The ETI Nuclear Cost Drivers Project: Summary Report

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Executive Summary

The *UK Industrial Strategy* and *Clean Growth Strategy* identified nuclear energy as having 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 demonstrate that nuclear energy can be highly cost competitive.

The Project Team identified and verified the most significant drivers of overall, 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 Difference, or strike price, this Project focused on potential trends impacting LCOE.

Cost reduction inherently requires increasing schedule and budget certainty. In doing so, there is less project risk and higher confidence in successful project delivery, which benefits all stakeholders, including the public *and* the 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.

Evidence gathered and analysed during this Project suggests that UK nuclear new build has very significant cost reduction potential. Sections 2 and 3 describe how the documented experience with successful multi-unit builds and intentional new build programmes in other countries indicate 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 4) are strongly supported by evidence from multiple sources and documented experience. Section 4 describes the key differences between high cost and low cost nuclear construction, identifying important and consistent themes in each, including the importance of design completion before construction starts. This evidence is further supported by a series of Case Studies in Section 5, underpinning a series of cost reduction opportunities transferable to the UK context in Section 6, conclusions in Section 7 and recommendations for next steps in Section 8.

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 SMRs. Whilst such technologies are not yet licensed, nor construction

[1] Recent analysis of published historic cost breakdowns of LWRs in the U.S. 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)

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.

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

Acknowledgements

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, for his exceptional guidance and steady support throughout. We also thank three officials at the 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.

1 Introduction

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

"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."[2]

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. 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."[3]

Recent nuclear new build projects, particularly in North America and Europe, have been vulnerable to schedule delays and cost increases.[4] By contrast, nuclear projects in other parts of the world are performing far better on cost and schedule. In the UK, the initial challenge for projects starting construction in the next 10 years will be to complete construction and commissioning within acceptable norms of schedule and budget variation, while delivering 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) or 'first-in-a-country' schedule risk, and the second requires strategies for programmatic reduction of construction duration and total capital costs as additional units are delivered.

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. 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.

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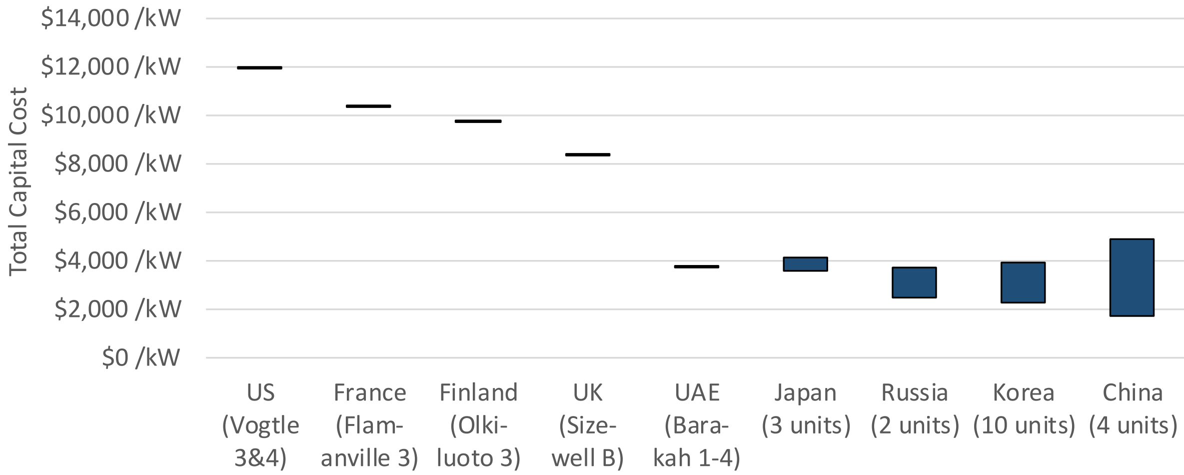
[2] *Industrial Strategy: Building a Britain Fit for the Future*, November 2017. This white paper sets out a long-term plan to boost the productivity and earning power of people throughout the UK.
[3] *Clean Growth Strategy*, October 2017 https://www.gov.uk/government/publications/clean-growth-strategy
[4] Recent analysis of published historic cost breakdowns of LWRs in the U.S. 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)

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



1.2 Objective of the ETI's Nuclear Cost Drivers Project: Potential Cost Reduction Opportunities Supported by Strong Evidence

The purpose of the Energy Technologies Institute (ETI) Nuclear Cost Drivers Project was to Identify what drives cost within nuclear projects completed globally in the last twenty-five years, as well as for contemporary, and advanced reactor designs. The goal was to then identify and quantify potential to deliver meaningful reductions in capital cost and levelised cost of energy (LCOE) in the UK.[5] Because significant cost reduction opportunities require coordinated and sustained action of multiple parties, a key outcome was a framework designed to enable shared understanding and coordination between all stakeholders.

While the principal charge of this study is to reveal the major cost drivers for nuclear projects, in practice, reducing cost also requires reducing project risk by increasing certainty on schedule and budget. Less risk and higher overall confidence in budget and schedule—and therefore cost of energy— benefit all stakeholders, including the public and the project developer. Cost reduction should therefore not be considered a zero-sum game that comes purely at the expense of vendor or EPC profit margins. Reducing project risk – whether related to project development, construction or supply chain - benefits all parties, creating a "win-win" outcome.

In general, there is an assumption that higher risk projects present an opportunity for higher returns. For nuclear projects, risk-adjusted returns do not conform with this assumption beyond certain risk levels. There is a point where project risk is simply too high regardless of return. This level of risk is reached when it becomes difficult to raise capital from traditional project investors. Therefore, reducing overall risk will be critically important to the long-term health of the sector.

[5] Note that LCOE is not the same as the CfD price or strike price. There are a number of factors that account for this, such as financing structure, taxes and other operating charges, site specific development and preconstruction expenses, and differences in depreciation periods, to name a few that are significant.

It is important to note that the use of the term 'risk reduction' in this report does not mean transferring risk from one party to another, for example from the developer to the government, which might occur through a mechanism such as a loan guarantee and would result in commercial lenders charging a lower risk premium on a loan to the project. Here the term is employed to mean actual reduction of risk in the project fundamentals from improvements in the supply chain, construction practices, labour productivity, or increased certainty in demand for future units, or direct support from government in the areas of permitting, labour relations, or the regulator. Improving these risk fundamentals will lower financing costs which the proposed nuclear sector deal (part of the UK Government's Industrial Strategy) identifies as an important potential contributor to cost reduction. Engaging in the right kind of collective action and demonstrating risk reduction by all project stakeholders can yield lower electricity costs for the consumer, allow for the vendor to realise its desired risk-adjusted rate of return, and can expand the market potential for new build projects.

1.3 Rigorous approach underpins data collection and analysis

To provide a rigorous evidence base for these cost reduction opportunities, the team developed a comprehensive cost database of thirty-five completed or close-to-completed projects, as well as proposed small modular reactors (SMRs) and advanced nuclear designs. The cost data for each unit included in the database was supplemented with a detailed interview about the construction process for that unit and a scoring of the factors that determined the ultimate cost of the unit. Data was anonymised to protect commercial sensitivity where necessary and the provenance for data entries were made clear, recognising differing levels of detail between projects. The database used a standardised code of accounts (based on the Generation-IV Cost Accounting Framework[6]) to enable meaningful 'apples-to-apples' comparisons among examples. An associated cost model with supporting dashboard metrics enables interaction with the database. Data from the database is collapsed into "genres" (based on technology and region) to illustrate the interaction between cost and the cost drivers. While the model enables sensitivity analysis of interest rates, financial approaches to reducing the cost of capital during construction and operation were out of scope, as was any examination of cost-reduction for decommissioning.

Further detail on the methodology is detailed in Section 2 below.

[6] Economic Modeling Working Group of the Generation IV International Forum. 2007. "Cost Estimating Guidelines for Generation IV Nuclear Energy Systems." https://www.gen-4.org/gif/upload/docs/application/pdf/2013-09/emwg_guidelines.pdf.

Figure 2. Summary of Methodology

*Performed regression analysis on cost drivers to estimate relative influence on total project cost. Regression coefficients were used in the interactive cost model.

1.4 Case studies exemplify key mechanisms of the cost drivers

This report includes several case studies that exemplify key mechanisms of cost reduction, these form an important part of the evidence base and provide another view of the cost drivers in action on real projects or proposed projects.

1.5 Project Team and External Reviewers

Through a competitive procurement process, the ETI awarded the project to CleanTech Catalyst Ltd. (CTC), which, along with its subcontractor, Lucid Strategy (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, and Charles Petersen Esq., Prof. Jacopo Buongiorno, and Dr. Ben Britton.

2 Cost Driver Analysis and Methodology

Identifying the primary cost drivers for new build nuclear projects is challenging for several reasons. First, most cost and project delivery information is confidential and little relevant data exists in the public domain. Second, while establishing the quantitative linkage between certain cost drivers and final project cost can be straightforward (e.g., cost and quantity of raw materials, financing interest rate, number of staff, etc.), for other drivers, the linkage is less direct. Third, some cost drivers are within the control of the project delivery consortium while others are not (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 for obtaining qualitative and quantitative information for the most significant cost drivers for dozens of individual reactors.

This approach enabled rich, detailed, and non-confidential conversations about the plant delivery experience. Interviewees were generally happy to share detailed stories about what drove plant costs and worked with the project team to assign scores that reflected the relative influence of each cost driver on the final cost. Experienced project managers love their craft and enjoyed talking about project learnings and cost reduction opportunities. Scoring methodology allowed the project team to turn comprehensive, structured interviews into a set of quantitative measures for each plant in the database (and enabled subsequent quantitative analysis of those measures).

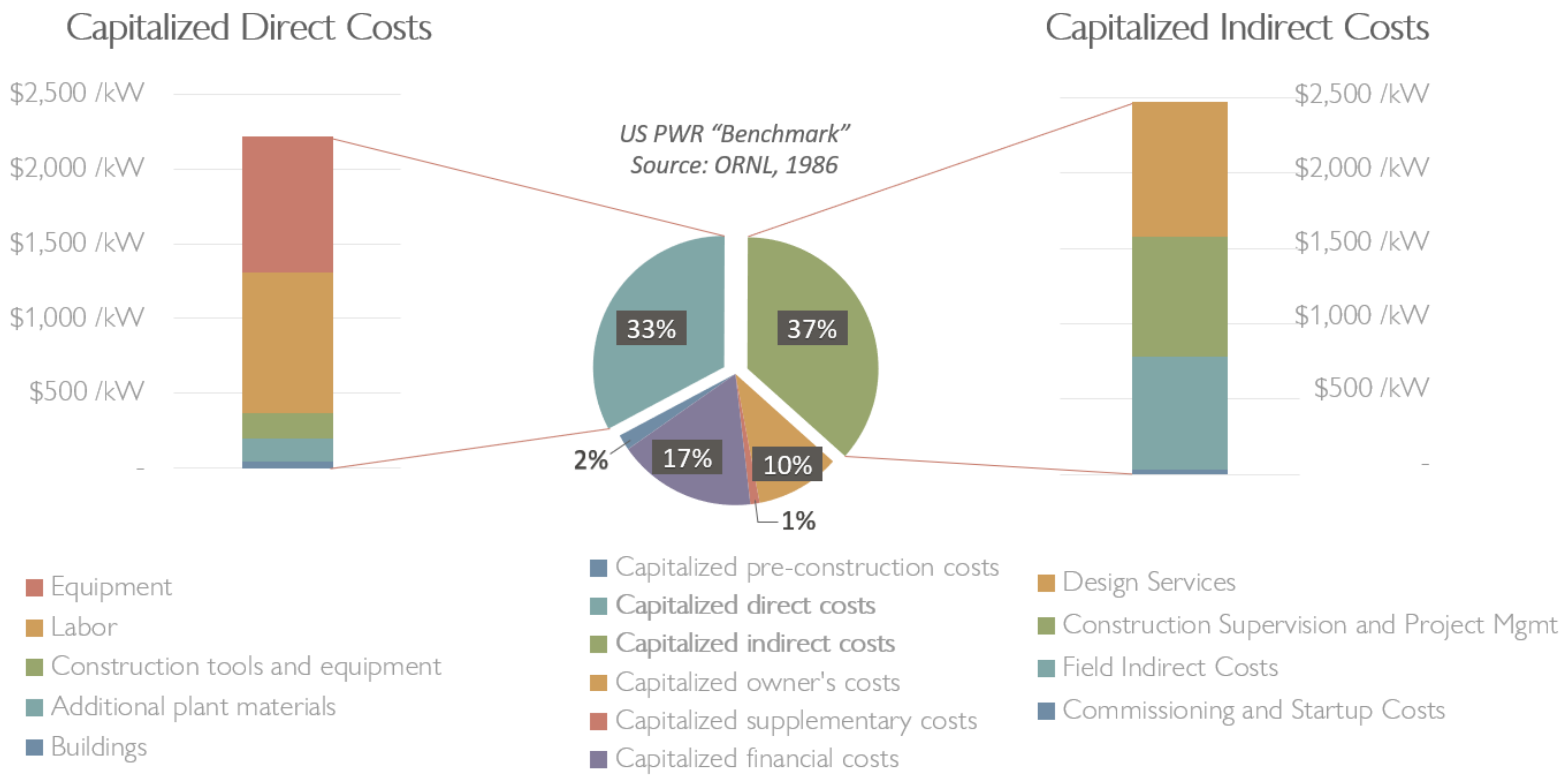
2.1 Benchmark Plant

An important component to the cost drivers' analysis was the selection of a benchmark nuclear plant upon which all plants could be compared. Having a single reference point to evaluate projects enabled an apples-to-apples comparison among the plants in the ETI Cost Database. The Project Team selected a historic US PWR from a 1986 Oak Ridge National Laboratory cost study as the benchmark (ORNL 1986).

2.1.1 Overnight vs. Total Cost

The chart below 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. It is important to note that this excludes annual operating costs, which is an important factor when calculating LCOE. 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 revealed once a plant is completed. 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.

Figure 3. Capitalised Cost Breakdown of the US PWR Benchmark



2.1.2 Major Cost Components in the PWR Benchmark

As shown in the pie chart above, Direct Costs and Indirect Costs and, to a lesser extent, financing costs dominate overall 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 not considering 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.

2.2 Methodology for Deciding on Cost Drivers and Data Collection

The following section describes the team's approach for identifying, prioritising, vetting, quantifying, validating, and ultimately analysing a final set of nuclear cost drivers. This process is described in three phases: (1) prior to company engagement, (2) company engagement, and (3) ETI Cost Database and ETI Cost Model development. The development of the ETI Cost Model is described in detail in subsequent sections.

Prior to engaging with companies, the Project Team defined the term "Cost Driver" and produced an initial exhaustive list of cost drivers for potential inclusion/consideration in 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, eight cost drivers were identified. Each driver is attributed an 'owner' and has multiple detailed quantitative and qualitative cost driver indicators. The 'owner' of a cost driver plays a functional role critical to the delivery of the project. 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.

- *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 1, 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. The scores and scorecards were designed so that confidentiality would not be an issue, enabling them to be included in the ETI Cost Database.

Table 1. 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

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 indicators for a "zero" score. This is presented in Table 2 below.

Table 2. Final Eight Cost Drivers and Associated Principal Actors

Cost Driver	Principal Actor	Description
Vendor Plant Design	Reactor Vendor	Includes all pre-construction efforts related to plant design, including design decisions, design completion, and ability to leverage past project designs. This covers specific plant details such as plant capacity, thermal efficiency, and seismic design, but also includes broader topics related to constructability and project planning processes.
Equipment and Materials	EPC	Encompasses quantities of equipment, concrete, and steel (both nuclear and non-nuclear grade) used in the plant but also covers strategies used to address materials cost.
Construction Execution	EPC	Covers all the decisions and practices carried out and support tools used by the EPC during project delivery. This starts with site planning and preparation and design rework costs and spans all onsite decisions (e.g. project execution strategies, schedule maintenance, interactivity with subcontractors and suppliers, etc.) until the Commercial Operation Date. This includes independent inspection processes, QA, QC, and other major cost and risk centres during project construction. This driver is a measure of efficiency and productivity across the entire delivery consortium. For multi-unit construction on the same site, this should get better with each subsequent unit.
Labour	Labour	Involves all direct and indirect construction labour performed on the project site. This also includes any labour related to offsite manufacturing or assembly. It covers productivity, wages, training and prep costs, percentage of skilled workers with direct applicable experience, etc. This driver measures efficiency and productivity at the individual level.
Project Governance and Project Development	Owner	This driver includes all factors related to developing, contracting, financing, and operating the project by the project owner. This covers topics from the interdisciplinary expertise of the owner's team to

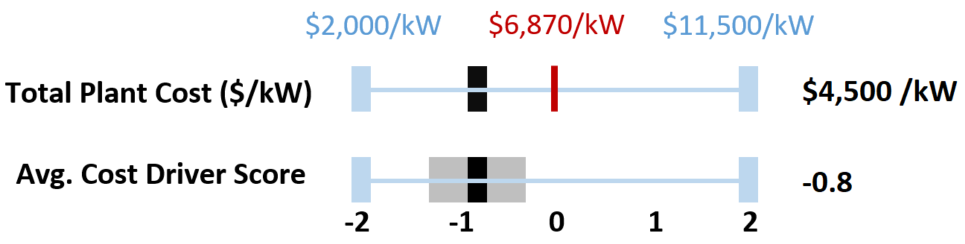
Cost Driver	Principal Actor	Description
		number of units ordered (at the same site), discretionary design changes, WACC, and contracting structures with the EPC and suppliers.
Political & Regulatory Context	Government and Regulator	Includes the country-specific factors related to regulatory interactions and political support (both legislatively and financially). This driver includes regulatory experience, pace of interactions, and details on the site licensing process. It also includes topics related to the government's role in financing and how well it plays certain roles otherwise reserved for the project customer.
Supply Chain	Supplier Vendors	Involves factors that characterise supply chain, experience, readiness, and cost of nuclear qualification as well as nuclear-grade and non-nuclear-grade equipment and materials.
Operations	Operator	Covers all costs related to nuclear power plant operations (e.g.., fuel price, staff head count, wages, capacity factor, unplanned outages, etc.)

Table 3. Indicative Cost Driver Values by Category for the 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% 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

The “zero score” was one of several components used to help assign a final score. The Scorecard also included two dynamic sliders (shown below) that changed positions as total plant cost and average cost driver scores were adjusted. This effectively constrained the participant into allocating the difference between their project and the benchmark cost subject to the constraint that the average score aligns with the final plant cost.

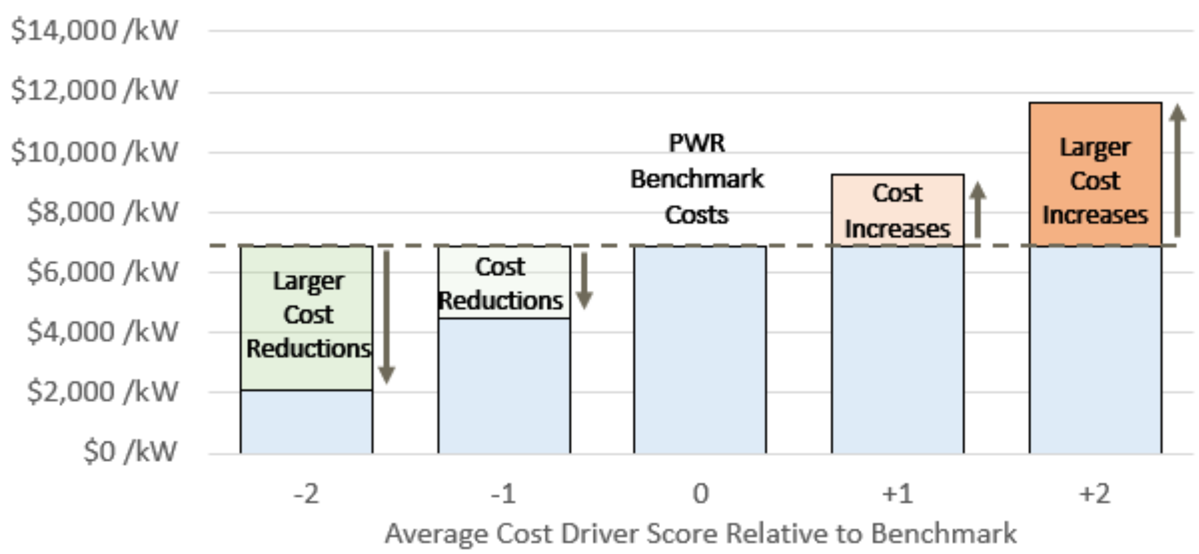
Figure 4. Dynamic Cost and Cost Driver Sliders on the plant “Scorecard”



The Scorecard also provided a place for respondents to enter “one-digit” plant costs according to the Gen-IV cost accounting framework.[7] We anticipated that a full set of one-digit cost detail be less onerous on the participating companies (than requesting 2- and 3-digit level cost data).

The following figure 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 5. Relationship Between Total Capital Costs and Average Driver Scores



[7] See the ETI Report on Cost Database and Associated Model for more detail on the Generation-IV cost accounting framework.

An eligibility cut-off date was set for plants that started construction past 1985, with priority given to plants most recently commissioned (including those that will be commissioned in 2018).

2.4 Company Engagement

Interviews with experts. The Project Team carried out semi-structured interviews with respondents (either under Non-Disclosure Agreements, or on a non-confidential basis) largely guided by the eight cost driver categories and their associated drivers. More than 150 hours of expert interviews were conducted over the phone and in person in the UK, France, USA, Korea, and Japan. A primary outcome was a populated "scorecard," which was then added to the ETI Cost Database. Where necessary, the Team triangulated plant cost entries and cost driver rationale against publicly-available information and with third party industry experts.

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
- Investors

In total, the Project Team obtained scorecards for 33 units that have been built or are currently under construction.

- *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. 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 33 plants in a very short period of time, it is a relatively small sample size for 8 independent variables. The regression results should be treated as indicative and considered alongside the results from the structured interviews, plant costs, and case studies.

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

- 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).[8] The Project Team added interest during construction (IDC) to the overnight costs using the methodology described above.

- *Consistent Currency Values* Cost information sources using US dollars from previous years were inflated to 2017 dollars using the Consumer Price Index from the US Bureau of Labor Statistics (BLS 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). Cost sources using a different currency than the US dollar were converted at the appropriate exchange rate for the time, and then inflated to 2017 dollars.

[8] Lovering, J. R., Yip, A. & Nordhaus, T. Historical construction costs of global nuclear power reactors. Energy Policy 91, 371–382 (2016). Some variables were originally sourced from the IAEA's Power Reactor Information System (PRIS) database, and more information can be found for individual reactors on their website: https://www.iaea.org/pris/

3 ETI Cost Model

The Project Team developed a methodology for storing, organising, synthesising, and distilling value from the confidential data it obtained to make it actionable to the ETI. Described in this section is the development, structure, and function of the ETI Cost Model. These outputs create an evidence base of primary cost drivers for different nuclear technologies in different markets. This helps define potential cost reduction for UK new build projects.

3.1 ETI Cost Model

The ETI Cost Drivers 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," which is an interface that allows users to load plant genres and adjust cost driver assumptions to see how they affect overall cost. Another important worksheet contains the values for the imported plant genres from the ETI Cost Database.

3.2 Plant Genres

In building the 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:

Table 4. Representative Plant "Genres" for Conventional and Advanced Reactor Technologies

Conventional (Generation II/III/III+)	Advanced (Generation IV)
1) Reference US PWR	4) Light Water SMRs
2) Conventional Plants - Europe / North America	5) High Temperature Gas Reactors 6) Liquid Metal Cooled Fast Reactors
3) Conventional Plants - Rest of World	7) Molten Salt Reactors

The “genre” concept serves two purposes. First, they are fundamental features of the cost model. Second, they enable confidential information to support estimates of genre costs, without publishing confidential data. 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.

3.2.1 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. These costs are 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 forecast costs and actual costs obtained from completed and operational plants (most, of which, have been refuelled multiple times).

4 Findings

A relatively small number of understandable factors drives the cost of nuclear plants. Building nuclear plants takes place through large, complex projects. However, there was a high degree of consensus among the experts consulted. The findings of this study are therefore straightforward.

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.

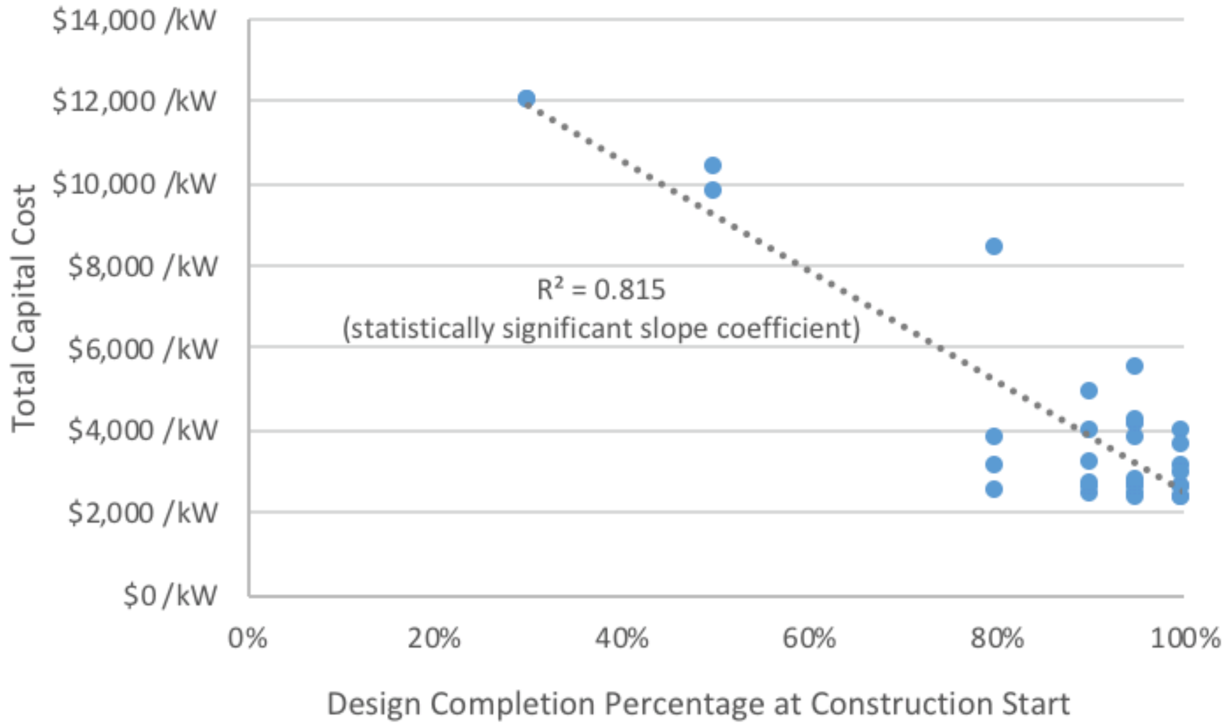
This section describes the key differences between high cost and low cost nuclear construction, identifies important and consistent themes in both of these. This evidence is further supported by a series of Case Studies in Section 5, underpinning a series of recommendations for cost reduction opportunities transferable to the UK context in Section 6.

4.1 Design Completion as an important factor

The Project Team's interviews with numerous nuclear plant experts revealed that the degree of design completion when construction began was one of the most important drivers of total capital cost. In several cases, the plant design reviewed and approved by the nuclear regulatory agency lacked many details necessary for actual construction. As the Project Team conducted interviews, prepared case studies, and added plant information to the ETI Cost Database, a strong pattern emerged that high-cost projects had started with incomplete 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 design completion prior to construction is an indicator under the Construction Execution cost driver. As the study progressed, however, several interviewees and expert reviewers suggested giving more prominence to 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 design completion at construction start for each unit. In Figure 6, each unit is a dot showing design completion and total capital cost, with a tight correlation across the dataset.

Figure 6. Design Completion Percentage and Total Capital Cost



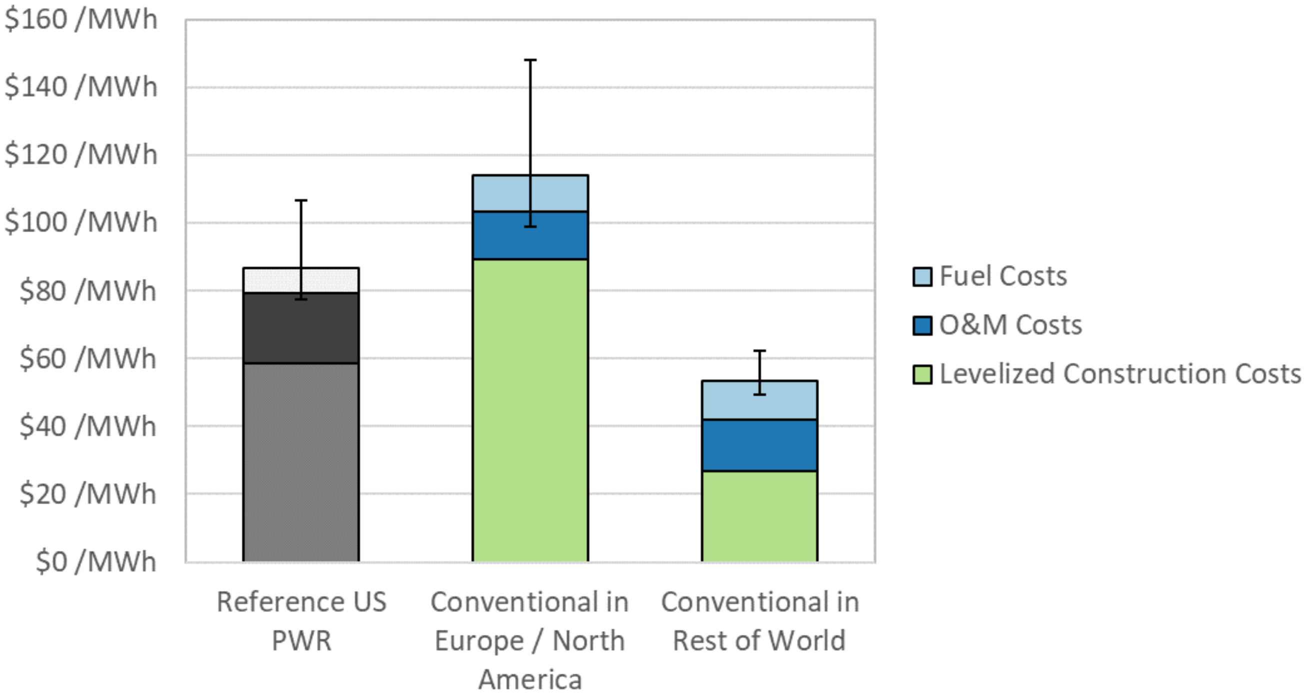
4.2 Conventional Plants

A total of 33 conventional nuclear plants are included in the ETI Cost Database - 25 pressurized 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"). 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.

In Figure 7 below, the 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 capitalised and annualised costs are provided in the Cost Drivers Analysis Report. 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 the Cost Drivers Analysis Report.

Figure 7. 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%.

4.3 Broad range of costs and scores in completed nuclear plants

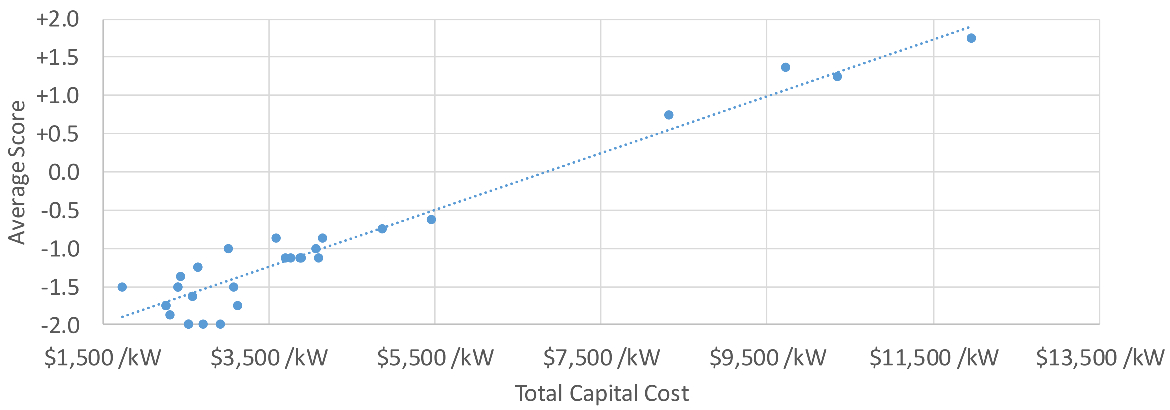
The chart below shows 33 completed units that were included in the ETI cost database, representing a wide range in terms of total capital cost (from $2,000/KW to $11,500/KW) and each units' associated cost driver scores (from -2 to +2).

A cluster of low cost plants scored well against all cost drivers, 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.

Table 5. Number of Units by Genre in the ETI Database

Genre	Number of Units in ETI Database
US PWR Benchmark	*1*
North America & Europe	*5*
Rest of World	*28*

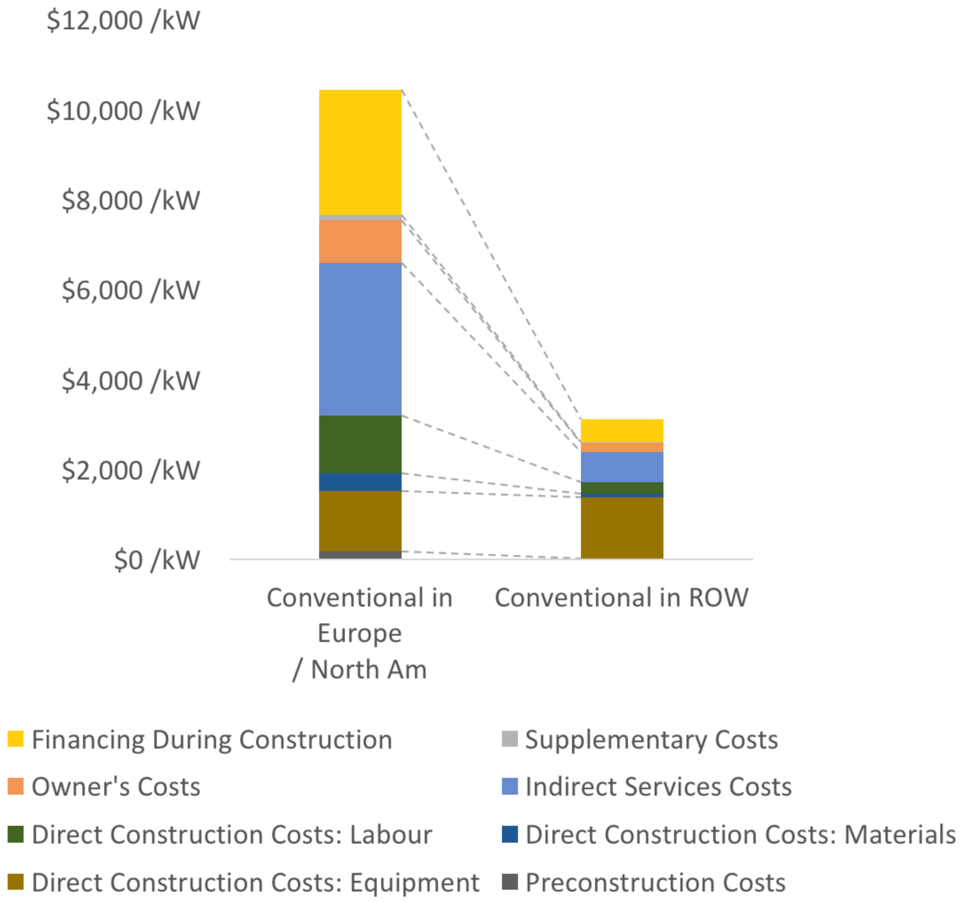
Figure 8. Relationship Between Total Capital Cost and Average Score for Projects in Database



4.4 Differences between high cost and low cost projects

The chart below contrasts the EU/US light water reactor genre (conventional in Europe and North America) and the Rest of World (ROW) genre. 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 9. "Genre" Cost Comparison: Europe/North America and ROW Costs



4.5 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 6. Characteristics of Low Cost and High Cost Plants

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

4.6 Alternative Cost Scenarios: Capital cost reduction is as important as reducing the cost of capital

Table 7 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 and third rows of the table reflect improvements in project delivery that lower all driver scores to 0 or -1. The table shows that reducing driver scores to 0 or -1 could reduce costs for a European or North American project significantly, especially when combined with low interest and discount rates.

It is important to note that it may not be possible for European or North American plants to achieve -2 scores and the associated low costs that are achieved in rest of world examples. Reaching a cross driver score of -1 or even zero in western Europe of North America will be a challenge, but an average of almost minus 2 is too challenging to envisage without multiple units of 4 or more per site, levels of worker hours not permitted by the EU working time directive, and levels of pay which some skills in nuclear site construction can command.

Table 7. Alternative Cost Scenarios for Conventional Nuclear in Europe/North America

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

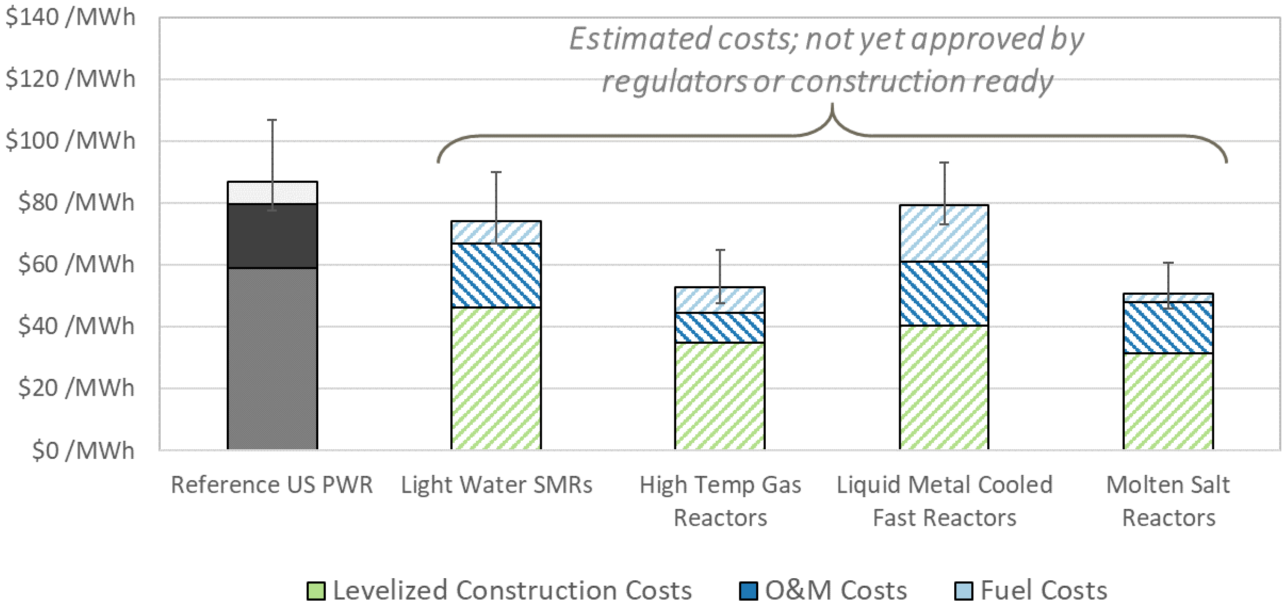
4.7 SMRs and Advanced Reactors: Potential cost reduction from several factors when commercial deployment can occur

The project included light water Small Modular Reactors (SMRs) and three advanced reactor ("Gen-IV") technologies: High Temperature Gas Reactors (HTGRs), Molten Salt Reactors (MSRs), Liquid-metal cooled fast reactors (LFRs). All the advanced reactors in commercial development are based upon reactor technologies that have had decades of development and some degree of prototyping/testing at national nuclear laboratories. Companies are combining this experience with more recent scientific and computing breakthroughs to develop improved designs that address many of the challenges of the current, conventional nuclear fleet and associated delivery models.

Gen-IV plants are still in relatively early stages of commercial development. None of the companies have a completed detailed design and all are actively engaged (or preparing to engage) in the first stages of reactor licensing activities. Only after obtaining a reactor license and completing a detailed design can a company build commercial demonstration or FOAK plant. While advanced reactor companies are projecting lower costs than conventional plants, these costs will remain inherently uncertain until FOAK (and perhaps several additional plants) are delivered. At present, these reactor technologies are not available for near-term deployment.

The methodology for calculating genre-specific CAPEX and OPEX for advanced reactor technologies can be found in the Cost Drivers Analysis Report. The following figure presents the average capitalised and annualised operating costs for SMRs and the three types of advanced reactors included in the analysis.

Figure 10. LCOE for SMRs and Advanced Reactor Technologies



The Project Team assumes that the same drivers for conventional plants will be relevant to advanced reactors. Many companies view that not yet having a detailed design provides continued opportunity to integrate cost reduction into the design. SMRs and Advanced Reactors can implement cost reduction opportunities earlier in the design process. While this is true, the lack of a detailed design inherently obscures cost and risk. The design should be considered incomplete until licensed, 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 plague conventional, stick-built construction and are integrating several cost reduction approaches into their plant design and delivery strategy. Typical strategies being pursued by advanced reactor and AMR/SMR vendors that may reduce construction costs include:

- Reduced construction scope, duration, and labour, particularly at site due to fewer buildings and fewer safety systems needed due to passive safety design.
- Designed to enable a much higher percentage of factory production of key components and assemblies.
- Simpler plants design enabling a less labour-intensive Quality Assurance and verification.
- Highly-standardised, modular designs
- 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 in EU/US markets compared to conventional EU/North America – although uncertainties remain.

One challenge will be to significantly reduce fixed costs associated with site licencing, control systems, and planning approval, for example. Historically, vendors increased plant capacity to spread fixed costs and, as a result, reduce LCOE.[9] However, the resultant increase in the scale of the capital required and complexity of the project can significantly increase risk unless the project delivery organisation has a proven record of successfully managing such risk. The following figures provide a comparison of the conventional genres as well as NOAK estimates from the three advanced reactor genres.

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

Figure 11. Comparison of Capitalised Costs Across All Genres

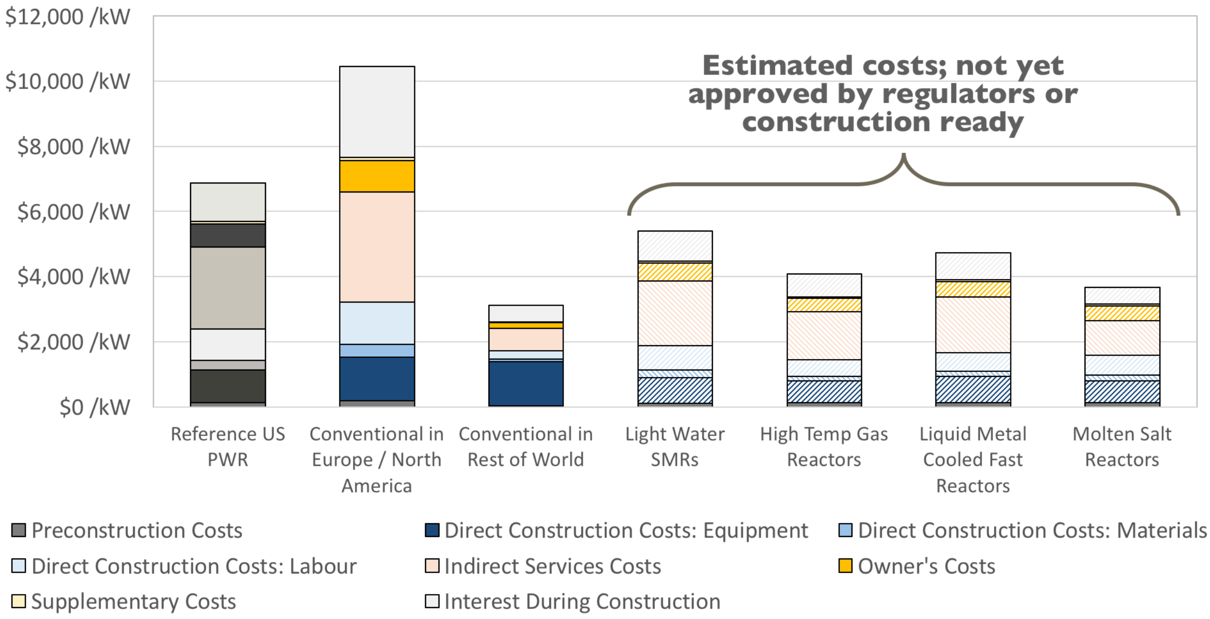
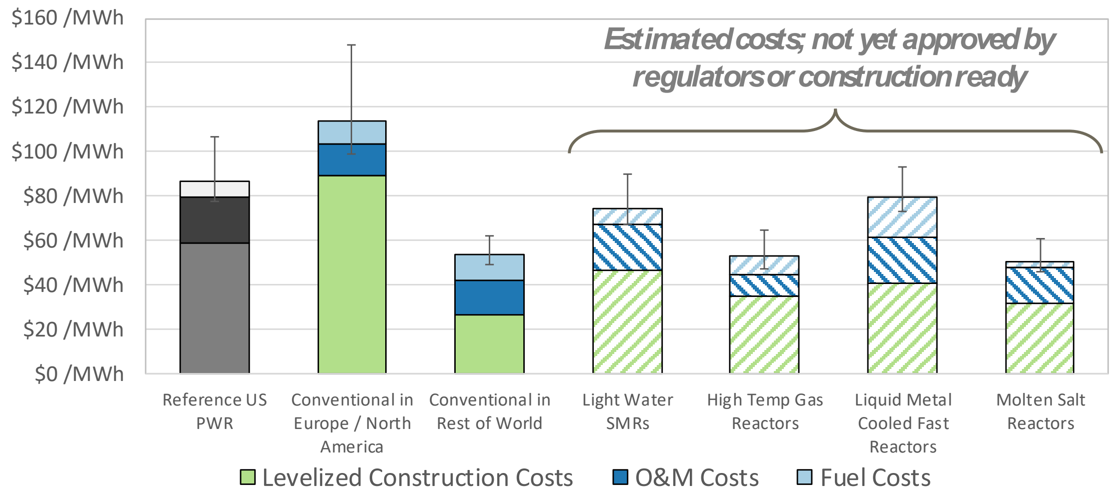


Figure 12. Comparison of LCOE Across All Genres



5 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 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 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.

Case Study Overview Table 8 below 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 orange circles denote negative factors associated with high costs.

Table 8. 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	Operation
Sizewell B and Nuclear Electric's Proposal for Sizewell C	UK	🟢	○	🟢	○	🟢	🟢	🟢	○
Barakah	UAE	🟢	○	○	🟢	🟢	○	○	○
Vogtle	US	🟠	○	○	○	🟠	○	🟠	○
Rolls Royce SMR	UK	🟢	○	🟢	🟢	○	○	○	○
HTTR	Japan	🟢	○	○	🟢	🟢	○	○	○
Generic MSR	UK	🟢	🟢	🟢	○	○	○	🟢	🟢
Offshore Wind	UK	🟢	🟢	🟢	○	○	○	🟢	🟢

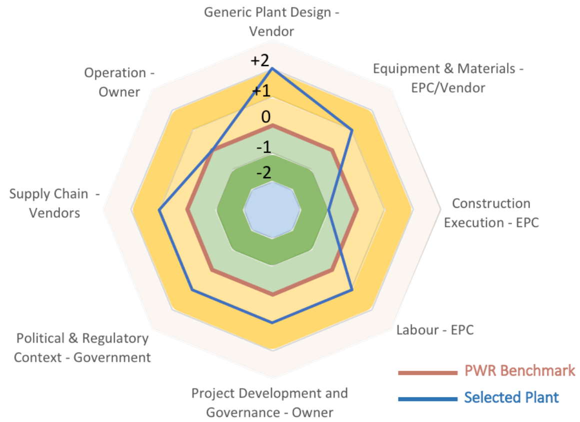
🟢 – Positively influences Driver 🟠 – Negatively influences Driver ○ – Less Relative Significance

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

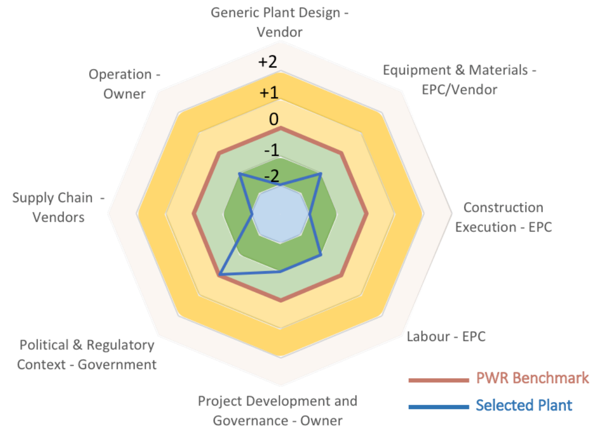
Important finding: All projects that have achieved low costs have built multiple units on a single site enabling maximum learning for cost reduction, shared use of infrastructure, shared operational facilities, and more organised and efficiently-timed construction to optimise the use of labour and project management resources.[10] The factors that make a project expensive (e.g. FOAK, new supply chain, inexperience labour, etc.) 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 first of a kind project and avoided significant schedule delays and cost overruns. Nuclear Electric planned Sizewell C ("NE's Sizewell C") in the 1990s, but it was not built (and current expansion plans at Sizewell are not addressed here). Cost information in the figure for Sizewell B includes some very high first-of-a-kind expenses for the project, such as plant design, software, interest during construction[11]. NE's Sizewell C shows potential cost reductions from a multi-unit construction programme. 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 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.

Sizewell B - 1,345 MW
(Operating)
CAPEX with IDC: $8,315/kW; LCOE: $113/MWh

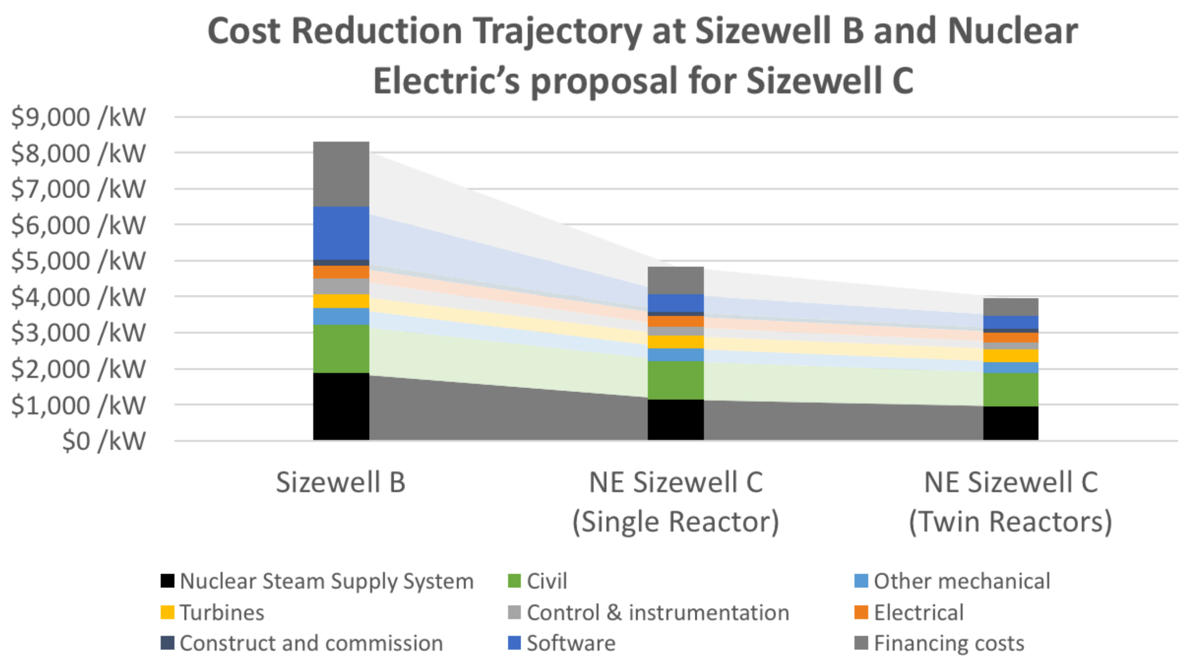


Nuclear Electric's Sizewell C (Twin) – 2,690 MW
(Planned in 1990s)
CAPEX with IDC: $3,963/kW; LCOE: $71/MWh



[10] 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.
[11] 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.

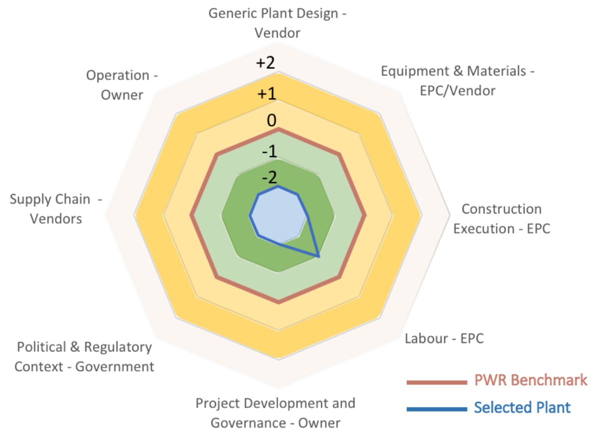
Cost Driver	Experience
• Vendor Plant Design	Sizewell B uses a basic PWR design from two previous plants in the United States with additional safety features to achieve licensability in the UK. NE's Sizewell C would have largely reused the blueprints for Sizewell B, but with 25% reductions achieved in 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.



5.2 Barakah 1-4 (Partially Complete)[12]

Barakah Unit 4 - 1,345 MWe
(Under construction)

CAPEX with IDC (extrapolated): $2,300/kW; LCOE: $51/MWh



Important finding: Multi-unit efficiencies included factors such as shared site infrastructure, one site mobilisation effort (not separate or requiring of stop/start mobilisation), bulk purchasing, same contracts and overhead, etc. Numerous multiple learning effects enabled continual improvements in efficiency and productivity. 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.).

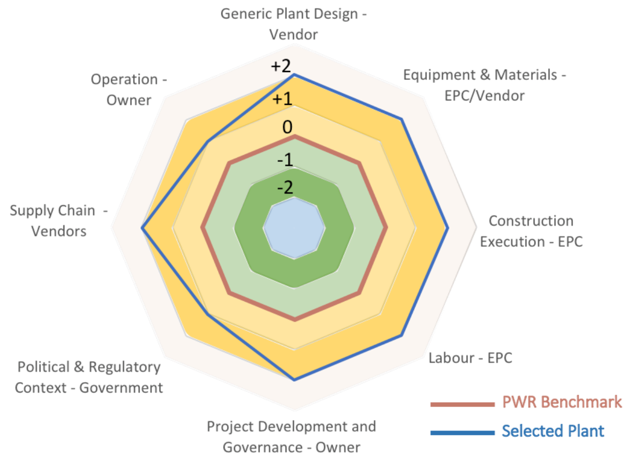
Cost Driver	Experience
• Vendor Plant Design	The UAE selected the KEPCO consortium partly because of successful recent projects in Korea. The UAE did not want to experiment with an unproven design or one with a less successful track record.
• Labour	KEPCO management was very committed to winning the 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.

[12] 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).

5.3 Vogtle 3&4 (Under Construction)

Vogtle 3&4 – 2,234 MWe

CAPEX with IDC: $11,950/kW; LCOE: $127/MWh



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 and 4 are the first Westinghouse AP1000 PWRs in the United States and the country's first new nuclear projects in three decades (the recent Watts Bar 2 project completed work begun 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.

5.4 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	Notes
• Vendor Plant Design	Rolls-Royce is "productizing" 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 learner 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.

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

Important finding: Japan's HTTR shows the potential viability of a low-cost advanced nuclear concept.

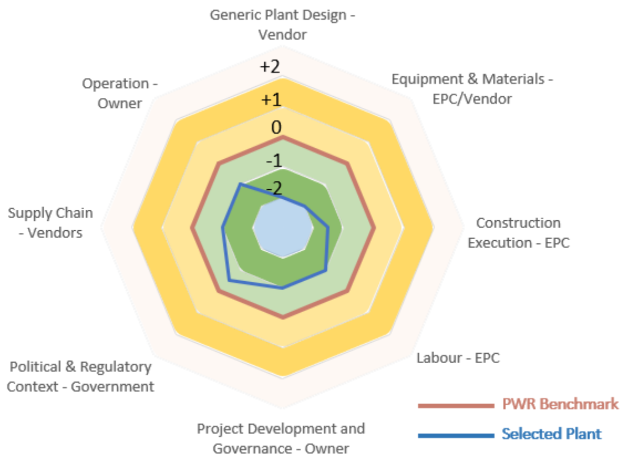
The Japan Atomic Energy Agency (JAEA) has been developing high temperature gas reactor technology since the mid 1980's. In the early 1990's a decision was made to build a test facility that was large enough to meaningfully test commercial scale or close to commercial scale components and provide the 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.

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.

Cost Driver	Notes
● 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 materials.
● Equipment and materials	The HTTR is expected to be lower cost than other HTGRs in part due to its direct cycle helium gas turbine power generation system which eliminates the need for several components. It also increases efficiency from a typical rating of 33% for most current nuclear plants to between 45-50%. This 40% increase in efficiency, is equivalent to a 30% reduction in capital cost, and also reduces LCOE further by reducing fuel cost per MWh.

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

Generic Molten Salt Reactor
190 – 1,000 MWe
CAPEX with IDC: $3,664; LCOE: $51
(N^{th}-of-a-kind design)



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	Notes
● Vendor Plant Design	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 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.
● 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.

5.7 Offshore Wind

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 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, U.K. can optimise the offshore fleet.

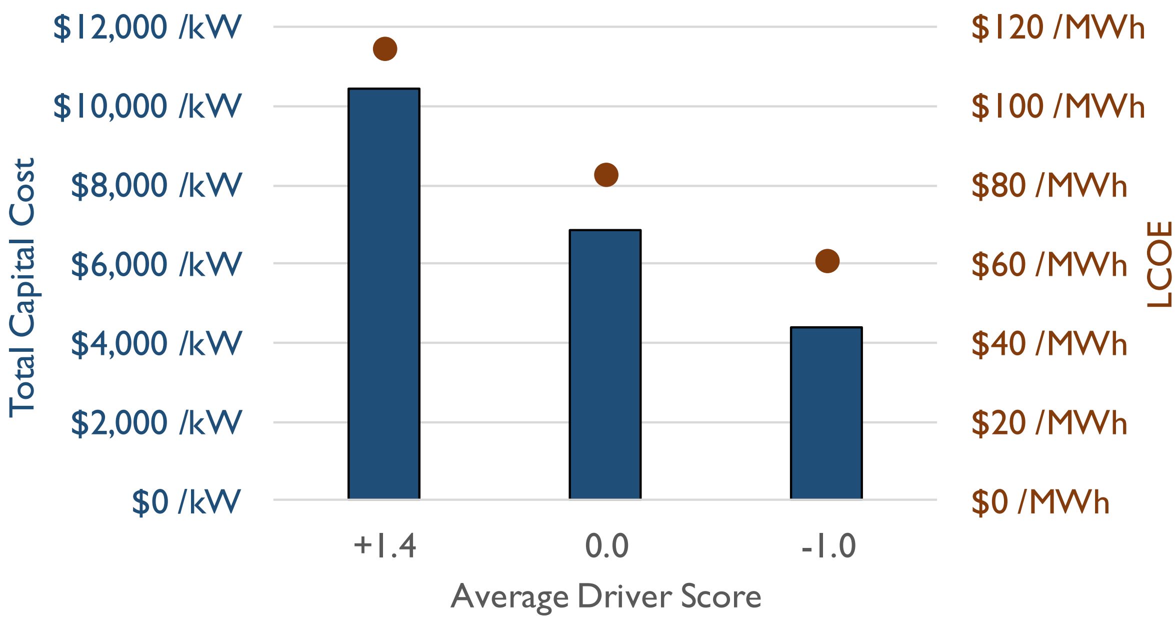
Conclusion: The rising tide that lifts all boats. Learning from the success of the offshore wind industry suggests that in addition to design and delivery improvements, innovation through collaboration; cost and risk sharing across the public sector, supply chains and developers will be critical in realising 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.

6 Cost Reduction Opportunities

6.1 Cost Reduction Opportunities for the EU/US Genre

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. The chart below shows cost reduction potential for the EU/US genre if best practices were applied across all cost driver categories. These improvements would need to be applied over time and across an intentional programme designed to capture learning, with a strong emphasis on cost reduction and improved performance.

Figure 13. Cost Reduction Opportunities for EU/US Genre



6.2 Relative importance of cost drivers in dataset

The Project Team performed the regression on completed plants or those that are planning to commission within 2018. (Note that the regression excludes SMRs and advanced concepts because their costs remain uncertain until actual plants are built.) The table below presents relative importance for each cost driver as they relate to capitalised costs. It is important to note that statistical analysis was based on a relatively small plant sample. Increasing the number of plants in the database will provide greater precision in estimating the relative influence. Major problems in any of these categories could significantly impact the final cost

Table 9. Relative importance of cost drivers in dataset

Cost Driver	Relative Importance
Supply Chain	High
Labour	High
Project Governance and Project Development	High
Construction Execution	Med
Political and Regulatory Context	Med
Equipment and Materials	Med
Vendor Plant Design	Med
Operations	-

6.3 Key Cost Reduction Strategies

This table below 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. There was a high degree of convergence on the opportunities between the scorecards (particularly those providing rationale for low cost plants) Project Advisor reviews, and interviews.

Table 10. Cost Reduction Strategies by Cost Driver

Cost Driver	Responsible Party	Key Cost Reduction Strategies
Project Governance and Project Development	Owner	• The owner's organisation needs an experienced, multi-disciplinary team • Project owner should develop multiple units at a single site • 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
Construction Execution	EPC	• 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
Political and Regulatory Context	Owner	• 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 program 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 cost-effective safety • Engage the Regulator early and agree on a process for resolving licensing issues • Reform and update nuclear safety culture
Equipment and Materials	EPC / Vendor	• Reduce quantity of 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

Cost Driver	Responsible Party	Key Cost Reduction Strategies
Supply chain	Supplier Vendors	• 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
Vendor Plant Design	Vendor	• Complete 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
Labour	Labour	• 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
Operation	Operator	• 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

7 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 Levelised Cost of Energy (LCOE). This is principally driven by three factors, overnight cost (CAPEX), 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. While 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.

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

- **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), (see explanation of how we created genres on page 35) 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. 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 "learner effects." Continuity through on-going construction allows companies to systematically realise learnings, 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 Rest of World (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. They benefit from significantly less expensive and more productive labour (i.e. more hours on task). The regulator is paid by the government as opposed to the reactor vendor or project developer and the regulator while being sufficiently independent is aligned 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 these 'contextual' factors would prevent an effective cost-reduction programme from being implemented 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 include the following:

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

8 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 could 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 underpinning evidence.

The Project also identified the potential for a step-reduction in the cost of advanced reactor technologies and SMRs. Whilst 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.

Appendix 1 Reliability of Report Contents

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

- **Evidence-base and systematic approach**.
- **Large pool of project participants and consultees with direct project experience**. 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 Project advisors and contributors are amongst the most highly respected and at the top of their respective fields within the global 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.

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.

Appendix 2 Project Team, Advisors, and Independent Reviewer

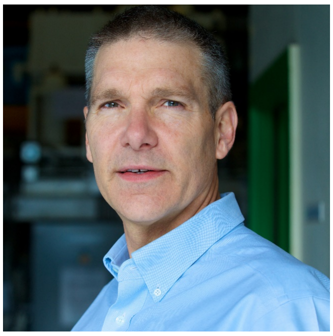
Kirsty Gogan

+15 years experience as a senior advisor to Government, industry and non-profits; including No.10 and the Office of the Deputy Prime Minister

Senior trusted advisor and consultant e.g. to UK government; IAEA expert lecturer; strong links with OECD-NEA; World Economic Forum; nuclear industry

As Deputy Head, Civil Nuclear Security, reformed civil nuclear emergency communications protocol and led national public consultation on new nuclear sites

Recent nuclear-sector clients in a consulting capacity include BEIS, NuGen, Cumbria Centre of Nuclear Excellence (CoNE), and the Nuclear Decommissioning Authority



Eric Ingersoll

Strategic advisor and entrepreneur with deep experience in the commercialization of new energy technologies

Designated nuclear cost expert for MIT's Future of Nuclear Study

Led the following nuclear cost analyses:

Two-year assessment of nuclear start-ups, their commercialization strategies, capital requirements, and the projected cost of their powerplants;

Analysis of cost drivers to explain the variance in nuclear costs among China, Korea, Japan, Finland, France, the UK, and the US; and

Three-year analysis on cost reduction potential for Gen III plants and LW SMR's, including alternative global manufacturing and deployment strategies

Andrew Foss

Played a central role in building Lucid's nuclear cost model and cost databases for the recent EON/EIRP advanced nuclear cost study

Has closely tracked nuclear trends in the UK, US, and around the world for several years, including in-depth information collection on the Hinckley Point and Horizon projects in the UK as well as the Vogtle and Summer projects in the US

Participates as a cost expert in MIT's Future of Nuclear Study

Has over 10 years of experience in quantitative analysis of innovative energy technologies, energy market dynamics, environmental quality, and related issues

John Herter

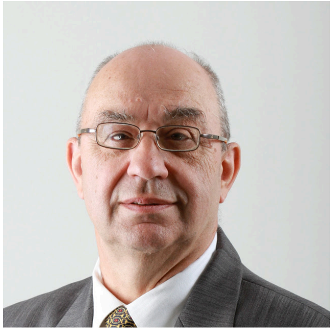
Lead author and project manager of recent EON/EIRP advanced nuclear cost study

Involved in an array of projects related to regulatory, financing, and project delivery barriers in the nuclear sector

Spent the past 12 years working for economic and corporate strategy consultancies and clean energy start-up companies

Involved in developing several capitalization strategies to take different types of nuclear technologies through to commercial demonstration

Project Advisors



Dr. Ken Petrunik

Former Chief Program Officer for the Emirates Nuclear Energy Corporation since 2009 is managing the Contract with KEPCO for the delivery of four APR 1400 nuclear power plants being constructed at Barakah in U.A.E.

Former President of the CANDU Reactor Division responsible for AECL's commercial CANDU business including new build reactors and services to operating stations.

Led the construction and project management of CANDU 6 nuclear power stations in Argentina (1), Korea (2), Romania (1) and China (2) on time and on budget.

Charles Peterson Esq.

Senior Partner of Pillsbury Winthrop Shaw Pittman LLP

Represented the UAE in its recent procurement process and negotiated the $20.5 fixed price contract with KEPCo to build 4 reactors in Abu Dhabi

Represented a major vendor during their successful negotiations to build four nuclear power plants in Turkey

Acting as legal counsel for KA.CARE in the development of the nuclear program in Saudi Arabia

Completed negotiations for the purchase of over $500 million in nuclear fuel from Russia as well as numerous other commercial transactions in the US, Japan, Russia, China and Europe

Prof. Jacopo Buongiorno

TEPCO Professor and Associate Department Head of Nuclear Science and Engineering at the Massachusetts Institute of Technology

Director of MIT's study on The Future of Nuclear Energy in a Carbon-Constrained World

Expertise in advanced reactor designs and SMRs, particularly with metal coolants

Published over 70 journal articles and received several awards for his teaching and research

Dr. Ben Britton

Researcher, Chartered Engineer and Chartered Scientist based in the Department of Materials at Imperial College London

Renown expert in nuclear materials and runs the MSc in Advanced Nuclear Engineering at Imperial College

Member of the Engineering Alloys Group, the Centre for Nuclear Engineering and the Rolls-Royce Nuclear UTC.

Recent recipient of Engineers Trust Young Engineer of the Year by the RAEng

Independent Reviewer

Dr. Tim Stone CBE

Former Expert Chair of the Office for Nuclear Development in DECC and the Senior Advisor to successive Secretaries of State responsible for energy

Chairman of Nuclear Risk Insurers and the longest serving member of the Board of the European Investment Bank

Non-executive director of Horizon Nuclear Power and a member of the Wylfa Newydd site licence company board

Only foreign member of the Expert Advisory Committee of the Royal Commission on the Nuclear Fuel Cycle established in 2015 by the government of S. Australia

Chairman of Nuclear Risk Insurers

Non-executive director of Horizon Nuclear Power

Former Chairman and founder of KPMG's Global Infrastructure and Projects Group

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