring the first nuclear concrete), followed by Unit 4 in 2017. The approval process and initial site work went slower than expected, and further problems arose with construction of the large concrete modules. The latest estimates put the cost at $11,950/kW and completion in 2021-2022. As the two most costly projects in the ETI Cost Database, the Vogtle units have scores of +2 in six cost driver categories.

A large amount of public non-proprietary information is available on the Vogtle units through filings with the PSC, which represents the interests of power customers in Georgia by approving or disapproving funding requests by GPC. The utility must submit detailed reports on work progress and expenditures to the PSC every six months. PSC staff and outside parties also perform in-depth analyses of the construction project as part of the regulatory process. LucidCatalyst used this public non-proprietary information from the PSC website to populate database values and prepare this case study for Vogtle 3 and 4.

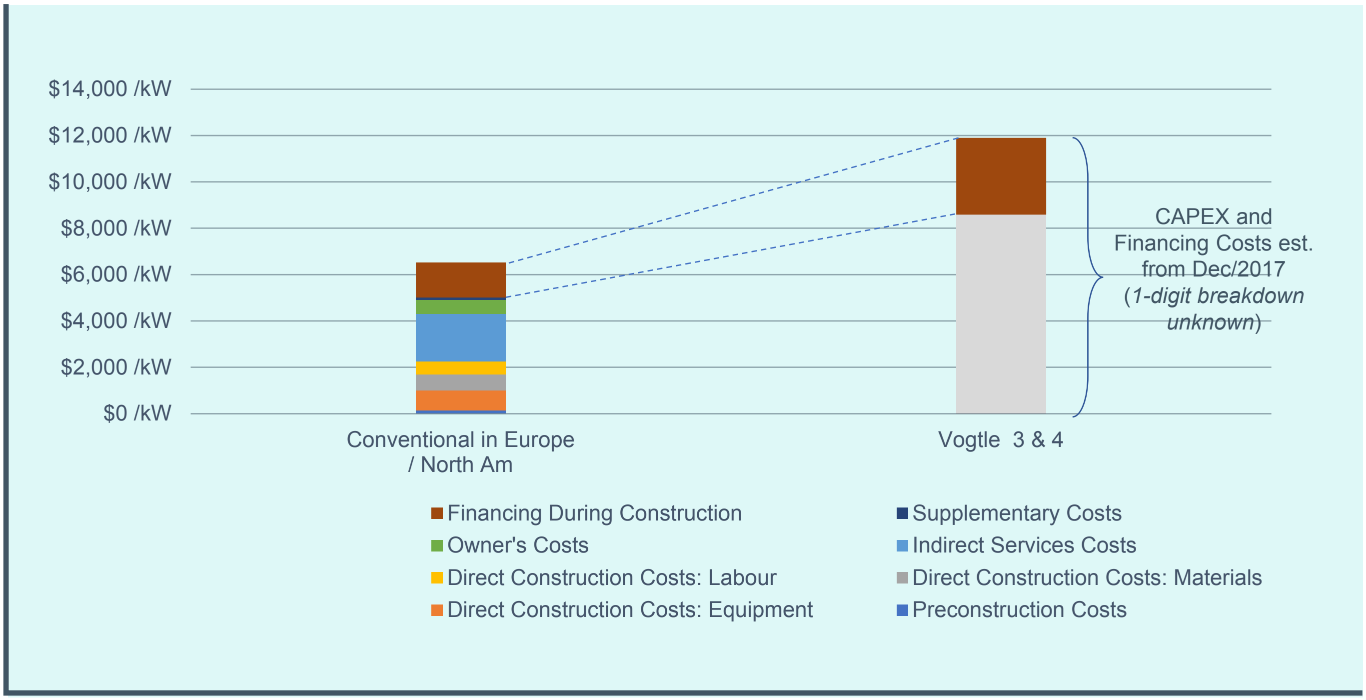
As shown in Table 16 below of Unit 3 milestones from recent sources, delays have occurred throughout the construction project. The latest forecast for completion date is over 13 years after schedule approval from the PSC and nearly 9 years after first nuclear concrete (which was pushed back by nearly 2 years from the initial plan). The next subsections describe the factors causing schedule delays and cost overruns in terms of three cost driver categories: (1) vendor plant design; (2) Project Governance and Project Development; and (3) supply chain.

Table 16. **Vogtle Unit 3 Milestones**

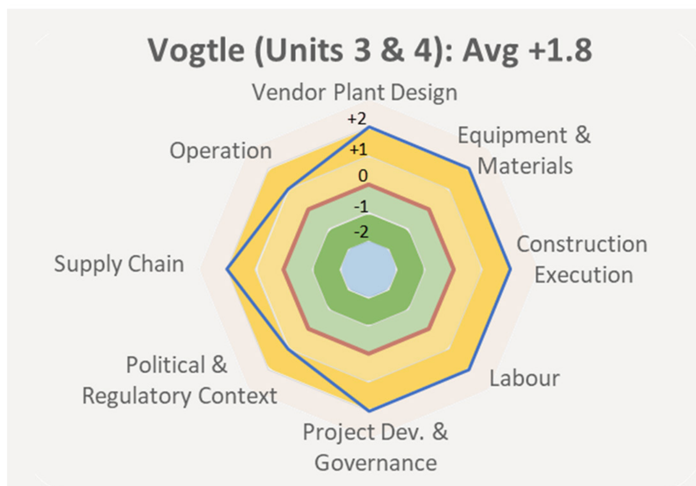
	Initial (July 2008) Schdule	**Actual Completion**	**Latest (August 2017) Schedule**	**Delay**
Receive scheduel approval from Georgia Public Service Commission	July 2008	-	-	-
Receive design approval from NRC	February 2011	December 2011	-	0.9 years
Start nuclear island rebar	May 2011	February 2012	-	0.8 years
Receive constuction and operation licence from NRC	June 2011	February 2012	-	0.6 years
Pour first nuclear concrete	June 2011	March 2013	-	1.7 years
Install fuel handling and storage module (CA20)	December 2011	March 2014	-	2.3 years
Install primary containment module (CA01)	March 2012	August 2015	-	3.4 years
Begin commercial operation	April 2016	-	November 2021	5.6 years
Duration from schedule approval to operation	**7.7 years**	**-**	**13.3 years**	**5.6 years**
Duration from first nuclear concrete to operation	**4.8 years**	**-**	**8.6 years**	**3.9 years**

Sources: The Kenrich Group, 2016, Figure 4 and Georgia Power Company, 2017.

Figure 22. **Cost Comparision of PWR Benchmark and Vogtle Units 3 & 4**



Vendor Plant Design



The AP1000 reactor from Westinghouse is a Gen III+ design with passive safety systems and modular assembly. It has 45% less seismic building volume, 35% fewer pumps, 50% fewer safety-grade valves, and 70% less cable than previous reactor designs without passive safety (Westinghouse, 2011, p. 7). The NRC approved the AP1000 generic design in 2006 after 4 years of review. GPC submitted requests to the NRC in 2008 for design approval and construction licences for two AP1000 units at the Vogtle site. Two plants in China – Sanmen and Haiyang – also began construction of AP1000 reactors in 2008.

Although the AP1000 projects in China provided some useful lessons to Westinghouse, GPC, and the NRC, it also delayed the Vogtle project because Westinghouse oftentimes gave the Chinese projects top priority and revised designs for Vogtle as issues arose at the Chinese sites (The Kenrich Group, 2016, p. 42). Another cause of delays during the regulatory review process was the NRC's announcement in 2009 of new design requirements to protect nuclear plants against aircraft impacts (US Nuclear Regulatory Commission, 2009).

As shown in the Table 16 above, these factors delayed design approval from NRC by 11 months and delayed the construction licence by 8 months. The construction team has submitted more than 60 licence amendment requests to the NRC since receiving the licence in 2012 (Georgia Power Company, 2017, pp. 26-27). By adding to engineering and financing costs, the long regulatory approval process and frequent redesigns have contributed significantly to high total costs for the Vogtle units.

Project Governance and Project Development

In December 2017, Georgia Public Service Commission (PSC) staff advised the PSC commissioners to cancel the costly and prolonged expansion at Vogtle, citing mismanagement by Georgia Power Company (GPC) and a dysfunctional contractor consortium. The PSC staff concluded that "the Project has not been effectively managed, and it is apparent that there has never been a realistic, and therefore achievable, fully integrated schedule for the Project" (Georgia Public Service Commission, 2017, p. 11). In January 2018, the PSC commissioners approved continuation of construction but introduced new penalty provisions on GPC, including a lower rate of return, if the units are not complete by 2021-2022 (Georgia Public Service Commission, 2018, pp. 17-19).

Governance problems at Vogtle stem largely from the complex contract in 2008 between GPC and a consortium led by Westinghouse. The company's triple role as nuclear system supplier, overall plant design engineer, and consortium leader posed acute challenges for Westinghouse, especially while its main focus was the Chinese projects (The Kenrich Group, 2016, pp. 41-42). The other main consortium members were The Shaw Group (including its subsidiary Stone & Webster) and CB&I. Shaw was already a minority owner of Westinghouse from the 2006 deal in which Toshiba acquired majority control. In 2013, Shaw executed a "put" option from that deal requiring Toshiba to buy out Shaw's stake in Westinghouse. In the same year, CB&I acquired Shaw. As costs at Vogtle escalated and major lawsuits loomed over the contract parties, Westinghouse acquired CB&I in 2016 and engaged Fluor as a new major subcontractor. It continued to face financial hardship, however, and declared bankruptcy in 2017, which has triggered large payments from Toshiba to GPC.

GPC did not exercise forceful oversight over the convoluted consortium. During testimony to the PSC in 2015, an expert witness noted contractual constraints: "The way the EPC contract is structured, there is not a great deal of management that the company can actually do. … Once they begin managing the work then they lose the protection of the EPC contract" (quoted in The Kenrich Group, 2016, p. 122). After the bankruptcy of Westinghouse in 2017, GPC took more control of the project and hired Bechtel to complete the work under a cost-plus contract (Georgia Public Service Commission, 2017, p. 9). The new contract structure gives GPC more financial incentive for effective management than the initial contract with Westinghouse, which set fees in advance subject to contingency and bonus provisions.

The evolution of project governance in this case study illustrates the importance of effective management by a plant owner who shares in financial risk and a clear chain of command through a prime contractor.

Supply Chain

Several supply chain problems also emerged early in the Vogtle project because "no new [nuclear] plants had been built in the United States in over 30 years" and "there was a limited supply of engineers, superintendents, craft, and other key construction personnel" with relevant experience (The Kenrich Group, 2016, p. 5). In a sign of trouble at the very beginning, the NRC determined in March 2012 that rebar installation for the nuclear island did not comply with approved designs. In response to these safety concerns, GPC ordered the contractors to remove the rebar and reinstall it. The rebar work was scheduled to take 3 months but actually took 13 months (The Kenrich Group, 2016, pp. 66-73).

Although the AP1000 design incorporates modularity and simplified systems, off-site submodule fabrication also pointed up significant supply chain issues. Shaw built submodules for the Vogtle units at a facility in Louisiana. A quality assurance manager at the facility later said the workers there were "clueless" about complex weld geometry and nuclear safety culture, adding that discussions between Westinghouse and Shaw vis-à-vis design changes always went through a "tortuous path, taking months and months" (Korman, 2017). When submodules arrived at the Vogtle site, many did not fit in with other plant components (The Kenrich Group, 2016, esp. pp. 104-105).

These supply chain problems show the obstacles to successful FOAK projects, particularly when the country lacks experienced nuclear construction workers and equipment vendors after a long period of inactivity.

Roll-Royce Small Modular Reactor (SMR) (Unbuilt; Design in Commercial Development)

Vendor Plant Design	Equipment and Materials	Construction Execution	Labour	Project Governance and Project Development	Political and Regulatory Context	Supply Chain	Operation
●	○	●	●	○	○	○	○

Status	Proposed
Plant Capacity (MWe)	400 – 450
Vendor plant design	-1
Equipment and materials	0
Construction execution	-2
Labour	-1
Project Governance and Project Development	-1
Political and regulatory context	-1
Supply chain	-1
Operation	0
Average Cost Driver Score	**-0.9**

Key Highlights

- SMR plant design incorporates many of the key delivery recommendations included in this report
- Design basis reflects ease of licensing, maximisation of manufactured content and on-site assembly (significantly reducing on-site construction), operations, decommissioning, ability to access project financing capital, LCOE, and several considerations specific to the target market (e.g. supply chain readiness, seismic conditions, etc.)
- Innovative, modular concept, which, if successful, could revolutionize nuclear power plant delivery
- Plant design is more amenable to the benefits /cost reductions provided by a “fleet” of plants

Rolls-Royce is continuing to develop its design for a small, modular PWR with a power rating between 400 – 450 MWe. The company’s plant design includes multiple, advanced passive safety systems and reflects a comprehensive understanding of the broad range of risks and challenges faced by conventional approaches to nuclear plant delivery. In addition to their primary focus of reducing LCOE, the company has intentionally incorporated several “down-stream” considerations into the design process such as: ease of plant licensing, manufacturability, design reuse, reduced construction scope, Optimised inspection and QA, operation, and decommissioning, and ease of accessing commercial financing. The SMR design significantly reduces or avoids major cost and risk centres associated with stick-built construction approaches. While the company continues to develop its first-of-a-kind plant, the costs and cost drivers presented in this section reflects the “best case” scenario for its 5th-of-a-kind plant. As such, it assumes a licensed design as well as supply chain with the experience, learning, and “tooling up” gained over four preceding plants.

Vendor Plant Design

Rolls-Royce's SMR design philosophy represents is a dramatic departure from previous nuclear designs. Fundamentally, the company is "productising" a nuclear power station (i.e. designing something that can be produced repeatedly with little to no modification), which represents a dramatic departure from the traditional "project-based" approach. Their plant design reflects every effort to "design out" or minimise major cost and risk centres whilst Optimising for LCOE. Every plant component (including the reactor itself) is small enough to enable standardisation and modularisation across the entire power station. Modules can be transported to the site by road, rail, or sea, which supports the company's aspirational target of a 500-day build schedule.

The SMR design is built in a 4D software environment which allows Rolls-Royce to choreograph and Optimise the entire build schedule upfront. The location of each module is known at any given time and suppliers are provided explicit details on their design envelope and delivery logistics. This helps lower construction risk, which has the effect of lowering construction financing. Rolls-Royce's SMR also includes conventional PWR technology that allows them to leverage the existing fuel supply chain and provide a relatively straightforward licensing process for the UK regulator.

In theory, a standardised, modular design and factory-based manufacturing approach should allow for a more efficient inspection process by the regulator and 3rd party inspectors. The use of such technologies like radio frequency identification reader (RFID) tags, blockchain, and other self-tracking technology can improve the quality and transparency of data across the supply chain and allow 3rd party inspectors (e.g. Lloyd's Register) or regulators to quickly understand the provenance and/or operating life of important components.

Construction Execution

Rolls-Royce's plant delivery approach includes two, distinct work phases. The first phase includes all the required civil works and construction of a foundation slab equipped with an aseismic bearing pad. The aseismic bearing pad "neutralises" the seismic and thermal loads of the region. Solving for the local geologic and geographic constraints enables the plant (sitting atop this foundation) to be highly standardised. The second work phase includes all other construction activities through COD. Rolls-Royce plans to complete both work phases under a purpose-built, site construction canopy that provides protection from the environment (and vice versa). The controlled and protected working area allows for 24/7 working conditions and dedicated teams that can bring learning from one power station to another.

Before starting construction, Rolls-Royce's plant design is required to be nearly 100% complete. A completed design and well-developed project planning process (discussed above) is essential to successful project delivery. The organising principle around Rolls-Royce's design is the assembly of pre-fabricated modules on site. Under Rolls-Royce's protective canopy is a large, organised laydown area for the modules as well as three, fixed cranes to move the modules into place. The build site operates more as a large factory than a typical construction site.

Modular construction provides a substantially greater opportunity to reduce sequential delay linkages during construction. In other words, delays in Rolls-Royce's plant delivery can be measured as the longest individual delay (in delivering or installing one module) instead of the sum of all individual delays. Also, a reduction in schedule exceedance risk directly translates to reduction in budget exceedance risk (which, can dramatically reducing interest payments). With modules constructed offsite, rate limiting steps to plant delivery are effectively limited to the pace of assembly and QA, and ability for supplier to deliver on time.

Rolls-Royce's two phased delivery approach bifurcates risk into a small, higher-risk pool and larger, lower-risk pool. The first phase is expected to be 10% of CAPEX and require relatively higher borrowing costs. The second phase is considered relatively low-risk – especially as more plants are deployed – and accounts for the remaining 90%. Therefore, the overall borrowing costs are expected to be relatively low.

Labour

Reducing onsite labour is critical to reducing costs. The hours actually spent on task can be highly variable and training costs are often significant. Depending on the region, work breaks, daily security briefings, transportation to/from site, and other commitments can reduce the number of actual hours on task per day. Costs associated with labour training on nuclear sites – especially for specialised skills such as welding and pipework – can be significant (this is particularly true in markets that have not experienced a new build project in many years and/or have not been able to preserve or pass down learnings and experience from previous projects).

In replacing onsite labour with offsite module manufacturing, Rolls-Royce allows for much greater overall productivity, controlled environments for higher and more consistent quality, greater opportunities for learning effects by dedicated teams, cost control, as well as the avoidance of expensive, one-off components. Members of Rolls-Royce's project consortium have reported man hour reductions >40% on actual construction projects through modularisation and offsite manufacturing. Reduction in man-hours also translates to reduction in supervision, which is a non-trivial percentage of total construction costs.

Rolls-Royce includes its designers and contractors into an overall, multi-disciplinary project management organisation. This organisation performs comprehensive pre-planning and produces integrated programs and detailed scheduling with support from main contractors. This type of coordination and planning keeps the project on the critical path and helps avoid disputes between contractors and labour.

Advanced Reactors: Generic Molten Salt Reactor

Vendor Plant Design	Equipment and Materials	Construction Execution	Labour	Project Governance and Project Development	Political and Regulatory Context	Supply Chain	Operation
●	●	●	○	○	○	●	●

Status	Proposed
Plant Capacity (MWe)	190 – 1,000 MWe
Total Capital Cost ($/kW)	$3,664
LCOE ($/MWh)	$51
Vendor plant design	-2.0
Equipment and materials	-2.0
Construction execution	-1.5
Labour	-1.0
Project Governance and Project Development	-1.0
Political and regulatory context	-0.5
Supply chain	-1.0
Operation	-1.0
Average Cost Driver Score	**-1.3**

Key Highlights

- Inherent safety eliminates the need for complex expensive safety systems
- Compact core leads to ease of construction and lower costs
- Molten salt fuel guarantees no off-site radioactive release that results in harm to the public
- Some designs economically reuse spent nuclear fuel
- Dramatically less waste and no long-term waste storage issues

Molten salt reactors (MSR) are a class of advanced reactors that use molten fluoride or chloride salts as the primary reactor coolant and, oftentimes, the fuel itself. Companies are developing several different reactor and salt configurations, each leveraging the unique safety and design advantages of a stable, molten liquid fuel and/or coolant. A typical MSR concept leverages the inherent benefits of molten salt includes dissolving nuclear fuel (enriched Uranium or in some designs, spent nuclear fuel) into the coolant. This enables several benefits over conventional light water reactors, particularly relating to safety, economics, and waste:

Safety

- Unlike conventional reactors, the rate of fission in a MSR is inherently stable. Once the reactor reaches its desired temperature, any increase in temperature results in volumetric expansion of the salt, thereby reducing the rate of reactivity and thus temperature. Therefore, MSRs are considered ‘walk away safe” and could not over heat – even if forced by the operator.
- MSR reactors work at near atmospheric pressure, eliminating the risk of explosion and large release of volatile radioactive substances.
- Melt-down events do not occur as both fuel and coolant are already in a liquid state well below boiling point. Additional safety measures such as control rods or a “freeze plug”[1] may also be used.

Economics

- Higher operating temperatures enables higher thermodynamic efficiencies, the ability to produce high-quality process heat, and a smaller required plant footprint.
- Better load following capabilities than conventional reactors as the reactivity increases when heat is withdrawn via the heat exchangers.
- Operating at low-pressure obviates the need for expensive containment, steel core vessel, piping and safety equipment needed to contain radioactive steam in conventional reactors. Containments can be smaller and thinner.
- Many MSR designs have the capability of on-line fueling, which enables higher capacity factors and thus improved LCOE.
- Possibility of air-cooling or low requirement for cooling water.

Waste

- Very high fuel burn-up is achievable (typically over 90%), which creates relatively less radioactive waste per unit of electricity. Typical enriched uranium fuel is rendered inactive after only a few percent burn-up.

- Gases released from the molten fuel can be can continuously captured and removed. Because the molten fuel is unaffected by these releases, it can be left in the reactor until nearly all the actinides are fissioned, leaving only elements that are radioactive for a relatively short time (300 years or less). This means that not only do MSRs create relatively little waste, the waste only requires a few hundred years of safe management as opposed to several thousand years for conventional nuclear plants.

As of spring 2018, there are at least 13 different companies and organisations developing molten salt reactors.[2]

Vendor Plant Design

The inherently safe operating characteristics of molten salt reactors enables several design benefits. The reactor operates near atmospheric pressure, which dramatically reduces both the quantity of engineered safety systems as well as the specification (or classification) of the safety systems. Such low operating pressures make an expensive pressure vessel unnecessary and the containment building can be

1 A freeze plug describes a device that, if the temperature gets too hot in the reactor, melts and empties all the liquid fuel by gravity into graphite tanks configured to prevent criticality.

2 In alphabetical order: CNRS (FR); Copenhagen Atomics (DK); Elysium (US); Flibe (US); International Thorium Energy & Molten Salt Technologies Inc. Company (JPN); Kairos (US); Moltex (UK); Seaborg (DK); Shanghai Institute of Applied Physics (CHINA); TerraPower (US); Terrestrial Energy (CAN); ThorCon (US); Transatomic (US).

held to much less strict design specification. Many MSR reactor designs are placed below the ground level. Without high pressure steam in the nuclear island, there is no need for the related equipment or engineering, which reduces overall construction complexity and cost. Many MSR designs have orders of magnitude smaller footprints than conventional reactors of the same power rating.

Many MSR designs in commercial development are modular and expected to be partially or completely fabricated in a factory environment. Most modules are sized to be road transportable. One company, ThorCon, has a plant design that will be almost entirely fabricated in a shipyard.

Equipment and Materials

MSR plant designs are much smaller (and more power dense) than conventional plants and require less safety-grade materials (and components). This means that materials are not only less expensive, but the training, qualification, documentation, supply chain QA (and onsite component QA) is drastically reduced.

Construction Execution

Most MSR designs are based on having a relatively high degree of factory- or shipyard-based production. This is intended to limit on-site construction and shorten construction schedules. Shortening the design and construction period leads to lower borrowing costs overall, and lower financing costs on the borrowed amount.

Operations

The continuous refueling capability and reduced reactivity controls for MSR reactors mean that it can operate for very long periods without shutting down. This improves its economic efficiency and reduces stresses on plant components arising from thermal cycling. Online refueling also enables far simpler reactor control systems.

Japan Atomic Energy Agency's High Temperature Gas Reactor (HTTR) (Test Reactor; Design in Commercial Development)

Vendor Plant Design	Equipment and Materials	Construction Execution	Labour	Project Governance and Project Development	Political and Regulatory Context	Supply Chain	Operation
●	●	○	○	○	○	○	○

Status	Proposed
Plant Capacity (MW)	275 MWe
Total Capital Cost ($/kW)	$2,687
LCOE ($/MWh)	$41
Vendor plant design	-1
Equipment and materials	0
Construction execution	-2
Labour	-1
Project Governance and Project Development	-1
Political and regulatory context	-1
Supply chain	-1
Operation	0
Average Cost Driver Score	**-0.9**

Key Highlights

- More cost-competitive than most other commercially-available nuclear technologies
- Operational HTGR test reactor with over 15,000 hours of continuous operation
- 20 years of R&D for complimentary helium gas turbine, which can enable a ~50% efficiency for a 275 MWe plant
- Demonstrated continuous hydrogen production at ~50% efficiency
- Production-ready quotes from suppliers suggest a ~$2,500/kW CAPEX for a 4-unit, 1,100 MWe plant (4 x 275 MWe)

The Japan Atomic Energy Agency (JAEA) has been developing high temperature gas reactor technology since the mid 1980's. In the early 1990's a decision was made to build a test facility that was large enough to meaningfully test commercial scale or close to commercial scale components and provide the technical basis for all aspects of a 100MWe+ commercial scale power plant. The 30MWt High Temperature Engineering Test Reactor (HTTR) was completed in 1998 and has been undergoing test operations ever since. JAEA's HTGR developments constitute a relatively mature advanced reactor technology platform due to extensive testing of fuels, reactor materials, fuel handling procedures, control systems, balance of plant component development and demonstration, safety related tests, and accident simulations. In addition to the technology validation, there has been an intensive design focus on cost reduction through: simplification, modularity, factory-based manufacturing, simplicity of safety, simplicity of operation and control-reduced operational cost (fewer staff). Operational testing has exceeded 15,000 hours of continuous operation, enabling the development of the full complement of operational procedures and numerous safety related tests have been conducted and documented.

Due to the Great Eastern Japan Earthquake of 2011, all nuclear power plants and test facilities in Japan have undergone a thorough safety review and many new requirements have been put in place. The HTTR facility has also been the subject of an extensive and successful review by the Nuclear Regulation Authority (NRA) and, as a result the NRA has become very familiar with the design and operation of the HTTR and the design and safety case for the proposed commercial pilot.

Concurrent R&D work has demonstrated key components of a complimentary helium-based gas turbine technology that allows a more efficient and lower cost direct cycle power generation system. Compared with steam turbine technology, the direct cycle helium turbine enables an improvement in overall efficiency, a more compact arrangement for the plant, and the turbine power cycle components are expected to cost less than a comparable steam turbine system. The helium gas turbine has been under development for 20 years and several key milestones have been reached, including demonstrating a compressor with commercial level of efficiency (89%) for a 150 MWe turbine (~50% power level for a 275 MWe unit design). High temperature gas cycle enables CHP for medium temperature applications such a desalination and industrial heat, without reducing electrical production, which is not possible with steam cycle.

The HTTR was also designed to demonstrate highly efficient direct thermochemical hydrogen (~50% efficient) using the sulphur-iodine process. Development work has focussed on process validation and materials qualification, with suppliers fabricating components using commercial processes and methods.

Costing for the 275MWe and 100MWe+ commercial designs has been developed through production-ready quotations from suppliers who have been involved in the project for over 15 years, first participating in building the 30MWt HTTR and then participating in the design and cost reduction process for the commercial scale units (see Table 17 below). These commercial suppliers have designed the required components to enable cost-effective manufacturing in their facilities and the JAEA team has led several rounds of design for cost reduction with these manufacturing partners.

The combination of extensive development and testing, design for manufacturability engagement with suppliers, and review of the designs and operations with the NRA supports the proposal by the management team at JAEA's HTTR that they could have a 100MWe+ commercial prototype built at the JAEA site and operational in approximately 5 years if funding were made available today. If true, this is a considerably shorter time horizon for deployment of this technology than is typically assumed in UK nuclear policy frameworks.

Table 17. **Estimated cost of a 1,110 MWe (4 x 275) HTGR***

	$/kW	$ Million (2017)	$ Million (2005)	Million Yen (2005)
Components	**$1,744**	**$479.53**	**$396.31**	**¥43,594**
Reactor Components	$683	$187.88	$155.27	¥17,080
Reactor pressure vessel	$164	$45.05	$37.23	¥4,095
Core components	$169	$46.52	$38.45	¥4,229
Reactivity control system	$122	$33.66	$27.82	¥3,060
Shutdown cooling system	$38	$10.52	$8.69	¥956
Vessel cooling system	$51	$14.14	$11.68	¥1,285
Fuel handling and storage system	$124	$34.11	$28.19	¥3,101
Radioactive waste treatement system	$14	$3.89	$3.22	¥354
Power conversion system	$560	$154.12	$127.37	¥14,011
Turbine and compressor	$137	$37.55	$31.04	¥3,414
Generator	$57	$15.79	$13.05	¥1,435
Power conversion vessel	$75	$20.59	$17.02	¥1,872
Heat exchanger	$120	$33.09	$27.35	¥3,008
Heat exchanger vessel	$89	$24.42	$20.18	¥2,220
Hot piping	$82	$22.68	$18.75	¥2,062
Auxiliary system	$269	$73.95	$61.12	¥6,723
Helium purification system	$45	$12.38	$10.23	¥1,125
Helium storage and supply system	$45	$12.44	$10.28	¥1,131
Cooling water system	$59	$16.27	$13.45	¥1,479
Radiation management system	$39	$10.62	$8.77	¥965
Ventilitation and air conditioning system	$55	$15.14	$12.51	¥1,376
Other systems	$26	$7.12	$5.88	¥647
Electric system, controls, instrumentation	$231	$63.58	$52.55	¥5,780
Electric system	$160	$44.00	$36.36	¥4,000
Controls and instrumentation	$71	$19.58	$16.18	¥1,780
Buildings	**$443**	**$121.78**	**$100.65**	**¥11,071**
Total	**$2,187**	**$601.32**	**$496.95**	**¥54,665**

* Cost estimate performed by the project team based on Table 1 in Takei et al. (2006). A similar table can be found in Yan, Xing L. (2017).
The inflation factor used to inflate 2004 dollars to 2017 dollars was retrieved from https://inflationdata.com/.
2003 Dollar Yen exchange rate was retrieved from http://www.macrotrends.net/

The categories of the costs for the 275MWe HTGR are based on quotations for the manufacturing and installation of the listed components, and the NCD project team has clarified that they represent ‘all-in’ costs (i.e. they include some prorated amounts for project management, inspection, design, etc. In this regard, they do not precisely align with the accounting framework used elsewhere in this study. They do not include owner’s costs, operational setup costs (training etc.), and interest during construction (IDC), and some other indirect costs. In a four-unit plant (275MWe X 4) an indicative ‘bottom up’ estimate by the NCD project team indicates that another $500/kW of owner’s and additional indirect costs may be prudent to add to the JAEA estimate yielding a capital cost of $2500/kW. This is the estimate used in our LCOE calculation.

Vendor Plant Design

JAEA’s HTTR technology is estimated to be more cost-competitive than most other commercially-available nuclear technologies. These economics can be further improved by the cogeneration applications being pursued by JAEA. They have already demonstrated H_2 production and are now validating the process using commercially-available components and materials.

Equipment and Materials

The HTTR technology platform has validated key aspects of its complementary, helium Direct Cycle gas turbine power generation system, which is significantly simpler and cheaper than a comparable steam turbine power cycle. This also increases efficiency from a typical rating of 33% typical of Light Water designs to 45-50%. This has the effect of lowers CAPEX/kW by increasing output by approximately 40%. OPEX is also reduced by increasing the output per unit of operating expense.

OffShore Wind Case Study

The offshore wind industry recently smashed expectations with astonishingly low prices – £57.50 per MWh for new build starting in 2022/23. This represents a halving of costs achieved in a five-year period, illustrating very well the power of innovation, collaboration and drive. By identifying and demonstrating cost reduction across key areas including foundations, high voltage cables, electrical systems, access in high seas and wind measurement, the sector has transformed its overall performance on cost and delivery.

Technical routes to increase reliability and size have been examined and achieved. 9MW turbines are already 190m high and need to get even higher. The optimum size will be as tall as the Shard and 15MW. In order to meet the required fleet size (30GW by 2035) off-shore wind deployment must increase significantly from current levels: from one to two turbines per day, whilst moving towards higher power density. Current projects to 2023 / 2025 aim for 10GW installed capacity by 2022, equivalent to 110 turbines per year, at one per day. Future build aims for 30GW by 2035, delivering two per day.

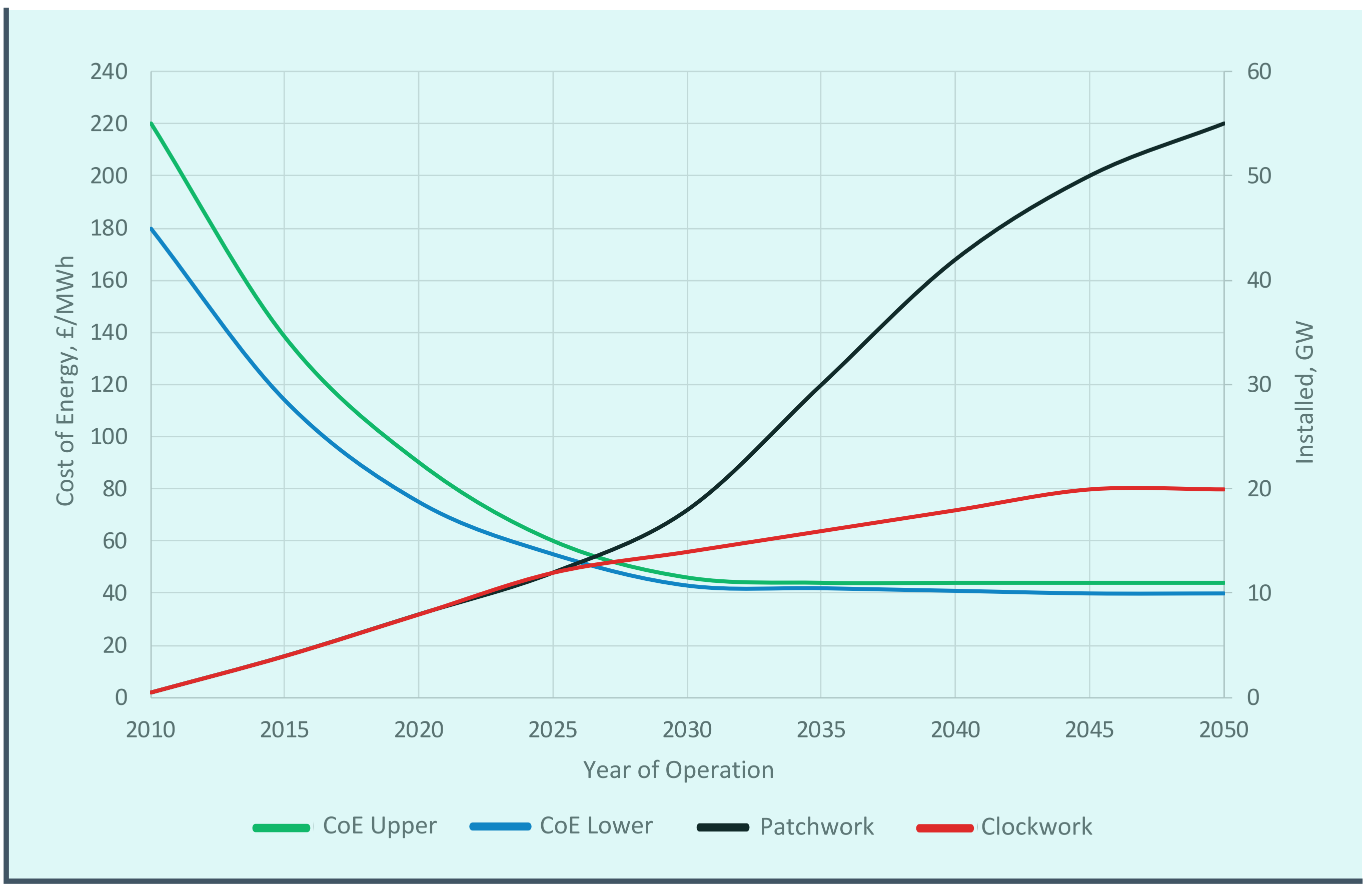
Cost reduction efforts have been identified and achieved across design, delivery, and deployment

Design: Economy of scale: 1600 turbines now delivered. Standardisation of design enabling non-recurring engineering costs to be absorbed by a much larger number of units.

Delivery: Standardisation of components, including using existing kit from wider supply chain. Modularisation – capital cost to start manufacture is one tenth of the cost. Cost of operation and maintenance reduced. Lifetime extended from 20 years to 25 years.

Deployment: With a range of fixed and floating foundations, the UK can optimise the offshore fleet.

Figure 23. **Offshore Wind Cost of Energy**



The next section outlines some key features of the off-shore wind cost reduction programme in terms of design, delivery and deployment.

Design

Technical route to increasing performance

A key identified priority was to reduce operation and maintenance costs, first by identifying high-cost maintainable items, and then finding ways to either eliminate or improve them. A major study by Peter Tavner at Durham University[3] identified gearboxes as a major cost driver. To provide some context, the torque in one of today's 8MW wind turbine machines is equivalent to every single taxi and truck in London combined. With a lot of moving parts (castings, bearings and seals) in contact with each other, gearboxes tended to fail early and take excessive downtime. The gearbox was becoming obsolete in the move towards larger turbines anyway, supporting the case towards an alternative. The development of the direct drive generator was a major innovation, connected the low-speed part to the power converter by magnetic flux, therefore providing for wider tolerances, requiring less precision in manufacture. The direct drive generator enabled turbine size to increase from 3MW towards 15MW. Next generation turbines above 15MW will need high temperature super conducting machines. In addition to manufacturability improvements, the move from gearbox to direct drive generator represented a significant improvement in terms of reduced operations and maintenance cost, less downtime / increased availability, as well as improved overall efficiency, from 92% to 97% electrical efficiency.

Delivery

Modularisation: Blades are the prime mover in off-shore wind. An industry-wide effort to increase size, efficiency and delivery of these key components resulted in major innovation, contributing towards a sector-wide improvement in economic performance.

Turbine blades had previously been made in single piece moulds. Each mould might cost £7million and entailed significant other constraints, including tolerances, handling issues and TAKT time[4] (amount of time to get a unit out the door).

The innovative transition to modularisation facilitates mass manufacture. The manufacturing process also enables a high degree of effective and efficient quality assurance and control, contributing towards highly efficient assembly and on-site installation. Precision manufacture also enables higher degrees of accuracy, reducing the impact on moving parts, resulting in a longer operational life, less downtime during operation, and lower overall O&M costs. Having identified this as a strategic priority, the ETI issued a call for tenders to build the world's longest blade. Southampton-based, Blade Dynamics, won the contract, and through public/private sector investment, increased the blade size from 49 metres to 79 metres, and established a path towards 100 metres, whilst facilitating much lower production tooling costs and therefore a more attractive return.

Longer blades are made possible by manufacturing smaller modules that are then joined together like Lego blocks into much longer blades far more quickly. This improved delivery model has enabled larger, higher quality blades whilst increasing production towards the goal of two per day, from the current level of one turbine per day.

Deployment: Overcoming Siting Constraints

For off-shore wind to make a meaningful contribution towards meeting climate and energy security goals, requires a build rate of 50 per annum (9MW wind turbine nominal rating) increasing to 170 per annum (9MW) for the next 32 years. For context, the oil and gas sector only build a rig type every 35 years. The off-shore wind industry has instead looked to mass-manufacturing sectors, and particularly to the commercial ship building industry, for learning.

3 Tavner, P.J. (2012). Offshore wind turbines: Reliability, availability and maintenance.

4 See Wikepedia description of TAKT time.

Siting was identified as a significant constraint in scaling up deployment to levels indicated above. For the lowest cost of energy, windy sites, close to shore, representing effective energy conversion were chosen. “Good wind resource” means that the wind blows often and with good speed. “Close to shore” means within 70km to avoid HVDC[5] and high AC losses, and within 3 hours of a maintenance port by fast workboat. “Available and reliable power conversion” means that the floating structure should have no or little impact on the wind turbine generator’s operation, and that the chosen generator will be reliable.

Existing Arrays are built in water generally less than 40m deep, on sandbanks in low-wave height areas. In order to increase siting options beyond shallow depths, to access deeper water sites, the ETI issued a competitive tender, which was won by US-based company, Glosten Associates.

A range of foundation types were assessed against identified cost drivers (see Table 18 below). The clear winner was the tether leg platform. Public/private investment enabled development of a design for a full-scale demonstrator for a specific site with validated costs. A further goal was to understand LCOE potential of Glosten TLP technology.

With a range of Fixed and Floating foundations, UK can optimise the offshore fleet. Floating wind has potential to deliver costs at less than £65/MWh from mid-2020s, and further significant cost reduction beyond.

Table 18. **Offshore Wind Cost Drivers**

Cost Drivers	Jacket	HyWind	WindFloat	*PelaStar*
Onshore Assembly	×	×	✓	✓
Lightweight Structure		×	×	✓
Turbine Performance	✓	✓	×	✓
Siting Flexibility	×	×	✓	✓
Serial Production	×	✓	✓	✓

Conclusion: The rising tide that lifts all boats

Learning from the success of the offshore wind industry suggests that in addition to design and delivery improvements, innovation through collaboration; cost and risk sharing across the public sector, supply chains and developers will be critical in realising strategic priorities for the nuclear sector. Such priorities include the need to tackle construction delay; cost over-runs; slow build rate; and high financing costs. A key feature of the off-shore wind sector transformation was a transition to modular build and factory-based assembly of mass-produced units that can be manufactured and shipped to sites for installation rather than custom-built, thereby speeding up delivery times and lowering direct and financing costs. Investment in engineering solutions that are subsequently standardised and deployed at scale enables non-recurring engineering costs to be absorbed across a higher number of units. Technological innovation has been coupled with a laser-like focus on accelerating commercialisation of new products, at scale, within rapid timescales.

5 High-voltage Direct Current means above 50kV DC. The advantage of HVDC is lower cable costs and losses for long cable runs.

C

Appendix: Genre Summaries and Methodological Assumptions

Below are summary tables that include the 1-digit costs and cost driver category scores for each genre included in the ETI Cost Database and associate ETI Cost Model.[1]

Table 19. **Genre Summaries for Conventional Plants**

Genre Label	Reference US PWR	Conventional in Europe/ North America	Rest of World
Representative Parameters for Each Genre			
Vendor Plant Design – Vendor	0.0	+2.0	-1.2
Equipment and Materials – EPC/Vendor	0.0	+1.8	-1.3
Construction Execution – EPC	0.0	+1.4	-1.5
Labour – EPC	0.0	+1.4	-1.4
Project Governance and Project Development – Owner	0.0	+1.2	-1.4
Political and Regulatory Context – Government	0.0	+1.0	-1.2
Supply Chain – Vendors	0.0	+1.7	-1.6
Operation – Owner	0.0	+0.4	-1.5
Genre Average	**0.0**	**+1.4**	**-1.4**
Construction Duration	**5.0 years**	**9.8 years**	**5.3 years**
Single-Digit Representative Costs for Each Genre			
Capital			
10s Preconstruction Costs	$133 /kW	$178 /kW	$52 /kW
20s E Direct Construction Costs: Equipment	$1,006 /kW	$1,345 /kW	$784 /kW
20s M Direct Construction Costs: Materials	$292 /kW	$391 /kW	$114 /kW

1 The cost breakdown for single-digit representative costs, unless specified, are based on the proportional cost breakdown for the US PWR benchmark plant. These are similar to the cost breakdowns of several nuclear cost studies for advanced reactors (for example, see ORNL (1980). *Conceptual Design Characteristics of a Denatured Molten Salt Reactor with Once-Through Fuelling*).

Genre Label		Reference US PWR	Conventional in Europe/ North America	Rest of World
20s L	Direct Construction Costs: Labour	$957 /kW	$1,279 /kW	$373 /kW
30s	Indirect Services Costs	$2,512 /kW	$3,357 /kW	$980 /kW
40s	Owner's Costs	$715 /kW	$956 /kW	$279 /kW
50s	Supplementary Costs	$79 /kW	$105 /kW	$31 /kW
60s	Financing During Construction	$1,175 /kW	$2,776 /kW	$512 /kW
Total Construction Costs		**$6,870 /kW**	**$10,387 /kW**	**$3,125 /kW**
Levelised Construction Costs		**$59 /MWh**	**$89 /MWh**	**$27 /MWh**
Operating				
70s	O&M Costs	$21 /MWh	$14 /MWh	$15 /MWh
80s	Fuel Costs	$7 /MWh	$10 /MWh	$11 /MWh
90s	Financing During Operation	$0 /MWh	$0 /MWh	$0 /MWh
Total Operating Costs		**$28 /MWh**	**$25 /MWh**	**$27 /MWh**
Levelised Cost of Electricity		**$87 /MWh**	**$114 /MWh**	**$54 /MWh**

Table 20. **Methodological Assumptions for Calculating Genre-Specific CAPEX and OPEX for Conventional Nuclear Technologies**

	Europe/North America	Rest of World
CAPEX calculation	Averaged overnight costs and interest during construction across all units within genre	
1-digit Capitalised cost calculation	Absent more detail, assumed the same percentage breakdown of Capitalised costs as the benchmark PWR	Absent more detail, assumed the same percentage cost breakdown listed for Chinese plants from Deutsche Bank report[1]
OPEX calculation	Averaged OPEX across all European countries in 2015 IEA Report[2]	Averaged OPEX across all Rest of World countries in 2015 IEA Report[2]

1 Deutsche Bank Markets Research. Industry: China Nuclear. 7 Jan 2015, p. 46.

2 IEA, Projected Costs of Generating Electricity, 2015, pp. 48-49.

Table 21. **Genre Summaries for Advanced Reactors**

Genre Label	Light Water SMRs	High Temp Gas Reactors	Liquid Metal Cooled Fast Reactors	Molten Salt Reactors
Representative Parameters for Each Genre				
Vendor Plant Design – Vendor	-1.5	-1.5	-1.0	-2.0
Equipment and Materials – EPC/Vendor	-1.0	-1.0	-0.5	-2.0
Construction Execution – EPC	-1.5	-2.0	-1.5	-1.5
Labour – EPC	-1.0	-1.5	-1.0	-1.0
Project Governance and Project Development – Owner	-0.5	-0.5	-0.5	-1.0
Political and Regulatory Context – Government	-0.5	0.0	-0.5	-0.5
Supply Chain – Vendors	-0.5	-1.0	-0.5	-1.0
Operation – Owner	-0.5	-0.5	-0.5	-1.0
Genre Average	**-1.0**	**-1.0**	**-0.8**	**-1.3**
Single-Digit Representative Costs for Each Genre				
Capital				
10s Preconstruction Costs	$105 /kW	$133 /kW	$133 /kW	$133 /kW
20s E Direct Construction Costs: Equipment	$792 /kW	$659 /kW	$802 /kW	$670 /kW
20s M Direct Construction Costs: Materials	$230 /kW	$137 /kW	$147 /kW	$167 /kW
20s L Direct Construction Costs: Labour	$753 /kW	$519 /kW	$581 /kW	$603 /kW
30s Indirect Services Costs	$1,977 /kW	$1,465 /kW	$1,704 /kW	$1,070 /kW
40s Owner's Costs	$563 /kW	$417 /kW	$485 /kW	$457 /kW
50s Supplementary Costs	$62 /kW	$43 /kW	$56 /kW	$57 /kW
60s Financing During Construction	$924 /kW	$699 /kW	$821 /kW	$507 /kW
Total Construction Costs	**$5,406 /kW**	**$4,073 /kW**	**$4,730 /kW**	**$3,664 /kW**
Levelised Construction Costs	**$46 /MWh**	**$35 /MWh**	**$40 /MWh**	**$31 /MWh**
Operating				
70s O&M Costs	$21 /MWh	$10 /MWh	$21 /MWh	$17 /MWh
80s Fuel Costs	$7 /MWh	$8 /MWh	$18 /MWh	$3 /MWh
90s Financing During Operation	$0 /MWh	$0 /MWh	$0 /MWh	$0 /MWh
Total Operating Costs	**$28 /MWh**	**$18 /MWh**	**$39 /MWh**	**$19 /MWh**
Levelised Cost of Electricity	**$74 /MWh**	**$53 /MWh**	**$79 /MWh**	**$51 /MWh**

Table 22. **Methodological Assumptions for Calculating Genre-Specific CAPEX and OPEX for Advanced Nuclear Technologies**

	Light Water SMRs	**High Temp Gas Reactors**	**Liquid Metal Cooled Fast Reactors**	**Molten Salt Reactors**
CAPEX calculation	Collected FOAK cost estimates from 2016 Atkins report[1], adjusted for NOAK plants using 2014 INL report[2], and aligned (approximately) with confidential cost estimates from vendors	Collected FOAK cost estimates from 2012 INL report[3], adjusted for NOAK plants using 2014 INL report[2], and aligned (approximately) with confidential cost estimates from vendors	Collected NOAK cost estimates from 1986 ORNL report[6] and aligned (approximately) with confidential cost estimates from vendors	Collected NOAK cost estimates from 1980 ORNL report[7] and aligned (approximately) with confidential cost estimates from vendors
1-digit Capitalised cost calculation	Based on percentages for PWR Benchmark plant (described above)	Based on CAPEX cost components as described above	Based on CAPEX cost components as described above	Based on CAPEX cost components as described above
OPEX calculation	Based on PWR Benchmark plant (described above)	Collected estimates from 2012 ORNL report,[3] 1987 ORNL report,[4] and 2012 Gen IV Forum article[5]	Collected estimates from 1987 ORNL report[4] and 2012 Gen IV Forum article[5]	Collected estimates from 1987 ORNL report[4] and 2012 Gen IV Forum article[5]

1 Atkins. 2016. “SMR Techno-Economic Assessment,” 21 July, p. 76.

2 Idaho National Laboratory (Bolden, Lauren M., and Piyush Sabharwall). 2014. “Small Modular Reactor: First-of-a-Kind (FOAK) and Nth-of-a-Kind (NOAK) Economic Analysis,” August, p. 2.

3 Idaho National Laboratory. 2012. “Assessment of High Temperature Gas-Cooled Reactor (HTGR) Capital and Operating Costs.”

4 Oak Ridge National Laboratory (Bowers, Fuller, and Myers). 1987. “Cost Estimating Relationships for Nuclear Power Plant Operation and Maintenance.” November, Table 3.1.

5 Van Heek, A.; F. Roelofs, and A. Ehlert. 2012. “Cost Estimation with G4-ECONS for Generation IV Reactor Designs.” Proceedings of the 2nd Symposium of the Generation IV International Forum, embedded in ANS Winter Meeting, San Diego, US, Nov. 2012, pp. 29 – 33.

6 Oak Ridge National Laboratory. 1986. Phase VIII Update (1986) “Report for The Energy Economic Data Base Program EEDB.” Table 5-5 (Large-Scale Prototype Breeder Reactor).

7 Oak Ridge National Laboratory. 1980. “Conceptual Design Characteristics of a Denatured Molten-Salt Reactor with Once-Through Fuelling.” Table A.1.

D

Appendix: Assumptions

This appendix lists the assumptions underlying this study and states their rationales.

1. Plants Included in ETI Cost Database

ID	Assumption	Rationale
1.1	**US PWR Benchmark:** Costs for the US PWR benchmark plant were pulled from table 5-3 of the 1986 ORNL report (see References). Values were brought from 1986 to 2016 dollars using a factor of 2.2 (calculated using annual rate increases in the US Bureau of Labor Statistics Consumer Price Index). Values were converted from million dollars to dollars per kW using representative plant capacity in the source report (1,144 MWe).	The rationale for this Benchmark is described in Section 2.1.
1.2	**Recent plants:** The database includes plants built after the Three Mile Island nuclear plant incident in the United States in 1979	Plants built after this incident have more safety features and more rigorous regulatory review than previous plants.
1.3	**Existing, under construction, proposed, and conceptual:** The database includes these four status categories for nuclear plants around the world. The regression analysis, however, applies only to existing plants and those within 12 months of construction completion, as discussed below	In addition to existing plants and plants currently under construction, the database contains proposed plants and conceptual SMR/advanced plants for completeness though their cost values and cost driver settings are inherently less certain.

2. Cost Values

ID	Assumption	Rationale
2.1	**Interest rates:** To calculate interest costs during construction in a consistent manner, we assumed a standard pre-tax interest rate (weighted average cost of capital (WACC) for debt and equity) of 7% in real terms for all plants	This rate assumption lies within the range of typical costs of capital shown in Lazard (2017, p. 14) and Davis (2011, p. 7), with a small reduction for inflation (approximately 1%) to convert from nominal to real rates. The analysis uses pre-tax parameters because tax issues are outside the study scope.
2.2	**Other cost components:** If no plant-specific information available on cost components such as direct and indirect costs from public sources or expert interactions (but total overnight cost is known), used component percentages of total overnight cost from the PWR Reference plant	Assuming the same cost component proportions as for the PWR Reference seems reasonable for database estimates. Note that this assumption does not affect the regression analysis, which does not use individual cost components (only total cost and the cost driver scores).
2.3	**LCOE parameters:** To convert capital costs to dollars per MWh for calculating the levelised cost of electricity (LCOE), we assumed a capacity factor of 95%, a capitalisation period of 60 years, and a discount rate of 7%	The study scope called for uniform assumptions on LCOE parameters to maintain a focus on other cost drivers. The period of 60 years is from the UK Department for Business, Energy, and Industrial Strategy (BEIS) (2016, p. 70). The capacity factor and discount rate parameter values seem reasonable as generic assumptions.
2.4	**LCOE formula:** The team used the following LCOE formula: LCOE = {(Total Capital Cost per kW * Capital Recovery Factor * 1,000) / (8,760 * Capacity Factor)} + Total Operating Cost per MWh Capital Recovery Factor (CRF) = {r * (1 + r)^n} / {[(1 + r)^n] - 1}, where n is the Capitalisation period and r is the discount rate	The formula is taken from the "LCOE Calculator" developed by the US National Renewable Energy Laboratory (2017). While it neglects year-by- year variations in operating costs, tax expenses, corporate overhead (if additional to plant O&M), and other factors requiring additional assumptions, it is a consistent and vetted approach to calculating LCOE across a range of energy projects. It is a simplified approach that enables an apples-to-apples cost comparison across multiple electricity generation modes. Of note is that, as used here, it reflects the cost of providing electricity over the design life of the plant – it does not predict the price that a company may decide to charge.

3. Cost Drivers

ID	Assumption	Rationale
3.1	**Plant cost driver scores:** We used a range from -2 to +2 in integer increments (5 bins) to assign cost driver scores for each plant in the database, with 0 corresponding to the PWR Reference plant's costs and drivers	Our use of 5 bins centred around 0 allows for variation among the plants. Using many more bins could have introduced false precision in the database and regression because the drivers inherently reflect some qualitative information and judgment.
3.2	**Choice of cost driver categories:** We selected driver categories to capture the many factors that influence nuclear plant costs while limiting the drivers to a manageable number	Although other cost driver categories could perhaps have isolated the impacts of key factors more directly, such as categories for country and prevailing interest rates, our focus was to help stakeholders understand the impacts of factors under their control for planning purposes in the UK and elsewhere.

4. Regression Analysis

ID	Assumption	Rationale
4.1	**Plant inclusion in regression sample**: We included completed nuclear plants (since the Three Mile Island incident as discussed above) based on data availability and global representativeness for the study	We excluded ongoing and proposed nuclear plants from the regression sample, as well as SMR and advanced concepts, to ensure that our regression results would accurately reflect actual experience.
4.2	**Same calibration coefficients for all genres:** The cost model uses the same calibration coefficients to predict the cost impacts of driver settings for SMR and advanced concepts as for conventional plants in our regression sample, even though SMR and advanced concepts are not in the regression	This assumption is necessary for the model to produce cost estimates for SMR and advanced concepts without including them in the regression analysis (because their costs are speculative at this point). Note that default cost estimates for SMR and advanced concepts reflect each specific genre, while the regression coefficients are used to estimate deviations from their default estimates due to drivers.
4.3	**Some regression coefficients not statistically significant:** We kept cost driver categories in the regression analysis even if the results indicated that their values may be 0 (low explanatory power for differences in cost)	With this moderate number of plant observations and relatively high number of cost driver categories as independent variables, it is virtually inevitable that several coefficients will lack statistical significance. We are following established regression practices by including such variables anyway, and noting their significance levels, if reasoning suggests they should have impacts on the dependent variable (in this case costs).
4.4	**Coefficient value for operating costs**. The database and model use an assumption of $1/MWh reduction in operating costs per integer improvement in Operations score	This conservative assumption of a small change in operating costs per change in Operations score was necessary in the absence of sufficient data on operating costs for plants in the database to perform a full regression on operating costs.

5. Plant Genres

ID	Assumption	Rationale
5.1	**Conventional nuclear genres distinguished by location:** Our two genres for conventional nuclear plants, with different average cost values and cost driver settings from plant information in the database, reflect (1) plants in Europe and North America, or (2) plants in the rest of the world	We divided the conventional nuclear genres into these two geographic bins because cost values and cost driver scores differ significantly between them, though there is also substantial variation among the conventional nuclear plants in each bin.
5.2	**Advanced nuclear genres distinguished by reactor type:** The analysis uses separate categories for light water SMRs, HTGRs, LMCFRs, and MSRs	These categories for SMRs and advanced concepts cover the spectrum of new nuclear technologies making progress toward commercial deployment.
5.3	**Cost components for genres.** Where the breakdown of total costs to one-digit costs is unknown for a given plant, we follow the cost breakdown for the associated genre as a template. That is, the proportion of total costs that are allocated to each one-digit cost category is assumed to be the same as the representative "genre" plant.	The percentage breakdown of total cost to one-digit cost is different between the genre benchmarks. For example, because of inherent safety of HTGR fuel, the safety systems costs are lower but HTGR fuel costs are relatively high. Similarly, because the HTGR and MSR reactors operate at much lower pressure than PWRs, the containment vessel requires less material and is considerably less expensive. That said, the reactor may be more expensive or require more design work during construction, which leads to differences in the overall cost breakdowns between the genres.

6. ETI Cost Model

ID	Assumption	Rationale
6.1	**Genre-specific adders.** After calculating the cost estimate for genres from their cost driver settings and regression coefficients, the model adds a value for each genre to match its known cost from the database	Without the genre-specific adders, cost estimates from the driver settings and calibration coefficients would not match the known genre costs from the database, because the same calibration coefficients are used for all genres, as discussed above.

E

Appendix: Best Practices

The nuclear power plant delivery "best practices" listed below reflect discussions with nuclear cost experts and our project advisors. These are not opportunities to reduce cost as much as they are actions that any delivery organisation should take to increase the probability of on-time, on-budget delivery.

Cost Driver	Best Practice
Vendor Plant Design	**Install the reactor pressure vessel (RPV) as early as possible.** This may require procuring large (e.g. Goliath) cranes to lift the RPV and insert it into place from an opening in the top of the containment building ("open top installation"). This can dramatically shorten the critical path and allow other construction activities – previously done in sequence to accommodate RPV installation – to be done in parallel.
Vendor Plant Design	**Prioritise the critical path above all else.** Implement any/all necessary measures to ensure that everything not on the established critical path says off the critical path throughout the project, including the regulatory approvals and permissions process.
Vendor Plant Design	**Engage an experienced multidisciplinary team (including but not limited to civil, mechanical, electrical) to review the design for constructability.** Conduct a detailed review of the design by area (room by room) to plan choreography in the construction process and ensure the project director has a clear overview of needs of the project delivery team in terms of site access, machine requirements etc. Flexibility will be needed during construction, but good planning can avoid derailing the project schedule, and team building can enable a shared approach to problem solving across disciplines.
Vendor Plant Design	**Clearly define the "engineering envelope"** and provide contractors a limited "menu" of options (e.g. pre-selected components, pipes, fasteners, cables, wires, embedment lengths, electrical connections and terminations, etc.) from which to choose. Providing a clear "envelope" prevents contractors from developing "local solutions" to problems, which can later drive delays in the project schedule.
Vendor Plant Design	**Commission structured constructability reviews** of the design, execution plan, work requirements, and related documents. This should be performed by a multidisciplinary team (including but not limited to civil, mechanical, and electrical engineers) and can reveal conflicts that can otherwise impact construction time and cost and should be perform before the bid cycle begins to give ample time for corrections to be made. For example, in recent plants, seismic design requirements have resulted in rebar congestion issues. These types of issues can be identified and avoided with design alternatives through the constructability review process.

Cost Driver	Best Practice
Vendor Plant Design	**Reduce the total number of man-hours on site.** There are several ways to accomplish this, including some of the ideas detailed elsewhere in this report. Key actions include: ■ Increasing the amount of modularity in the plant design (i.e. increasing the quantity of the work that can be fabricated offsite), ■ Simplifying the plant design as much as possible (through multiple design reviews from multidisciplinary design team) ■ Instituting “productivity-enablers” for labour (described in Section 6), ■ Organise working arrangements to ensure maximum productive hours per shift by careful deployment of facilities and Labour Agreements, and ■ Reduce rework reduction through good planning and QA
Vendor Plant Design	**Design for Decommissioning: Perform Dismantling, Assessment, and Demolition assessment prior to project construction.** Decommissioning can cost hundreds of millions to over $1B and can take decades (Reuters, 2011). Understanding how to dismantle a nuclear power plant and incorporating those insights into the design process – as well as having a dedicated 4D deconstruction plan - can help reduce overall decommissioning costs. This type of deconstruction analysis is performed routinely in France.
Equipment and Materials	**Follow best practices to reduce material use.** The following are recognised best practices for material uses in nuclear power plants. Some of these techniques, but often not all, are routinely followed by the industry. ■ **Concrete**. Contractors should limit the variety of standardised concrete mixes used (from ~10 to around 3) and use advanced, composite concrete where possible. ■ **Rebar**. Contractors should limit rebar congestion (too much rebar can prevent the pouring of concrete), maximise the quantity of prefabricated rebar, and employ machines and techniques that can automatically install/assemble rebar into place. To reduce the overall amount of rebar, construction engineers may also use steel plate reinforced concrete. Instead of reinforcing concrete with rebar, concrete is poured between permanently placed, self-supporting steel plate forms. These forms can be modularised and prefabricated off-site, followed by placement and welding on site (International Atomic Energy Agency, 2009). ■ **Slip-forming**. Slip-forming is the process by which concrete is continuously poured at a calculated and monitored rate into a continuously moving form. Effectively, concrete is poured into a form and consolidated (via vibration) and once it is set enough to withstand a new layer poured on top of it, the form moves to accommodate the new pour. Because slip forming is a continuous process, it requires months of detailed and involved planning, especially to avoid weather-related or thermal issues. ■ **Designed formwork**. Building concrete forms offsite (i.e. temporary structures or moulds that support and confine concrete until it hardens) increase upfront costs but improves productivity and requires little on-site skilled labour to employ.
Construction Execution	**Job rotation:** A practice followed by the Koreans and Japanese is to rotate senior-level employees of a given discipline (e.g. design, manufacturing, operations, construction) to other disciplines. This helps breakdown the “siloes” between the fields, facilitates communication and coordination, creates a unified, team-oriented culture where people know each other (professionally and personally), which helps when needing to resolve issues relatively quickly. While this may or may not be a strategy that UK companies choose to adopt, a multi-disciplinary delivery team provide many of these emergent benefits.

Cost Driver	Best Practice
Construction Execution	**Adhere to Well-Developed and Successful Project Execution Strategies and Techniques** Ensuring on-time/on-budget delivery requires strict adherence to well-developed project execution strategies and techniques. Project managers must be able to quickly measure performance and progress while remaining highly responsive to changes in design, schedule, site layout, contractors, or otherwise. Similarly, contractors must easily understand their role among precedent and dependent construction activities. The following tools and best practices can help ensure timely execution: ■ Build on successful project execution strategies and incorporate learnings from less successful projects. Project execution plans should only improve over time as managers continually Optimise and start projects with an analysis of the previous project to understand the risks and identify over to reduce or overcome those risks. ■ "Entrust delivery to a sound and proven project manager." (Petrunik, 2015) ■ Project managers should have a very clear and well-established Earned Value Management (EVM) system for quick and systematic measurements of scope, schedule, and costs throughout the project's lifecycle. ■ A common, open architecture information system should be accessible to all project stakeholders, so they can view the schedule and progress (etc.) as well as upload relevant information and generate progress reports. System users should be properly trained and adhere to defined reporting standards. Project managers (i.e. managing contractors or dedicated project delivery team) should be able to understand exactly where progress stands against approved upon construction plans and the established definitions of "completion" for various tasks. This will enable them to take corrective action where necessary. Having the system accessible to a wide group of contractors can generate "positive peer pressure" by incentivising workers not to be the ones responsible for holding up the project (this is particularly useful if a collective contingency/bonus fund has been set up among the contractors). ■ Project directors should apply strict discipline in adhering to the planned schedule, defined milestones, and critical path. This includes close monitoring of the project schedule and establishing the right level of reporting and corrective action meetings/processes that involve all contractors.
Construction Execution	**Use an Integrated Engineering Change Management Process** Using an integrated Engineering Change Management Process can allow the project delivery organisation to quickly respond to discretionary changes (or those requested by the regulator) and have them cascade through the design, procurement process, safety case, and supply chain. A Project Management Information System (PMIS) or single project database that includes design details, procurement specifications, and communicates with an integrated supply chain procurement change control process is essential in enabling the project delivery organisation to quickly promulgate changes before or during construction. It is advisable to "rehearse" such a change control process during the construction planning process.
Construction Execution	**Apply state-of-the-art construction techniques from around the world**. Construction best practices are recommended (open top construction, slip-forming techniques, modularisation, robotic welding, etc.). This includes best practices for sequencing contractors, general construction management (i.e. ensuring latest software and management techniques) and applying the latest innovations (e.g. robotic earth moving, mechanical splicing, etc.) to improve labour productivity.

Cost Driver	Best Practice
Construction Execution	**Follow proven project management practices.** Several nuclear construction project managers identified project management best practices that should be followed. These include the following: ■ **Project manager should have single point of contact with the owner** ■ **Put the best minds in the room to solve problems.** Problems invariably arise during construction and it is essential that any outstanding legal arguments do not obstruct or distract from a collective effort at identifying the solution. This requires mature managers with technical expertise. It also requires that problem-solving produces (e.g. a fixed time period for making the recommendation) are well defined, agreed upon in advance, and adhered to. ■ **Create an integrated project delivery team** (as discussed in Section 6.5.2 on page 62) ■ **Maximise on-site decision-making authority**. The pace of decision-making is material to adhering to tight budgets and schedules. Many, successful nuclear projects have been led by a small group of decision makers with seemingly "dictatorial" authority. This enabled quick and efficient decision making that is rarely available in the current corporate climate where more external governance (i.e. "headquarters" and/or the Board of Directors) and oversight procedures are required. This can significantly slow progress and, at times, cause entirely new (and unnecessary) delays. ■ **Openness and transparency.** Leadership should promote a culture of trust and openness among contractors and labourers so that, for example, people are not fired for making a mistake but fired for hiding it. It is important to create a culture that encourages people to say when something is wrong so it does not spread and create further issues. Creating that culture requires managers to support labourers, contractors, and suppliers when they make mistakes, experience accidents, or have taken on too much responsibility/risk
Political and Regulatory Context	**Develop benchmarking process to ensure use of latest construction best practices.** The UK should government should ensure that each new build project is incorporating the best practices and lessons learned from the global construction industry. A state-of-the-art benchmarking process should be established to fulfil this role. Evidence suggests some recent advances in construction are not yet being applied by the nuclear industry (given the paucity of new builds).
Operation	**Pay fastidious attention to Foreign Material Exclusions (FMEs) in the construction and commissioning phases.** Systems should be set up to prevent any foreign materials getting near primary circuits or any other critical systems. Dust and other particulates, especially those that can be irradiated (carbide, cobalt, etc.), can cause "hot spots" in certain parts of the plant. This not only reduces operational efficiency but can be expensive to solve. Ensuring successful commissioning and early operations must include strict attention to preventing any FME contamination.

References

Atkins. 2016. SMR Techno-Economic Assessment. 21 July.

Berthelemy, Michel and Francoise Leveque. 2011. Korea nuclear exports: Why did the Koreans win the UAE tender? Will Korea achieve its goal of exporting 80 nuclear reactors by 2030? April.

Buongiorno, Prof. J. (2017, October 17). Personal interview at Massachusetts Institute of Technology.

Dawson, Karen; Sabharwall, Piyush. 2017. A Review of Light Water Reactor Costs and Cost Drivers. Light Water Reactor Sustainability Program, Idaho National Laboratory. September 2017.

Davis, Lucas W. 2011. Prospects for US Nuclear Power After Fukushima, Energy Institute at Haas.

De Clercq, Geert and Jane Chung. 2018. "Exclusive: Arab world's first nuclear reactor delayed again over training - sources." Reuters. March 22.

Deutsche Bank Markets Research. 2015. Industry: China Nuclear. 7 Jan 2015, p. 46.

El-Guebaly, L, Cadwallader, L., Merrill, B. 2009. ARIES Safety-Related Components and Nuclear Grade Requirements. ARIES-Pathways Project Meeting, December 15-16, 2009. San Diego.

Energy Collective. 2017. "News About What Went Wrong at VC Summer Gets Worse."

Georgia Power Company (GPC) 2017. Sixteenth Semi-Annual Vogtle Construction Monitoring Report. February. See updated report issued in Aug 2019.

Georgia Public Service Commission (PSC). 2017. Proposed Order of the Public Interest Advocacy Staff. December 19.

Georgia Public Service Commission. 2018. Order on the Seventeenth Semi-Annual Vogtle Construction Monitoring Report. January 11. Document Filing #170765

Song, Hyomin; Sangyong Kim; Yooseok Shin; and Gwang-Hee Kim. 2014. "Case Study of Reactor Containment Building Construction in Nuclear Power Plant." Journal of Building Construction and Planning Research.

Idaho National Laboratory (INL). 2012. Assessment of High Temperature Gas-Cooled Reactor Capital and Operating Costs.

Idaho National Laboratory (Bolden, Lauren M., and Piyush Sabharwall). 2014. "Small Modular Reactor: First-of-a-Kind (FOAK) and Nth-of-a-Kind (NOAK) Economic Analysis." August.

International Atomic Energy Agency (IAEA) 2009. Advanced Construction Methods for New Nuclear Power Plants. NTR 2009 Supplement. See Annex 4.

International Energy Agency (IEA). 2015. Projected Costs of Generating Electricity, 2015, pp. 48-49.

Johnsen, T.E. and Lewis, M. 2009. Supplier Involvement in the Development of the A380 Super Jumbo. In Proceedings of the 17th Annual IPSERA Conference, Wiesbaden, Germany, April.

Kane, Chen and Miles A. Pomper. 2014. "Reactor Race: South Korea's Nuclear Export Success and Challenges." On Korea, vol. 7. Pp. 61-79.

Korman, Richard. 2017. "Witness to the Origins of a Huge Nuclear Construction Flop." Engineering News-Record. November 1.

Lazard. 2017. Levelised Cost of Energy Analysis. Version 11.

Lee, Chang Kun. 2007. "Korea's Nuclear Past, Present, and Future." 21st Century Science & Technology. Winter.

Logistics Middle East. 2018. FOCUS: The extraordinary A380 supply chain. Published January 30, 2018.

Lovering, Jessica; Yip, Arthur; Nordhaus, Ted. 2016. "Historical construction costs of global nuclear power reactors." Energy Policy. Vol. 91. April. Pp. 371-382. Some variables were originally sourced from the International Atomic Energy Agency's (IAEA) Power Reactor Information System (PRIS) database, and more information can be found for individual reactors on the IAEA website.

Markandya, A.; Wilkinson, P. 2007. Electricity generation and health. Lancet, Sept. 15, 2007, 370, 979−990

McKinsey Global Institute. 2017. "Reinventing Construction: A Route to Higher Productivity."

Nuclear Intelligence Weekly. 2012. "AP1000s Delayed by 6-12 Months, SNPTC Says." January 17, 2012.

Oak Ridge National Laboratory (ORNL). 1980. Conceptual Design Characteristics of a Denatured Molten Salt Reactor with Once-Through Fueling.

Oak Ridge National Laboratory (ORNL). 1986. Phase VIII Update Report for the Energy Economic Data Base Program.

Oak Ridge National Laboratory (Bowers, Fuller, and Myers). 1987. Cost Estimating Relationships for Nuclear Power Plant Operation and Maintenance. November.

Park, Ki-Chan and Francoise Chevalier. 2010. "The Winning Strategy of the Late-comer: How Korea Was Awarded the UAE Nuclear Power Contract." International Review of Business Research Papers, vol. 6, no. 2. July.

Petrunik, Ken. 2015. Practical Project Management. Friesen Press. 1st edition (November 18, 2015)

Peterson, Per F., Zhao, Haihua, Petroski, Robert. 2005. Metal and Concrete Inputs for Several Nuclear Power Plants. University of Berkeley.

Reuters, 2011. "Decommissioning a Nuclear Plant Can Cost $1 Billion and Take Decades."

Royal Academy of Engineering (RAE). 2010. Nuclear Lessons Learned.

Tavner, P.J. (2012). Offshore wind turbines: Reliability, availability and maintenance.

Takei et al. 2006. Economical Evaluation on Gas Turbine High Temperature Reactor 300 (GTHTR300). Atomic Energy Society of Japan. Vol. 5, No. 2, p. 109-117.

The Kenrich Group. 2016. Construction Monitoring Proceeding for Georgia Power Company's Plant Vogtle Units 3 and 4: Expert Report of Richard J. Sieracki and Mark Gentry. April 5. Document Filing #162918

The Post and Courier. 2017. "Missing documentation throws Santee Cooper, SCE&G nuclear project timeline, costs in doubt."

UK Department for Business, Energy, and Industrial Strategy (BEIS). 2016. Electricity Generation Costs. November.

UK Department for Business, Energy, and Industrial Strategy (BEIS). 2017. Industry Strategy – Building a Britain fit for the future. November.

UK Department for Business, Energy, and Industrial Strategy (BEIS). 2017. The Clean Growth Strategy – Leading the way to a low carbon future. October.

UK Office of National Statistics. 2016. International comparisons of UK productivity (ICP), final estimates: 2014. Published February 18, 2016.

UK Office of National Statistics. 2017. International comparisons of UK productivity (ICP), final estimates: 2015. Published April 5, 2017.

UK Parliament. 1987. Hansard for 12 March. "Sizewell B Nuclear Power Station."

U.S. Bureau of Labor Statistics (BLS). 2018. "Historical Consumer Price Index for All Urban Consumers."

US Nuclear Regulatory Commission. 2009. Consideration of Aircraft Impacts for New Nuclear Power Plants; Final Rule. June 12.

Utility DIVE. 2017. "VC Summer audit raised in Georgia hearings over fate of Vogtle nuclear project."

Van Heek, A.; F. Roelofs, and A. Ehlert. 2012. "Cost Estimation with G4-ECONS for Generation IV Reactor Designs." Proceedings of the 2nd Symposium of the Generation IV International Forum, embedded in ANS Winter Meeting, San Diego, United States, November 14-15, 2012

World Nuclear Association (WNA). 2015. Facilitating International Licensing of Small Modular Reactors. Cooperation in Reactor Design Evaluation and Licensing (CORDEL) Working Group.

World Nuclear Association (WNA). 2010. International Standardisation of Nuclear Reactor Designs. Cooperation in Reactor Design Evaluation and Licensing (CORDEL Group).

World Nuclear Association (WNA). 2018. "Reactor Database."

World Nuclear News (a). 2017. "Impact of Hanhikivi 1 licensing delay remains unclear." October 17, 2017.

World Nuclear News (b). 2017. "US governor releases report on VC Summer flaws." Sept 6, 2017.

World Nuclear News. 2018. "Barakah 1 construction formally complete." March 26, 2018.

Yan, Xing, L. HTGR Brayton Cycle- Technology and Operations. MIT Workshop on New Cross-cutting Technology for Nuclear Power Plants, Cambridge, USA, January 30-31, 2017.

Zhou, Yun; Rengifo, Christhian; Chen, Peipei; Hinze, Jonathan. 2011. "Is China ready for its nuclear expansion?" Energy Policy. Vol 39. 771-781.

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