The Effect of Supply Chain Configuration on Small Modular Reactor Economics

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Declaration

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Robbie Eric Lyons

This thesis examines the opportunity presented by small modular reactors (SMRs) to bring down the cost of nuclear power. The economies of scale that have traditionally driven nuclear vendors to design larger reactors can be overcome for small reactors by the combination of standardisation of design, modularisation of the build process, and progressive reduction in production cost through learning.

By employing the most comprehensive nuclear plant construction cost data available, in conjunction with established cost estimating methods, a model was devised to estimate the capital costs and levelized electricity cost of a SMR, based on conventional light water reactor technology. Key elements of supply chain configuration were parameterised in the model, enabling the investigation of its effect on SMR economics. Credible SMR supply chain configurations were hypothesised, by applying procurement decision models to industry data and nuclear sector specific constraints. These configurations were evaluated using the model against a range of programme conditions. Beyond single programme supply chain design, the challenges posed by global production and deployment were considered, such as the segmentation of market demand, variations in labour costs, and the implications of regulatory barriers and localisation for SMR cost reduction methods. The costs of first developing a SMR programme were also estimated.

It was established that in order for SMRs to become cost competitive with large nuclear plants, a sizeable programme of at least 10 GW of standard units is needed to achieve sufficient production volume and production rate. The preferred SMR size is in the region of 250 MWe, to achieve a balance between economies of scale and learning. Progress needs to be made in harmonising global technical standards and safety regulation to make the product-like reactor concept feasible. Moreover, a committed supply chain of collaborative enterprise partners, rather than competing transactional suppliers, is required to realise the necessary learning cost reduction.

Preface

This thesis is the culmination of a research project conducted by the author, and builds upon previous works produced by the author. The introduction in Section 1 is an updated version of that from the First Year Report produced for this project (Lyons, 2016), in which the background and motivation for the research was first articulated. Furthermore, significant elements of the cost model described in this thesis were first presented at the International Congress on Advances in Nuclear Power Plants 2018, and as such the explanation of these elements in Section 2 is adapted from the associated conference proceedings (Lyons & Roulstone, 2018).

The research itself was conducted with the camaraderie of Clara Lloyd, and generous support from Tony Roulstone. The treatment of indirect cost accounts described in Section 2.4.6 specifically was developed in collaboration with Lloyd, and is similarly presented in her thesis (Lloyd, 2019).

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Acronyms

BE	Better Experience
BEIS	Department for Business, Energy & Industrial Strategy
DPC	Direct Payroll-related Costs
EEDB	Energy Economic Data Base
EMWG	Economic Modeling Working Group
FOAK	First of a Kind
IDC	Interest During Construction
IEA	International Energy Agency
IRR	Internal Rate of Return
IRV	Integrated Reactor Vessel
LCOE	Levelised Cost of Electricity
ME	Median Experience
NEA	Nuclear Energy Agency
OCC	Overnight Capital Cost
O&M	Operation & Maintenance
ORNL	Oak Ridge National Laboratory
TCC	Total Capital Cost

1. Introduction

This introduction is an updated version of that from the First Year Report associated with this research project (Lyons, 2016).

1.1. Background

Nuclear power continues to be an appealing source of electricity generation, particularly for baseload provision, because of its stable operating costs and low carbon emissions. These characteristics contrast starkly with those of gas-fired power stations: their operation is sensitive to the fluctuating fuel price, and while cleaner than coal, burning natural gas still emits a significant amount of carbon dioxide (Energy Information Administration, 2016). While this would seem to give nuclear power plants a significant advantage over fossil fuels, they are currently held back by the fact that nuclear power is an expensive technology.

Based on cost data from the Department for Business, Energy & Industrial Strategy (2016), a nuclear plant costs over eight times more on a £/kW basis to construct than a combined cycle gas turbine (CCGT) plant (Department for Business, Energy & Industrial Strategy, 2016, pp. 66-70). Figure 1 shows the Levelised Cost of Electricity (LCOE) for different electricity generating technologies, as determined by BEIS (2016).

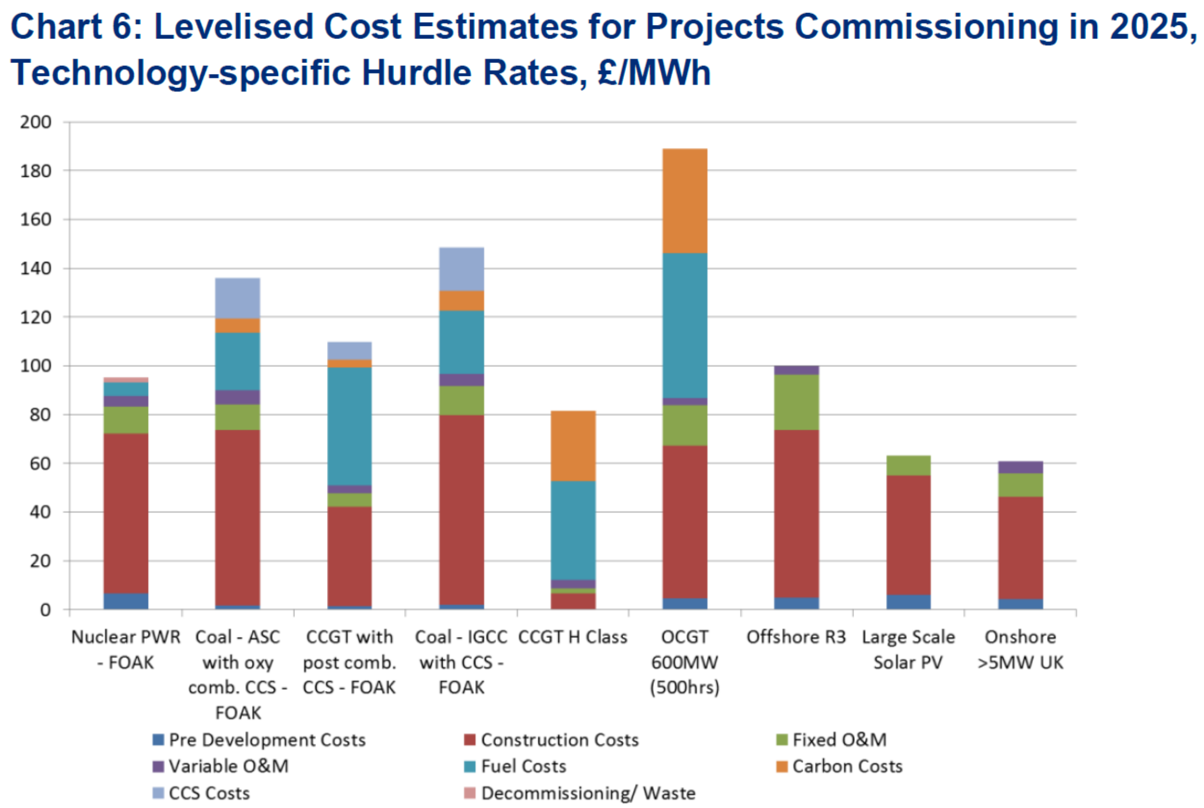

Figure 1: Graph of LCOE for different technologies (Department for Business, Energy & Industrial Strategy, 2016, p. 26)

Even with the fuel cost estimate of £40/MWh and a future carbon price of £29/MWh, a CCGT plant provides cheaper electricity than a First of a Kind (FOAK) nuclear power station (Department for Business, Energy & Industrial Strategy, 2016, p. 27). In countries such as the UK where the electricity generation market has been liberalised, this commercial challenge hinders the growth of the technology.

To understand why nuclear electricity is so expensive, it is useful to breakdown the LCOE figure into the contributions made by the various lifecycle costs. Figure 2 is based on the same data from BEIS (2016) as Figure 1; it shows that the majority of the levelised cost comes from the capital costs associated with construction of the plant. Consequently, to lower the cost of nuclear power, these large build costs must be addressed.

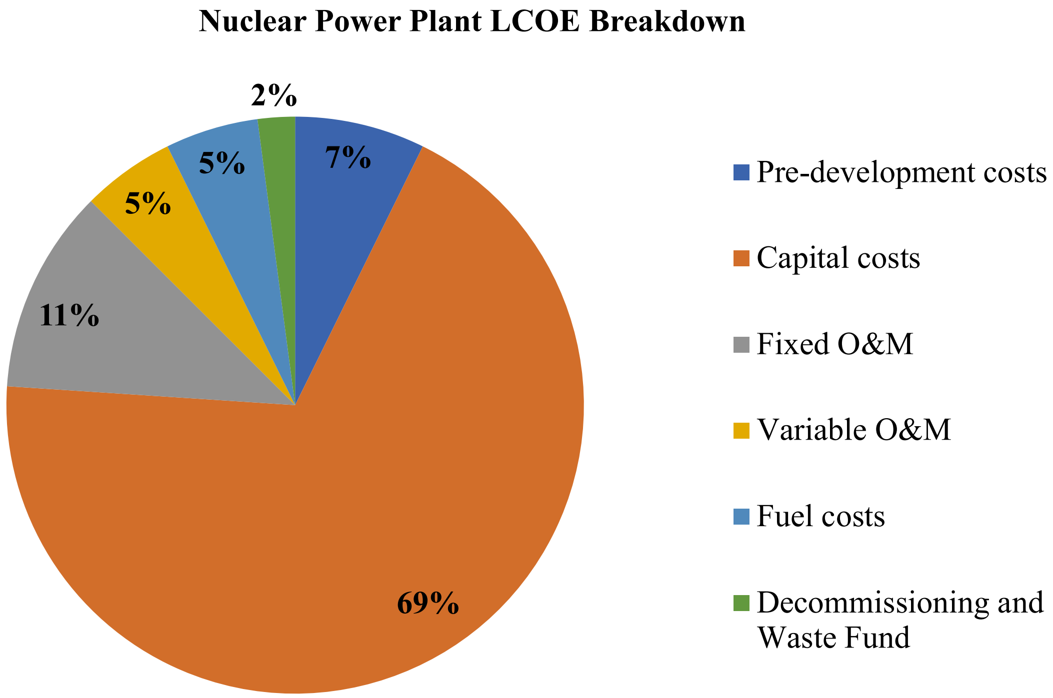

Figure 2: Levelised cost components for a conventional nuclear plant (Department for Business, Energy & Industrial Strategy, 2016, p. 27)

1.1.1. Construction of Large Nuclear Reactors

Since the start of commercial nuclear power in the 1950s, nuclear reactor units have grown by two orders of magnitude from the 60MW Magnox reactor of Calder Hall to the 1750MW EPR currently operating in China (World Nuclear Association, 2019). This can be attributed to the pursuit of 'economies of scale', whereby the specific costs of construction go down as the size of the reactor goes up. This cost behaviour is due to the spreading of fixed costs over a larger size, as well as greater operational efficiency (Carelli, et al., 2010, p. 407), and has been observed through numerous studies, as summarised by Bowers et al. (1983). However, historical construction data shows that an increase in scale of reactor units did not necessarily bring down costs. For example, data from the French nuclear programme (between 1978 and 2002) shows average specific construction costs were higher for 1450 MW reactors than for 900 MW (Cour des comptes, 2012, pp. 22-23). To explain similar observations from their analysis of US plant construction data, Cantor and Hewlett (1988) suggest that the cost benefits of increased size are outweighed by the longer construction periods for larger plants, due to the fact that 'the construction of a large plant is more difficult to manage, productivity is lower, or regulatory scrutiny is stricter' (Cantor & Hewlett, 1988, p. 331). This is corroborated by the analysis done by Ganda et al. (2016), which highlighted that the rises in US construction cost in the 1970s and 1980s were 'almost entirely driven by labor cost increases' (Ganda, et al., 2016, p. 968). This was attributed to 'decreased productivity which, in turn, was found to be affected predominately by (1) rework and (2) delays' (Ganda, et al., 2016, p. 968).

Such construction cost increases have not been realised in all nuclear programmes, as Lovering et al. (2016) showed in their study of historical construction costs. South Korea is highlighted as the one case where construction cost reductions of 1-2% per year have been achieved during a nuclear plant build programme (Lovering, et al., 2016, p. 378). The authors attribute the global variations in construction costs to differences in 'factors such as utility structure, reactor size, regulatory regime, and international collaboration' (Lovering, et al., 2016, p. 380). In the case of South Korea, their cost reduction can be credited to the use of standardised reactor design, a single consistent supply chain, and the implementation of modular construction as used in the Japanese nuclear programme (Roulstone, 2015a, pp. 5-6).

1.1.2. Small Modular Reactors

Todreas (2015) provides a clear definition of a small modular reactor (SMR): it is 'small' due to its output power falling in the range of 10-300 MWe, and it is modular because the reactor unit is constructed through the assembly of modules (Todreas, 2015, p. 3). These modules would be manufactured in a factory environment, thereby significantly reducing the amount of construction activity conducted on-site. As Todreas points out, neither of these two characteristics are novel. As already mentioned, the first commercial nuclear power plants were small, and modular construction techniques have already been applied to modern large reactors, such as the Hitachi ABWR (McDonald, 2013) and Westinghouse AP1000 (Bowser, 2010). However, the combination of these two attributes is intended to not only provide a more competitive form of nuclear power (i.e. with a lower LCOE), but also an alternative commercial proposition that could be more appealing to investors.

As already discussed, the largest component of a nuclear plant's LCOE is the levelised capital costs. In order for this to be significantly reduced, an SMR will need to have a lower specific capital cost than a conventional large reactor. As laid out by the NEA (2011), while economies of scale may not have been realised as a benefit for large reactors, they would be expected to result in significantly higher specific capital costs for an SMR. However, the SMR concept targets several different methods of cost reduction which would outweigh the scale effect. These are explored in detail by the Nuclear Energy Agency (2011, pp. 65-88), and can be summarised as follows:

1. **Factory manufacture**: the conditions of a factory environment improve productivity to give a one-off cost benefit, as well as facilitating learning-by-doing which lowers capital costs as the programme progresses;
2. **Shorter construction duration**: also enabled by the factory manufacture and site assembly approach, this reduces both the total standing costs of operating a construction site and the financing costs;
3. **Design simplification**: the smaller size of SMRs allows for the consolidation of the complex systems required by large reactors (Nuclear Energy Agency, 2011, p. 88).

Beyond the more competitive LCOE, the SMR concept differentiates itself from conventional large plants in two ways, as the NEA (2011) explains. Firstly, the small power output of an individual SMR unit makes it appropriate for deployment where electricity demand is not sufficient to necessitate a large reactor. Secondly, in a scenario where a large plant is needed, it would be possible to build the plant up in stages. An individual unit could go into operation before the others are built, or perhaps even ordered. This would not only reduce the initial capital investment required, but also allow the output of the plant to be scaled up when demand increases. These two differentiating factors mean that SMRs offer an alternative commercial proposition for investors, which could be more appealing than a conventional large plant (Nuclear Energy Agency, 2011, p. 12).

1.2. SMR Economics: Current Status of the Field of Research

An underlying problem with SMR economic arguments as they stand today is that an SMR has not yet been built, and therefore there is no real cost data available. Consequently, work has been done to try to estimate the costs of SMR construction, using a variety of different methods. Carelli et al. (2010) sought to determine the relationship between SMR and large reactor capital and operation and maintenance (O&M) costs. The authors built on the established knowledge of capital cost scaling, and developed cost reduction factors to account for the benefits of learning-by-doing, co-siting of multiple units, modularisation, and the potential financing options open to SMRs. This led to the determination that an SMR’s total capital cost would be broadly similar to that of a large reactor, given the SMR-to-large reactor capital cost factor ratio of 1.05. A similar methodology for O&M costs predicted that SMRs would be greater than 20% more costly during operation (Carelli, et al., 2010, p. 412). The Nuclear Energy Agency (NEA) conducted a similar top-down analysis of SMR costs, and concluded that they could not compete with large reactors on a LCOE basis (Nuclear Energy Agency, 2011, p. 26).

Abdulla et al. (2013) applied a different method to estimate SMR costs: expert assessment. The authors 'developed detailed technical descriptions of two SMR designs and then conduced [sic] elicitation interviews' (Abdulla, et al., 2013, p. 9686). Unsurprisingly, the authors received varied estimates for SMR construction costs, although the group of experts could be divided into those who thought SMRs would be marginally more expensive than large reactors, and those that thought they would be much more expensive (Abdulla, et al., 2013, p. 9689). This would suggest that those in the latter group were not convinced that the cost scaling effect could be overcome in the ways described in Section 1.1.2. On the other hand the experts largely agreed that SMRs could be built quicker than large reactors, 'because of the increased use of modular construction, the integration of all nuclear components into a single factory-built module, and the reduced complexity of the balance of plant' (Abdulla, et al., 2013, p. 9688).

Along with efforts to determine costs, studies have been done that explore potential build strategies for SMRs. Maronati et al. (2016) investigated the effect of the modular construction strategy on the total capital cost, by employing cash flow analysis and assumptions about productivity with regards to on-site verses off-site work. (Maronati, et al., 2016, p. 1). The results highlighted the cost reduction effect of modular construction, and in particular the benefits of employing factory manufacturing. These two methods applied together resulted in a total capital cost reduction of 39% compared to traditional 'stick construction' strategy (Maronati, et al., 2016, p. 4).

In their comprehensive review of the SMR proposition, Goldberg and Rosner (2011) modelled the effect of learning on SMR costs, with particular focus on the competition with gas-fired power plants. By assuming a level of learning cost reduction based on previous work (The University of Chicago, 2004), the authors modelled an SMR production programme which brought the LCOE down in line with natural gas combined cycle (NGCC) generation. Their results are summarised in Figure 3.

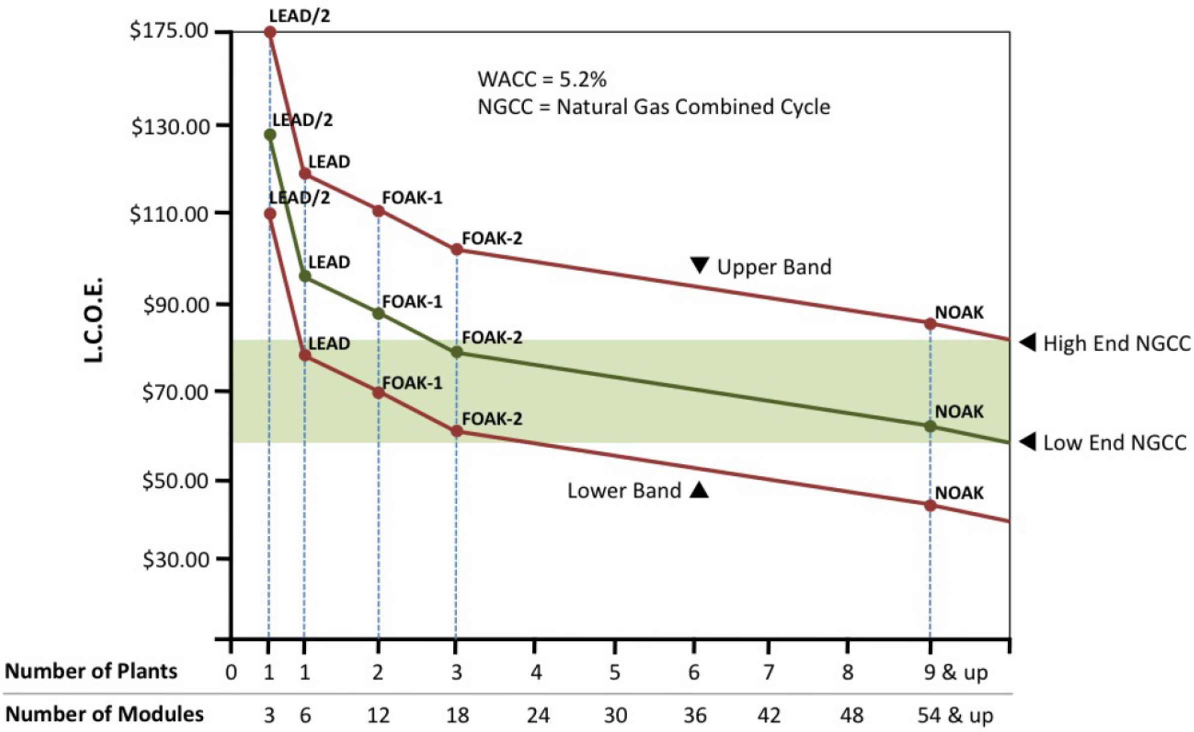

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Figure 3: LCOE of SMR plants (Rosner & Goldberg, 2011, p. 21)

The green band between 'High End NGCC' and 'Low End NGCC' represents the estimated range of the LCOE for an NGCC based on historical variations in the natural gas price (Rosner & Goldberg, 2011, p. 16). The upper and lower band curves arise from variations in the assumed specific capital cost of the first, or 'LEAD' plant, as well as the subsequent learning effect. The assumed case depicted by the green curve found that after 18 SMR units had been produced, the subsequent units could begin to compete with NGCC, having reached an LCOE of $80/MWh. It should also be noted that the study's model assumed 'an SMR multi-module manufacturing facility' (Rosner & Goldberg, 2011, p. 18), and the authors indicated the intention to explore in detail, the potential for learning in such a facility (Rosner & Goldberg, 2011, p. 18).

The report by Chen et al. (2013) details this subsequent study of factory learning. The authors modelled the manufacturing of the 'Integrated Reactor Vessel (IRV)' (Chen, et al., 2013) of the same generic SMR design used by Rosner & Goldberg (2011). Using a component breakdown of this posited IRV, the authors employed a manufacturing simulation tool which estimated the various manufacturing costs for the first IRV (Chen, et al., 2013, pp. 24-27). Most notably however, the simulation tool was also able to estimate the aggregate learning cost reduction as multiple IRVs were manufactured. This was achieved by estimating the basic manufacturing processes involved in the production of the individual subcomponents, and applying learning cost reduction to these specific activities. These levels of cost reduction were based either on the simulation tool's own library, or by the authors' insertion of learning rates based on data from comparable industries (Chen, et al., 2013, pp. 49-50). In this way, the authors determined an overall learning rate of 6.7% (Chen, et al., 2013, p. 69) for IRV manufacture. The significance of this study is that it derived the overall learning cost reduction, rather than simply applying an assumed rate to the total capital costs. Moreover, the authors explored how the production arrangements – specifically the 'lot size' – influenced this overall learning effect (Chen, et al., 2013, p. 61). This represents a significant step in characterising the factors that affect learning cost reduction in SMR production, and provides a conceptual foundation for the research that is presented in this thesis.

1.3. Research Objective

The economic case for SMRs relies on overcoming economies of scale by:

- producing multiple units of a standardised design;
- a high degree of modularisation, moving labour into a more productive environment and shortening build times;
- the realisation of cost reduction from learning due to the series production of these standard units.

While several studies have sought to estimate the balance of scaling and these cost reduction methods, absent from consideration has been the role of the supply chain structure that will deliver such a production programme. As for large reactors, a SMR supply chain will likely consist of a range of specialist suppliers, providing components for one or multiple plants, either directly or via module fabrication. Some components may be procured from multiple suppliers. These factors will affect learning in particular, as is discussed in Section 3.3, but also the extent to which standardisation and modularisation can be achieved. Beyond internal supply chain considerations, external market factors will also have an influence. The expected global demand for SMRs (Waddington, 2014) will not be a uniform market, nor one solely driven by cost considerations. Different countries have different regulatory regimes and technical standards, which challenge standardisation. The geopolitical nature of nuclear technology means that countries may prefer an expensive domestic programme rather than a cheaper import. Those countries that are open to international programmes may demand localisation of manufacturing as justification for their investment. Alternatively, the lack of local knowledge and skills may remove local supply as an option for vendors. These factors complicate the evaluation of learning cost reduction that can be achieved, and thus how economically competitive SMRs might be.

The objective of the research presented in this thesis was to determine how the supply chain configuration will affect the economic competitiveness of SMRs. To achieve this, answers were sought to the following questions:

1. What are the relevant factors that characterise a supply chain configuration when considering SMR economics?
2. What are credible supply chain configurations that could be adopted in a SMR production programme?
3. Can any of these configurations deliver cost competitive SMRs, and under what conditions?

In Section 2 the cost model developed to evaluate SMR costs is presented. In Section 3, supply chain theory from literature and practice from industry are examined; this provides the conceptual basis for the integration of supply chain configuration into the cost model. In Section 4 credible supply chain configurations for SMR production are derived, and then tested against a range of single programme conditions. In Section 5 possible global demand for SMRs, its geographic distribution and the resultant supply chain and programme constraints are considered. In Section 6 estimates are determined for the setup costs for an SMR programme, and the effect this will have on the competitiveness of the SMR units produced. In Section 7 the effect of uncertainties in the cost modelling approach on the calculated SMR costs is quantified. In Section 8, the findings from the research are discussed and the key conclusions presented.

2. Cost Estimation Methodology

Small modular reactors are intended to be realised at lower capital cost than conventional large reactors, principally by the application of three principles: standardisation of plant design and construction processes; modularisation, giving a greater degree of factory manufacturing and assembly; series production of multiple units. These principles are intended to overcome economies of scale that would otherwise make smaller reactors more expensive. Standardisation reduces cost by eliminating the repetition of detailed design needed to customise each plant. Modularisation raises productivity by changing the work environment, thus reducing labour costs; it also shortens the build schedule, which reduces site indirect costs and the costs of borrowed capital. Series production lowers costs through learning, which results in progressive improvements in labour performance, production processes and tooling.

In order to evaluate the effects of supply chain configuration on small modular reactor economics, a capital cost model was developed that incorporated supply chain parameters. It is challenging to predict costs of reactor designs that have not been built yet. The modelling approach used in this research is top-down, employing the best available data (as discussed in Section 2.3.6) and established cost estimating methods from the literature. A key limitation of this approach is that the costs are only representative of the specific technology and design of the reference data: in this case, a pressurised water reactor.

In this chapter, the underlying concepts and implementation of the cost model are described. First, the particular costs to be determined by the model are defined and explained, followed by a summary of the overall approach to estimating these costs. The reference cost data used in the model is then described. The specific cost modelling methods are then presented, starting with an explanation of power scaling, followed by the underlying principles of the cost reduction methods considered possible for SMRs. An idealised SMR supply chain map is then presented which highlights how both costs and the cost reduction methods are distributed across the supply chain. The implementation of the cost model is then presented, along with a set of sample results and sensitivities. This is followed by a discussion of model validation against available data, as well as the limitations of its use.

2.1. Cost Definitions

In discussions of SMR economics, as well as for other electricity generating technologies, different cost metrics are used, and with varying definitions. In order to discern the contributions of different effects, three different costs of a single SMR plant are calculated by this model: the Overnight Capital Cost (OCC), the Total Capital Cost (TCC), and the Levelised Cost of Electricity (LCOE).

The OCC is so called because it represents the cost of building a plant ‘overnight’, thus not including any financing costs. It is made up of Direct and Indirect costs, the former being the sum of labour and material costs that are directly attributable to elements of the plant, while the latter is the sum of associated costs of conducting the manufacturing and construction activities. The detailed breakdown of these costs is discussed in Section 2.3, as it is particular to the reference data set employed by the model. The OCC serves as the most direct measure of the impact of manufacturing and construction cost reduction efforts.

The TCC adds the cost of capital onto the OCC. The cost of capital is a function of the cost of equity and debt, as well as the duration of construction, making TCC an important measure of the benefits of schedule reduction, as well as perceived risk reduction. Finally, the LCOE goes beyond just capital costs by also factoring in the operation and maintenance costs, as well as subsequent decommissioning costs. The LCOE effectively stands as the price of the electricity generated by the plant that should be set in order to recoup these lifetime costs.

2.2. **Cost Modelling Approach**

Figure 4 gives an overview of the process used to calculate the OCC, TCC, and LCOE values for each SMR plant in a continuous programme. The costs are derived from a reference cost data set, which is described in detail in Section 2.3; in short, these costs represent the average experience of construction costs of an approximately 1 GW PWR plant in the United States in 1987. These costs are converted to those for a 250 MW SMR of essentially the same design and construction method by applying the top-down estimation method of power scaling. Having determined the scaled costs, the cost reduction approaches of standardisation, modularisation, and schedule reduction are applied to yield the OCC and TCC of the first unit of SMR production. Learning cost reduction is then applied over the course of a posited SMR programme to give the capital costs for successive production units. Scaling of reference large reactor operation and maintenance costs gives the additional components to determine the LCOE for each production SMR unit.

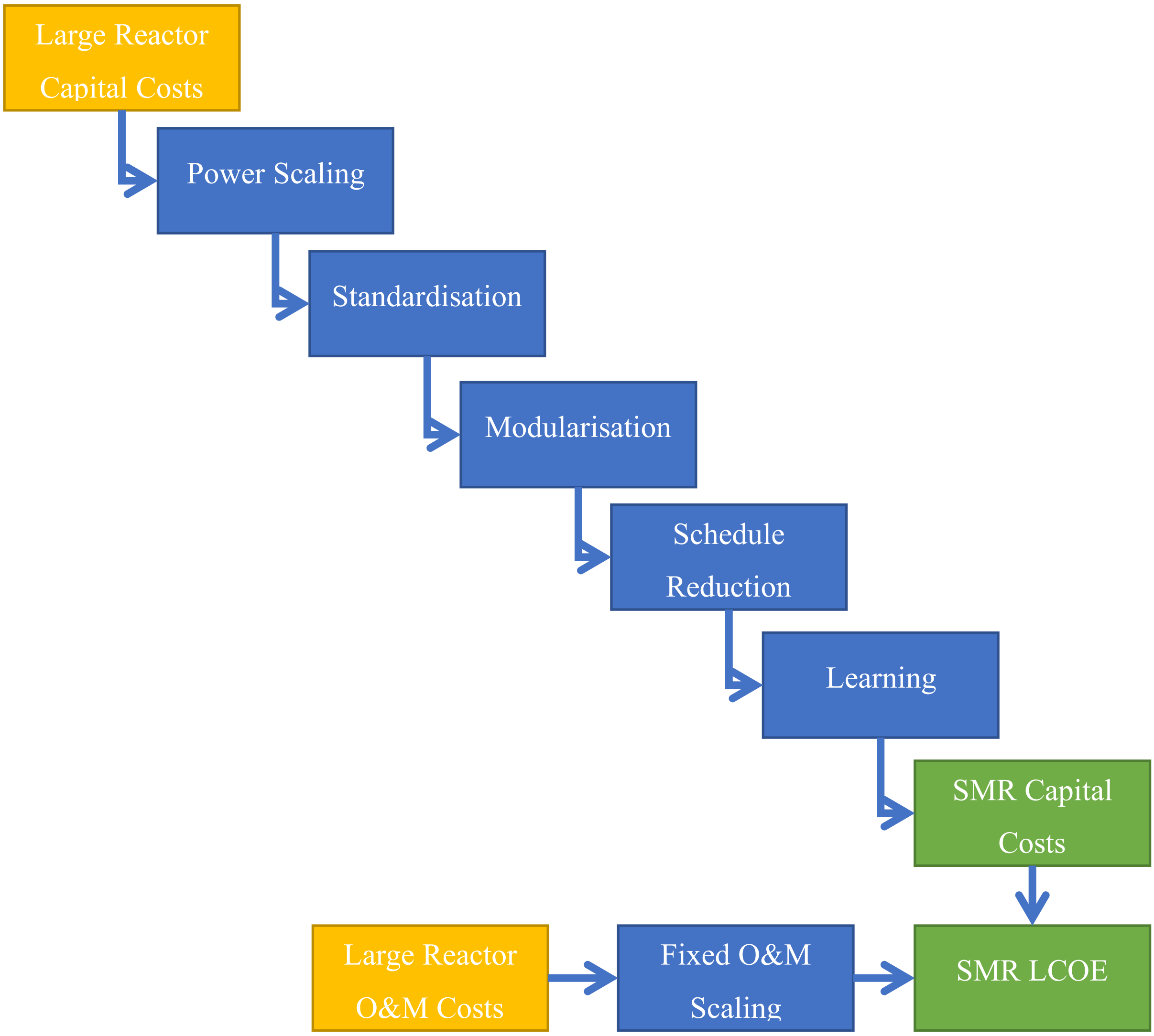

Figure 4: Cost modelling approach

2.3. **Reference Capital Cost Data**

The cost data that forms the foundation of the cost model is taken from the Energy Economic Data Base (EEDB), curated by Oak Ridge National Laboratory (ORNL). The EEDB was established in 1978, and regularly updated through to 1987, for the purpose of providing 'current, representative, and consistent power plant technical and cost information…for program planning' (United Engineers & Constructors Inc., 1988a, p. ES.1).

2.3.1. Design Basis

The data base provides base construction costs (the sum of direct and indirect costs) for a number of thermal plant types; of the nuclear power plants included, the PWR-12 reference data is used in this model. The PWR-12 plant design is based upon the Westinghouse standardized four loop single unit nuclear steam supply system, as described in the Westinghouse Reference Safety Analysis Report, and which corresponds to the Public Service Company of New Hampshire Seabrook Station (United Engineers & Constructors Inc., 1988b, p. 3.1). However, 'this design basis has been modified and updated' with each update to the EEDB, 'in order to reflect current industry practice, experience and response to regulations' (United Engineers & Constructors Inc., 1988b, p. 3.1). The most recent update, Phase IX, brings the design basis, and hence associated costs, up to January 1987. A summary of the key design features is given in Table 1.

Number of Reactor Units	1
Thermal Power (MWt)	3,417
Net Electrical Power (MWe)	1,144
Net Plant Efficiency (%)	33.48
Fuel Type	UO_2
Fuel Enrichment (%)	3
Number of Coolant Loops	4

Table 1: Key features of EEDB PWR-12 design basis (United Engineers & Constructors Inc., 1988b, pp. 3.2 - 3.4)

2.3.2. Cost Experiences

Furthermore, for the PWR-12 design basis the EEDB provides two base construction cost estimates: median experience and better experience. The former simply stands as the median within the range of cost experiences in US plant construction. The latter was introduced in the Phase VI update to the EEDB, 'because of the increasing spread in the nuclear power plant cost range'; it represents better cost experience as the result of 'regulatory reforms and improved construction practices' (United Engineers & Constructors Inc., 1988a, p. ES.5). The detailed differences between the median experience (ME) and better experience (BE) data are discussed in Section 2.3.5; at this stage it suffices to understand that because the BE data already takes credit for some of the cost reduction methods employed in the cost model, the ME data was selected as the appropriate reference data. The fact that the ME data represents the average experience also supported the judgement that it was the more appropriate starting point for SMR cost estimation.

2.3.3. Code of Accounts

The base constructions costs are broken down by a Code of Account system which is employed uniformly throughout the EEDB. As previously mentioned, the base construction costs are made up direct and indirect costs, which are broken down into 6 and 3 two-digit accounts respectively. These accounts are shown in Table 2.

	Account Number	Account Name
Direct Cost Accounts	21	Structures & Improvements
	22	Reactor Plant Equipment
	23	Turbine Plant Equipment
	24	Electrical Plant Equipment
	25	Miscellaneous Plant Equipment
	26	Main Condenser and Heat Rejection System
Indirect Cost Accounts	91	Construction Services
	92	Engineering & Home Office Services
	93	Field Supervision & Field Office Services

Table 2: EEDB Two Digit Accounts (United Engineers & Constructors Inc., 1988a, p. 5.11)

The EEDB is underpinned by technical data models for 'over 50 major structure/systems and up to 400 subsystems', with each including 'system design descriptions, engineering drawings, milestone schedules and a detailed equipment list' (United Engineers & Constructors Inc., 1988a, p. ES.4). While these models support accounts down to the nine digit level, the Phase IX report only provides the ME data down to the four digit level for direct accounts, and three digit level for indirect accounts. In total, data for 154 separate accounts is employed by this cost model.

2.3.4. Cost Categories

For each cost account, the total cost is further divided into three cost categories: factory equipment, site materials, and site labour. Factory equipment is defined as ‘manufactured or factory fabricated items’, while site materials is defined as ‘field purchased or bulk commodity items, such as concrete, reinforcing steel, formwork and structural steel’ (United Engineers & Constructors Inc., 1988a, p. 7.5). These cost categories are used for both the direct and indirect cost accounts; for the latter, these cost categories were judged to be misleading. Therefore, two further cost categories were introduced, indirect services and indirect site labour, which are used throughout this dissertation. Any factory or site material costs in the indirect accounts were re-categorised as indirect services, and site labour costs in these accounts were re-categorised as indirect site labour. The subsequent distribution of the reference base construction costs across these categories is shown in Figure 5.

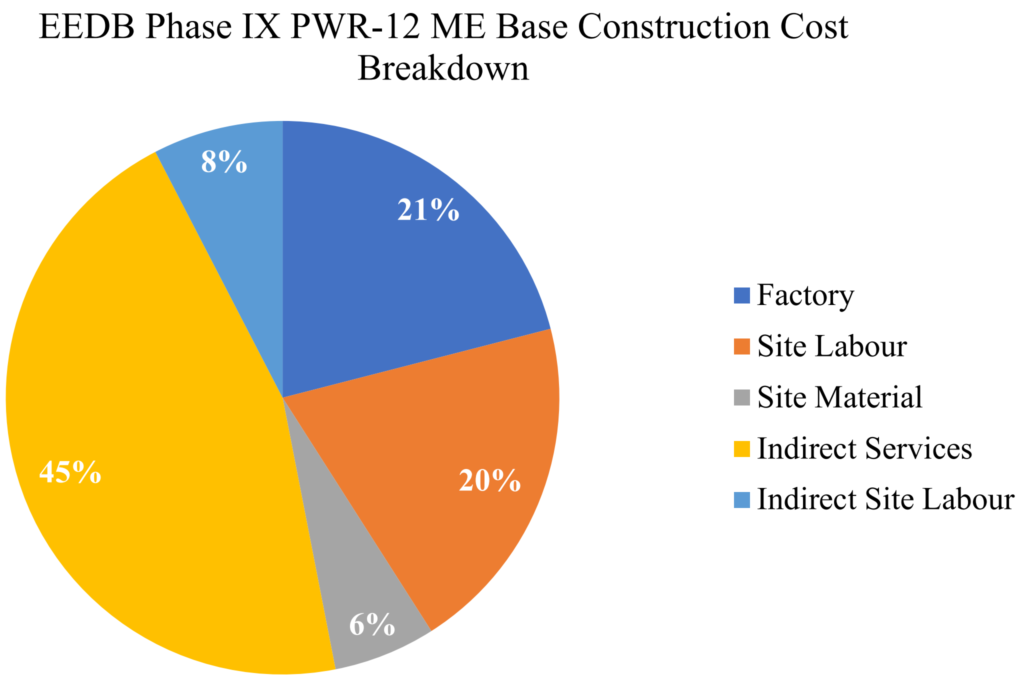

Figure 5: Cost category distribution (United Engineers & Constructors Inc., 1988a)

2.3.5. ME – BE Data Comparison

Table 3 compares the ME and BE cost data from the Phase IX report. The data is in 1987 US Dollars, and shows the absolute and percentage change in costs from the median to better estimates.

	ME	BE	Change	% Change
Factory	$531,024,972	$517,694,361	-$13,330,611	-3%
Site Labour	$505,145,424	$277,159,927	-$227,985,497	-45%
Site Material	$169,296,113	$121,233,944	-$48,062,169	-28%
Indirect Services	$1,131,576,000	$439,780,000	-$691,796,000	-61%
Indirect Labour	$192,293,000	$99,765,000	-$92,528,000	-48%
Total Base	$2,529,335,509	$1,455,633,232	-$1,073,702,277	-42%

Table 3: ME/BE data comparison (1987 $) (United Engineers & Constructors Inc., 1988a)

The median experience (ME) estimate total cost is ~$2.529bn, while the better experience (BE) estimate total cost is ~$1.456bn; this gives a difference of ~$1.074bn. While all five cost categories see a reduction between the two estimates, the largest percentage changes are in Indirect Services, Indirect Labour and Site Labour. Moreover, as can be seen in Figure 6, in absolute terms most of the ~$1.074bn cost reduction comes from Indirect Services.

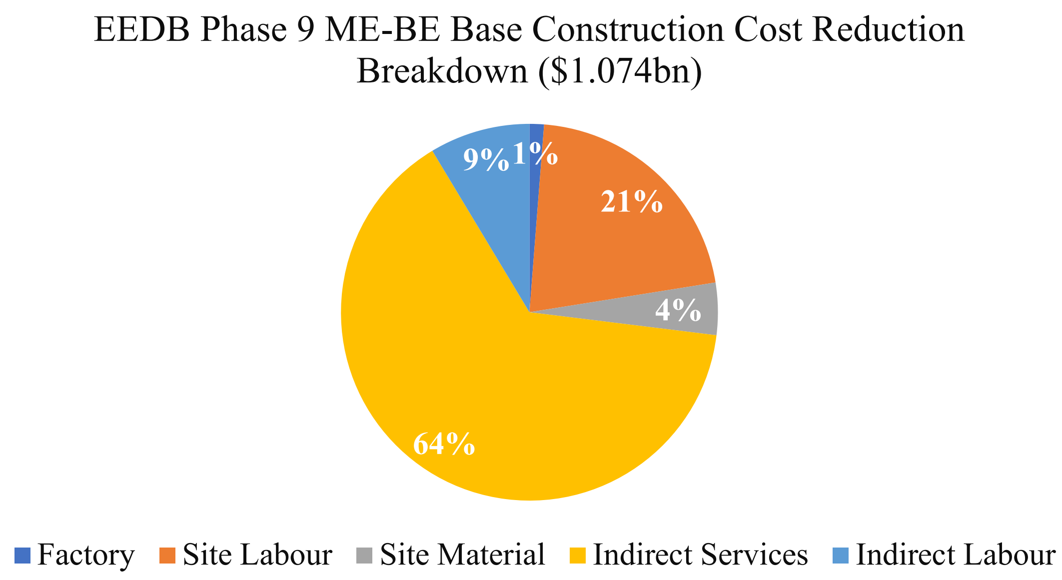

Figure 6: ME-BE cost reduction breakdown

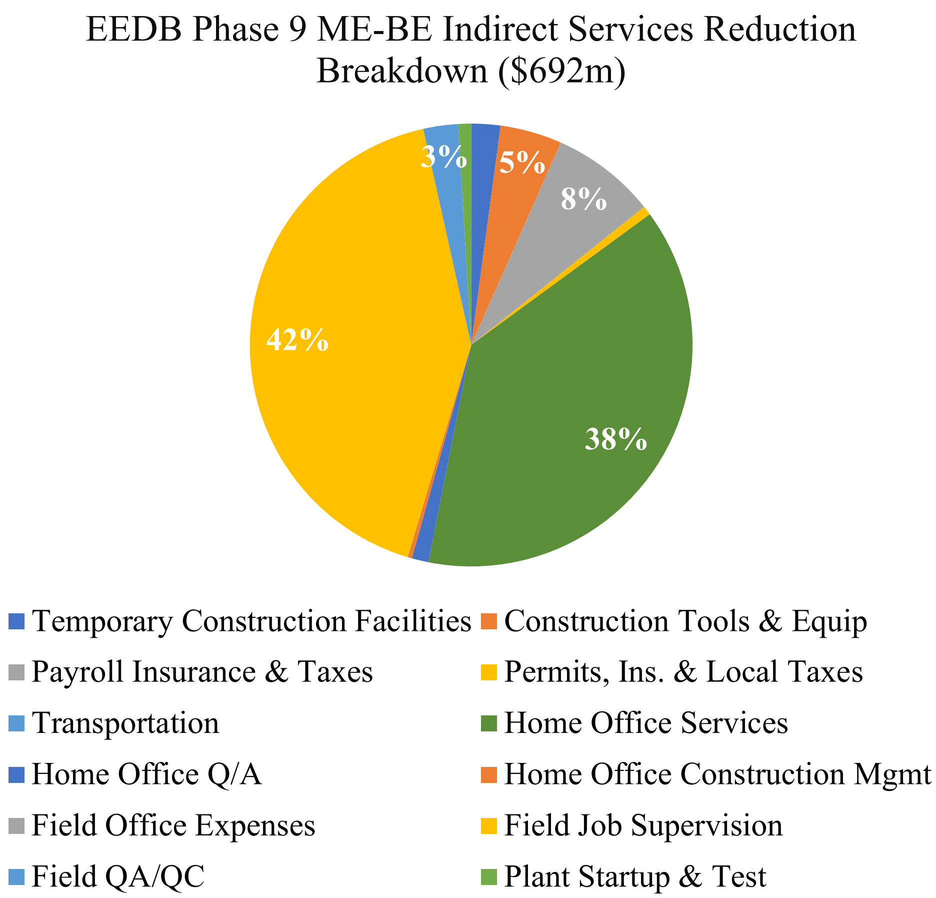

Figure 7: Indirect Services reduction breakdown

Figure 7 shows the breakdown of the Indirect Services cost reduction (~$692m), and highlights that it is dominated by savings in 'Home Office Services' and 'Field Job Supervision'. The Phase IX report provides the following definitions of these two accounts:

'Home Office Services: the salaries of personnel, direct payroll-related costs (DPC), overhead loading, expenses and related fees associated with the engineering and design (both home office and field), procurement and expediting activities, estimating and cost control, engineering planning and scheduling, and reproduction services, plus expenses associated with performance of the above functions (i.e., telephone, postage, computer use, travel, etc.)';

'Field Job Supervision: the salaries, DPC, overhead loading, relocation costs and fees associated with the resident construction superintendent and his assistants, craft labor supervisors, field accounting, payroll and administrative personnel, field construction schedulers, field purchasing personnel, warehouse personnel, survey parties, stenographers and clerical personnel.' (United Engineers & Constructors Inc., 1988a, pp. 7.10 - 7.11)

The cost category with the second largest cost reduction from ME to BE is Site Labour (~$228m), the breakdown of which is shown in Figure 8. Site Labour is a direct cost, with the largest savings being realised for the civil structures and reactor plant equipment.

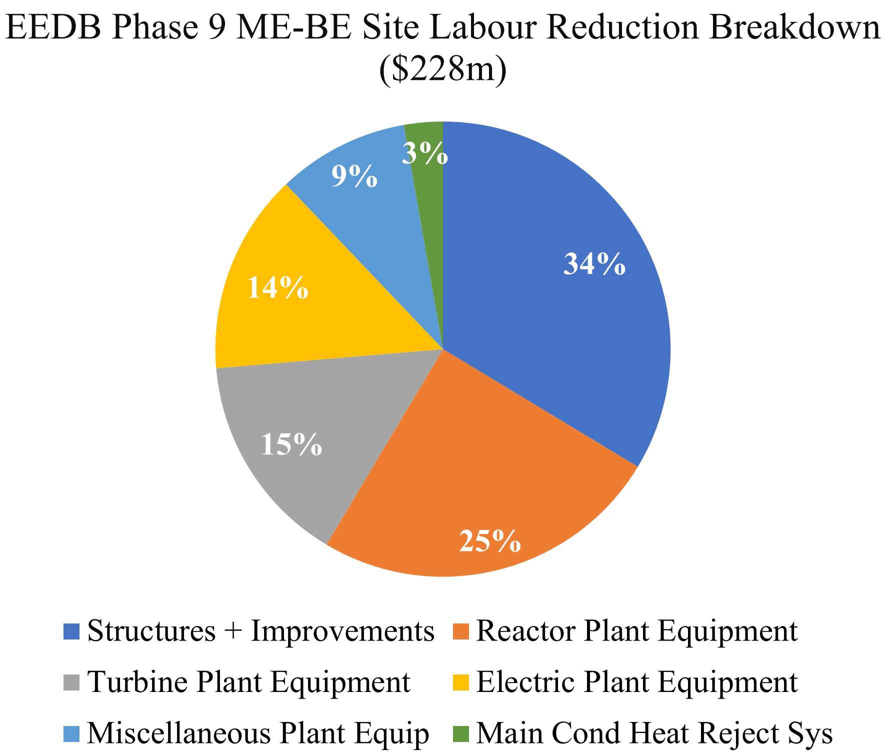

Figure 8: Site Labour cost reduction breakdown

The Phase IX report explains that these cost reductions between ME and BE can be attributed to the partial application of the following:

- ‘the availability of certified (pre-licensed) designs to reduce regulatory uncertainty in the areas of licensing, design and construction activities’;
- ‘a standardized approach to design and construction’;
- ‘modular construction as a means to reduce site labor and associated field supervision, and to improve interfaces among engineering, field supervision and site labor’ (United Engineers & Constructors Inc., 1988a, p. 3.32).

2.3.6. Justification for selected reference data

The principal reason for the selection of this reference data as the primary input to the cost model is the detail it provides. The combination of cost category and code of account breakdowns is a critical enabler of the cost reduction estimation, as it illustrates the distribution of costs within the supply chain. The code of accounts in particular aids cost comparisons not only between plants but also different technologies, and while the code has been adapted by different users, such as the EMWG (Economic Modeling Working Group, 2007) and the IAEA (International Atomic Energy Agency, 2000), the structure has remained relatively consistent. While nuclear construction data is available in the literature, particularly for the large US and French programmes as examined by Berthélemy & Rangel (2015), this data is not broken down to nearly the same extent as the EEDB.

It is important to highlight that the costs provided by the EEDB are for January 1987, and as discussed in detail by Ganda et al. (2016), one might expect the past trend in real terms cost increases above inflation to have continued since then. Ganda et al. (2016, pp. 962-963) present an approach to reconcile the EEDB's historical costs with current ones which includes the aforementioned real cost increase. However, the points of comparison are the Better Experience costs from the EEDB and costs from two recent US nuclear plant projects, VC Summer and Vogtle. The former represent costs of an industry with substantial and recent experience, in which the 'majority of workers have at least some nuclear construction experience' and the 'local supply chain is capable and has nuclear experience' (Energy Technologies Institute, 2018, p. 10); moreover these costs are the most competitive produced under these conditions. Meanwhile, the latter projects implement new reactor designs with an industry which has had a multi-decade hiatus in nuclear construction (World Nuclear Association, 2019), which are not the conditions likely to produce low costs.

Consequently, when starting with the more conservative Median Experience costs from 1987, these were increased to 2017 US dollars simply in line with inflation. This was judged to be appropriate for two reasons; firstly, it keeps the cost base credibly tied to the bottom-up work done by United Engineers & Constructors to produce the data; secondly, Ganda et al. explain that the real term construction cost increases were 'mostly driven by increased regulatory stringency', and that the period of nuclear construction after 1987 'included only the aftermath of the Chernobyl accident, which had a more muted impact than TMI on the U.S. regulatory stringency' (Ganda, et al., 2016, p. 962).

2.4. **Cost Modelling Methods**

2.4.1. Power Scaling

Estimating power plant costs via reactor power scaling is a conventional practice, as described by the NEA (2000), Economic Modelling Working Group (2007), and discussed in detail by Carelli et al. (2010). As explained by Locatelli et al. (2014), in the context of nuclear reactor power scaling, 'the economies of scale apply if and only if the comparison is 1 Large vs. 1 Small and the reactors are of a similar design' (Locatelli, et al., 2014, p. 76). The cost model described in this chapter is consequently limited to evaluating established PWR technology, with the cost reductions methods applied following scaling taking account of the manufacturing and construction practices uniquely applied to SMRs. Consequently, the scaled costs represent the construction cost of an SMR employing the same technology and construction processes as the large reactor design associated with the reference data.

2.4.2. Modularisation

The approach to adjusting costs to account for the conversion from traditional in-situ construction to module manufacturing is based on that from the cost estimating guidelines produced by the Economic Modeling Working Group (EMWG) of the Generation IV International Forum (Economic Modeling Working Group, 2007). In summary, the extent of modularisation is defined by modularisation percentages for each cost account, which indicate how much of the site labour and material costs are moved off-site. The labour and material costs that have thus been assigned to module production are adjusted to reflect productivity and labour rate differences between a construction site and factory environment. These 'shop labour' and 'shop material' costs are then used to estimate the additional indirect costs associated with module fabrication, transport to site, and installation.

The modularisation percentages and factors used in this study act as simplifying assumptions, as the direct impact of modularisation on SMR costs is not the focus of this work. A complementary study by Lloyd (2019) provides a detailed analysis of the potential for and effects of modularisation in the context of SMRs. Moreover, the cost modelling methods for modularisation and standardisation described in this chapter were developed in collaboration with Lloyd and are also employed in the aforementioned study.

2.4.3. Schedule Reduction

A shorter build schedule can reduce nuclear plant construction costs in two principal ways. Firstly, it reduces the indirect costs associated with running a construction site, such as the costs of renting equipment or facilities. Secondly, it reduces the interest accrued during construction on the capital used to fund it. The indirect costs would fall in direct proportion to the schedule reduction, while the interest reduction would be greater due to the effect of compounding.

2.4.4. Standardisation

The establishment of a fixed design and construction process would be expected to reduce cost by the avoidance of duplicate work and enabling of learning. However, the work to achieve standardisation would also be expected to incur significant up-front cost. This could range from computer-based modelling, to experimental testing, or perhaps to a full demonstration. The estimation of such up-front costs was ruled out of the scope of the main cost model, but is discussed later in Section 6. Consequently, only the cost reductions associated with standardisation are implemented in this model.

2.4.5. Learning

The concept of production learning was first articulated by Thomas Wright through his observations of man-hour reductions in the construction of aircraft (Wright, 1936); specifically, Wright determined that the 'labour input dropped by 20% for every doubling of cumulative output' (Yeh & Rubin, 2012, p. 763). This can be formulated as Equation 1, in which LR stands for the learning rate, which characterises the cost reduction, and d stands for the number of doublings of production units.

$$Average\ Unit\ Cost = First\ Unit\ Cost\ \times (1 - LR)^d$$

Equation 1: Learning cost reduction calculation

This representation of labour cost reduction has been expanded to cover the total unit price of a product, and is referred to as the 'experience curve' or 'progress curve' (Yeh & Rubin, 2012, p. 763). The formulation has also been adapted to determine n^{th} unit costs, rather than the average, and is widely used to forecast changes in technology cost (Rubin, et al., 2015, p. 199).

In order to model the potential cost savings realised from production learning, consideration must be given to the different causal factors. These are summarised by Dutton and Thomas (1984) as the following:

- Capital investment – 'technological change in capital goods';
- Direct labour learning – 'improvement in performance of fixed tasks';
- Indirect labour learning – 'tooling and process changes';
- Local system characteristics – such as 'degree of mechanization, the ratio of assembly to machining, the length of cycle times, and whether the process is continuous or batch';
- Production rate/volume – 'absorption of fixed costs', and production adaptations (Dutton & Thomas, 1984, pp. 239-240).

Direct labour learning refers to the cost reduction phenomenon observed by Wright: the same people doing the same physical task repeatedly learn to do it more efficiently. Indirect labour learning is a step removed from the physical task, by which tools, equipment, and indeed the work space itself are reconfigured to take advantage of lessons learnt. Capital investment is again a further step removed, factoring in the willingness of an organisation to invest resources to deliver the benefits from learning. Local system characteristics in short relates to the share of human labour within an activity; automated processes will not exhibit direct labour learning, although indirect learning would still be possible. Finally, increases in production rate will allow for a greater division of fixed costs and scaling up of production facilities. On the other hand, decreases in production rate also create the opportunity for 'forgetting' of learning (Benkard, 2000).

When considering that nuclear plants contain significant amounts of large, expensive equipment that is made by specialist suppliers, it becomes clear that the supply chain structure will have a significant bearing on the learning that is achieved. Specifically, there are two important factors: the number of component suppliers, and the relationship they have with the plant vendor. For a given component, a single long-term supplier will have access to the full volume, providing the greatest opportunity to progress down the experience curve and realise learning cost reduction. On the other hand, multiple competing suppliers will not only individually produce a smaller volume, but they will do so at a lower production rate, assuming that orders are spread evenly between them over the course of a programme. Furthermore, long-term suppliers with specialist skills and equipment have greater bargaining power in the relationship with the reactor vendor than competitive suppliers do; this can result in their retention of some of the cost savings realised from their production learning. Depending on the strength of these different effects, the supply chain structure will need to strike a balance in order to achieve the best aggregate learning results in an SMR programme.

In this study, the learning cost reduction is modelled using two parameters: production rate and supplier type. The implementation of the production rate parameter is explained in Section 2.6.6, but the implementation of the supplier type parameter is discussed later in Section 3.3, following the discussion of supply chain theory.

2.4.6. Treatment of indirect cost accounts

The indirect costs make a significant contribution to total capital costs of nuclear power plants. To simplify their treatment, three main groups of indirect costs were identified:

1. Those related to the operation of the construction site, proportional to the length of the build schedule;
2. Those directly in support of labour activities, proportional to the amount of on-site labour;
3. Those related to off-site services.

Each of the indirect costs was assigned to one of the above groups, and hence to a cost reduction method, based on the definitions of the cost accounts provided by United Engineers & Constructors Inc. (1988b, pp. 2.11 - 2.13). Those costs that were judged to be associated with running a construction site were assigned to schedule reduction. Costs related to labour supervision and overheads were assigned to modularisation, as they would reduce in proportion to reductions in direct site labour. Home Office Services was the only account assigned to Standardisation, as this account was judged to contain the eliminated engineering and design costs. All of the specific indirect cost accounts assignments are shown in Table 4. This treatment of indirect costs accounts was developed and implemented in collaboration with Lloyd (2019).

Account Number	Account Name	Treatment
91	*Construction Services*	
911	Temporary Construction Facilities	Schedule Reduction
912	Construction Tools & Equipment	Modularisation
913	Payroll Insurance & Taxes	Modularisation
914	Permits, Insurance & Taxes	Schedule Reduction
915	Transportation	n/a
92	*Engineering & Home Office Services*	
921	Home Office Services	Standardisation
922	Home Office Quality Assurance	Schedule Reduction
923	Home Office Construction Management	Schedule Reduction
93	*Field Supervision & Field Office Services*	
931	Field Office Expenses	Schedule Reduction
932	Field Job Supervision	Modularisation
933	Field Quality Assurance/Quality Control	Schedule Reduction
934	Plant Start-up and Test	Schedule Reduction

Table 4: Treatment of indirect cost accounts

2.5. Supply Chain Map

The idealised SMR supply chain map that acts as the underlying concept of the cost model is shown in Figure 9. It shows the flow of components and material from Suppliers to either the module manufacturing facility or directly to the plant site. It also shows the distribution of the cost categories and learning effects across the supply chain.

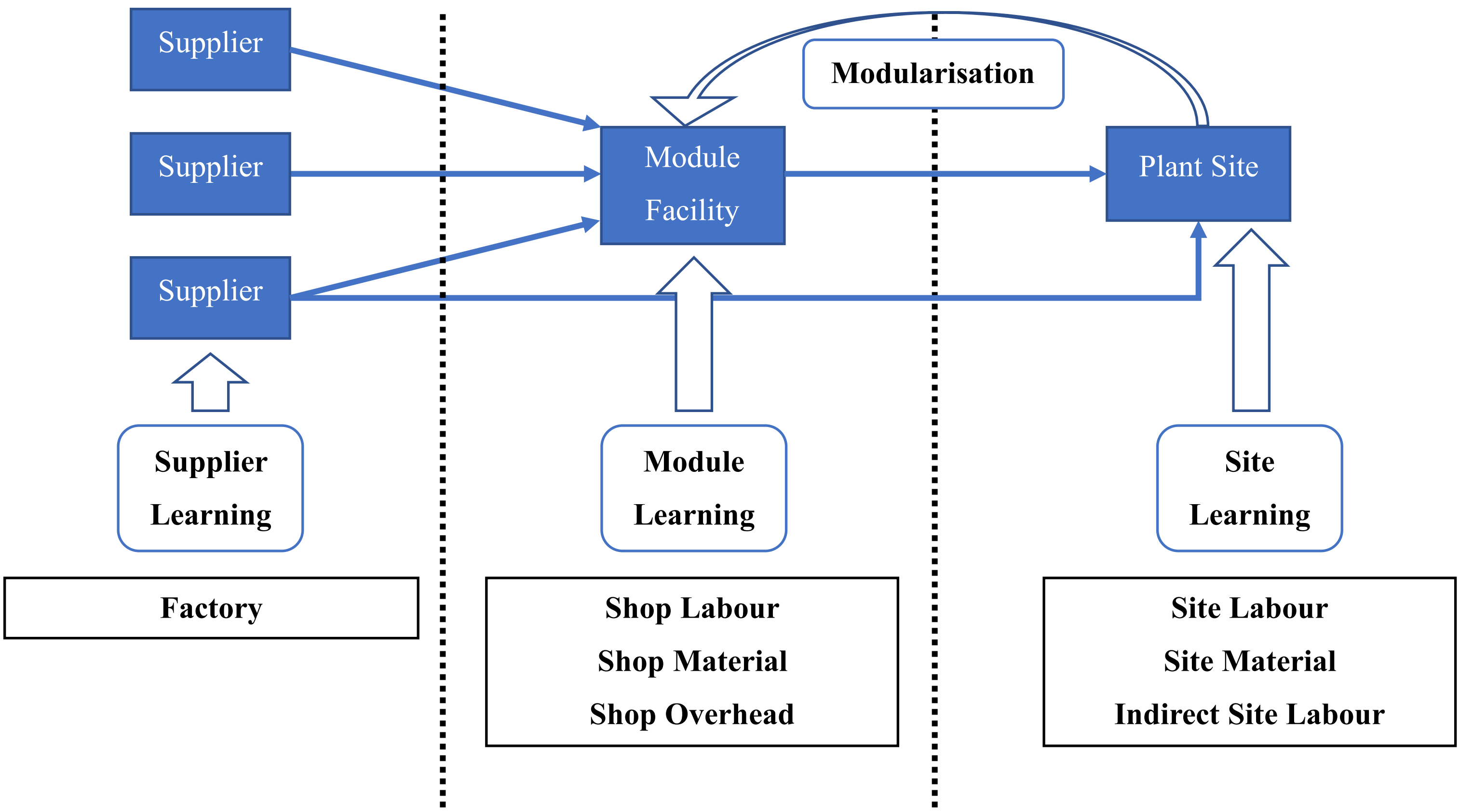

Figure 9: Idealised supply chain map

2.6. Model Implementation

Elements of this cost model were first presented at the International Congress on Advances in Nuclear Power Plants 2018. The detailed description of these methods are thus adapted from the associated conference proceedings (Lyons & Roulstone, 2018).

Figure 10 gives an overview of the process used to calculate the OCC, TCC, and LCOE for each SMR unit in a given production programme. The blue boxes indicate data values; the red boxes indicate cost modelling methods, which are detailed in Sections 2.6.2 – 2.6.6 and 2.6.8; the yellow boxes indicate general calculation steps, and the green boxes indicate the final output costs. The model was implemented in MATLAB, due to the ease of handling large data sets via matrix manipulation. The reference data for electricity generation and associated operating costs is taken from Lazard (2017); this source was used due to the breakdown of the costs provided and ability of the author to reproduce the resultant LCOEs provided in the report.

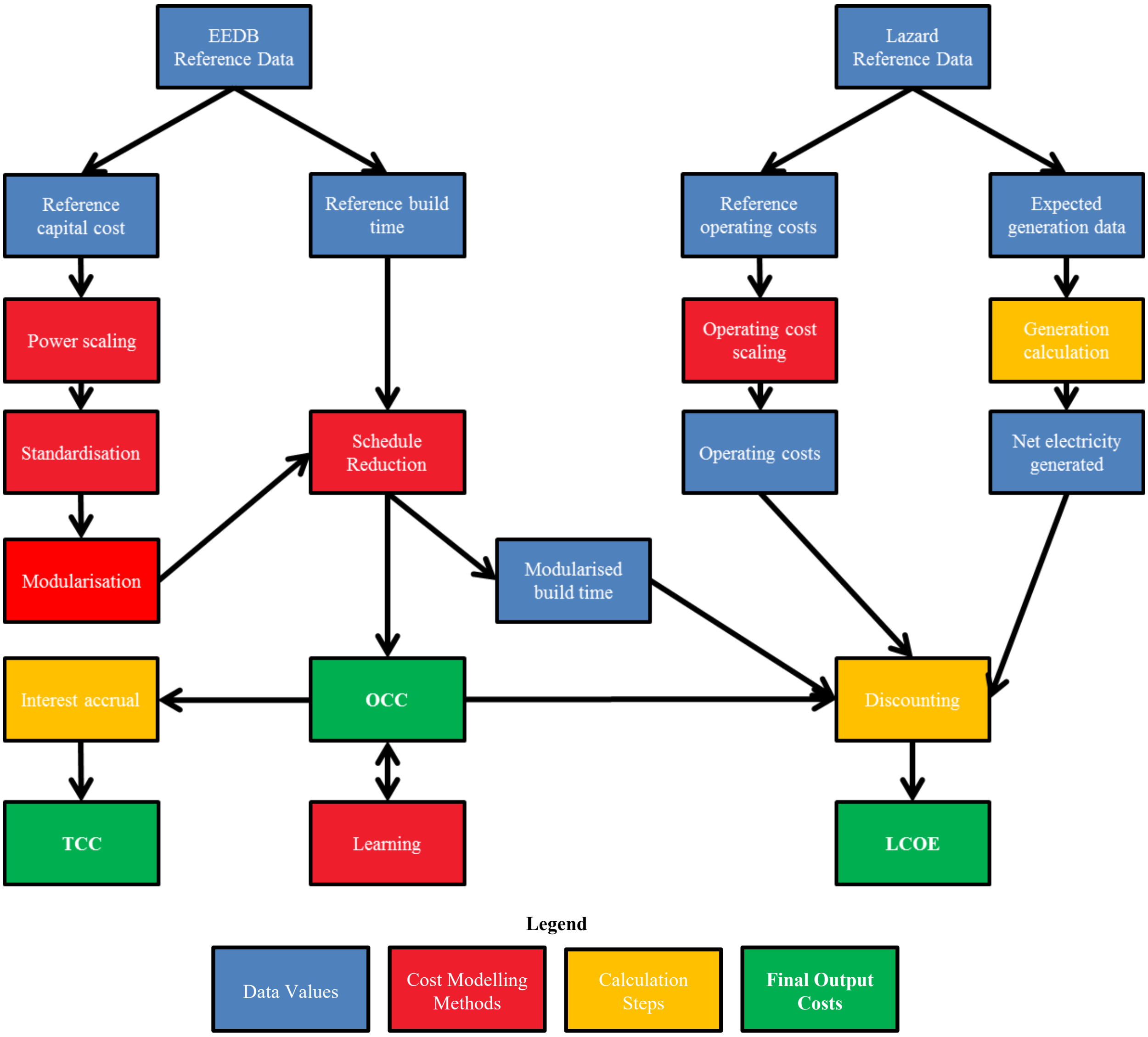

Figure 10: Cost model process overview

2.6.1. Inflation of reference capital cost data

To convert the ME data from 1987 US dollars to 2017 US dollars, an inflation factor of approximately 2.184 was applied; this was derived from US CPI data (Triami Media BV, 2017), as was done by Ganda et al. (2016). At this stage, the reference data was also converted into specific costs ($/kW), by dividing by the reference reactor power (1,144MWe).

For direct cost accounts, it was desirable to reproduce the four digit factory costs distribution, as this would enable more detailed supply chain modelling. To do this, the four digit factory cost distribution present in the PWR12-BE data was overlaid onto the three digit ME accounts; this was judged to be appropriate based on the analysis done by Ganda et al. (2016), who concluded that 'equipment costs for the PWR-BE and PWR-ME are very similar', to the extent that 'virtually no variation was observed for the installed cost of large and expensive equipment such as the Nuclear Steam Supply System and the Turbine Generator' (Ganda, et al., 2016, p. 963).

2.6.2. Power scaling

The reference construction costs were scaled to those for a 250 MW SMR using Equation 2.

$$Specific\ cost_{scaled} = Specific\ cost_{reference} \times \left(\frac{250MW}{1144MW}\right)^{(s-1)}$$

Equation 2: Cost power scaling implementation

While scaling was applied to four digit account costs in the case of direct costs, the scaling factors used were uniform across each two digit account, and are shown in Table 5.

Account Number	Account Name	Scaling factor, *s*
21	Structures & Improvements	0.59
22	Reactor Plant Equipment	0.53
23	Turbine Plant Equipment	0.83
24	Electrical Plant Equipment	0.49
25	Miscellaneous Plant Equipment	0.59
26	Main Condenser and Heat Rejection System	1.06
91	Construction Services	0.69
92	Engineering & Home Office Services	0.60
93	Field Supervision & Field Office Services	0.69

Table 5: Scaling factors (US Department of Energy, 1988, p. 31)

The Nuclear Energy Cost Data Base provides two sets of scaling factors for nuclear power plant cost power scaling: those provided by the CONCEPT code from ORNL (Hudson II, 1979), and those derived from the EEDB data itself. The EEDB factors are derived from comparison of the BE costs for the PWR12 and PWR6 models, the latter being a 583 MWe plant, similar to the PWR12, but with non-trivial differences such as reductions in the number of primary coolant loops and cooling towers. Such discontinuities lead to the recommendation that the CONCEPT code factors should be used for scaling of small power changes (<300 MWe), while the EEDB-derived factors should be used for larger power differences (US Department of Energy, 1988, p. 29). It is for this reason that the EEDB-derived factors were employed in this model. These values are also supported by their comparability to others cited in relevant literature, such as EMWG (2007), NEA (2000), and Carelli, et al. (2010).

Scaling was also applied to the site labour hours with the same scaling factors, based on the assumption that the site labour rates were not related to reactor power. As this was not done on a per unit power basis, Equation 3 was used.

$$Site\ labour\ hours_{scaled} = Site\ labour\ hours_{reference} \times \left(\frac{250MW}{1144MW}\right)^{s}$$

Equation 3: Labour hours power scaling implementation

2.6.3. Standardisation

As the definition of standardisation in this model was the establishment of a fixed and repeated plant design and construction process, the scope of its implementation was limited to the reduction of plant design costs. Based on the code of account definitions, these were judged to be contained in the one three digit indirect cost account: 921 – Home Office Services. Consequently, a single standardisation factor of 0.2 was applied to this account. This reflects the assumed 80% reduction in engineering and design costs, which is supported by United Engineers' own assessment of what is achievable (United Engineers & Constructors Inc., 1988a, p. 6.16).

2.6.4. Modularisation

To adjust the scaled SMR costs for modularisation, the following parameters were defined:

1. **Modularisation percentage** – the share of the costs in each account that are 'moved off-site' and assigned to module production;
2. **Structural material increase factor, 1.05** – the increase in structural material costs for modularised share;
3. **Non-structural material reduction factor, 0.9** – the reduction in non-structural material costs for modularised share;
4. **Shop productivity factor, 0.30** – the reduction in cost attributed to increase productivity in the module facility compared to on site;

5. **Labour rate factor, 0.35** – the reduction in cost attributed to the lower cost of module facility labour compared to site labour.

The modularisation percentages used for each account are shown in Appendix A. The percentages were applied at the three digit level, and were derived from the analysis done by Lloyd (2019). Essentially, Lloyd used dimensional transport constraints and specific modularisation schemes to estimate the maximum possible modularisation percentages for each cost account. For this study, a factor of 0.9 was applied to each percentage to take a non-limiting case as the central assumption. For the shop productivity factor, the EMWG guidelines provide separate values for the 'Nuclear island' (0.3125) and the 'Balance of Plant scope' (0.2500); as the boundary of these two areas is not readily discernible within the EEDB data, a compromise between the two of 0.3000 is used. The labour rate factor of 0.35 is based on the ratio of field and shop labour rates given in the guidelines, and the material increase/reduction factor values are also taken directly from the guidelines (Economic Modeling Working Group, 2007, pp. 110-112).

Equations 4 - 9 show the calculations steps that are applied to each direct cost account, *a,* based on the process given in the guidelines (Economic Modeling Working Group, 2007, p. 112):

$$Shop\ Equipment_a = Factory\ Cost_a \times \ \mu_a$$

Equation 4: Equipment costs allocated to modules

$$Shop\ Material_a = Site\ Material_a \times \ \mu_a \times Material\ Increase/Decrease\ Factor$$

Equation 5: Material costs allocated to module manufacturing

$$Shop\ Labour_a = Site\ Labour_a \times \mu_a \times 0.30 \times 0.35$$

Equation 6: Labour costs allocated to module manufacturing

$$Shop\ Overhead_a = Shop\ Labour_a \times 2$$

Equation 7: Indirect costs associated with module manufacturing

$$Module\ Freight_a = (Shop\ Equipment_a + Shop\ Labour_a + Shop\ Material_a + Shop\ Overhead_a) \times 0.02$$

Equation 8: Module transportation costs

$$Module\ Installation_a = Site\ Labour \times \mu_a \times 0.05$$

Equation 9: Module installation costs

For each account, the shop material, labour, and overhead costs are recorded as separate cost categories; the shop equipment costs remain under the Factory category; module installation costs are added to the remaining site labour costs. Module freight costs however are aggregated together in the Transportation account (Account 915).

For the indirect cost accounts subject to modularisation, the costs were reduced in proportion to the aggregate reduction in site labour hours; for each direct cost account, the site labour hours were reduced by the corresponding modularisation percentage.

2.6.5. Schedule reduction

While no direct costs accounts are altered by schedule reduction, the relevant indirect cost accounts are multiplied by a schedule reduction factor. This factor is the ratio of the assumed modularised SMR build schedule and the assumed build schedule for a stick built 250 MW SMR. The schedule reduction achieved by modularisation is the subject of detailed study by Lloyd (2019), using the build schedule from and critical path analysis of the UK's Sizewell B construction project. Modularisation schedule reduction factors can be derived from the ratio of the stick built and modularised plant build times produced by Lloyd's model. While the time values are specifically derived from the Sizewell B schedule, the change factors were judged suitable to be applied to the EEDB-derived data. The factors used in this study are shown in Table 6, along with their underpinning schedules.

Unit Power (MW)	Build Times (months)		Schedule Reduction Factor
	Stick Built	Modular Construction	
1198	79	70	0.89
500	66	50	0.76
250	59	40	0.68
100	54	34	0.63

Table 6: Modular construction schedule reduction factors (Lloyd, 2019)

The reference build time is the sum of the construction and start-up times for the PWR12-ME model. To determine the build time for a stick-built SMR, power scaling is applied in the same manner as for labour hours in Equation 3. The scaling factor was derived by comparing the PWR12-BE build schedule to that of the PWR6-BE model, both from the EEDB (United Engineers & Constructors Inc., 1988a, p. 6.17). The start-up time is constant at 6 months, irrespective of reactor power or experience range; consequently power scaling was only applied to construction time. The result of the construction time power scaling was a 76 month total build time for a stick built 250 MW SMR. The application of the 0.68 schedule reduction factor yielded a modularised SMR build time of 51 months.

PWR12-BE Construction Time	72 months
PWR6-BE Construction Time	62 months
Schedule Power Scaling Factor	0.22
PWR12-ME Construction Time	98 months
Stick built 250 MW SMR Construction Time	70 months
Start-up Time	6 months
Stick built 250 MW SMR Build Time	**76 months**
250MW Modularisation Schedule Change Factor	0.68
Modularised 250 MW SMR Build Time	**51 months**

Table 7: Derivation of stick built and modularised SMR build times

2.6.6. Learning

As shown in Figure 9, learning cost reduction is applied to several cost categories in this model. In all cases, costs for each unit are determined using Equation 1 (yielding marginal unit cost), but the learning rate employed in each instance varies.

For the reduction of labour, material, and associated indirect costs incurred on the plant construction site, a fixed learning rate of 2% is used. This is based on guidance from the Cost Estimate Guidelines produced by Oak Ridge National Laboratory (Delene & Hudson II, 1993, p. 14), and reflects the relatively poor conditions for learning associated with construction sites.

For learning occurring in component factories and module manufacturing facilities, the learning rate used is determined through a two-step process. Firstly, the rate of production of reactor units determines a normal distribution of learning rates, defined by a mean and standard deviation. Secondly, the relationship between the component/module supplier and the reactor vendor determines the learning rate from its position on this distribution. The explanation of the supplier relationship types and their resultant learning rates are provided in Section 3.3.

The relationship between production rate and learning rate employed in this model was built up from a combination of works from the literature. A study by the University of Chicago (2004) describes the conditions required for different learning rates, including production rate. The study associates low learning rates with the production of 1 unit per year or slower, and high learning rates with 'continuous construction'. Low levels of learning, and possibly even cost increases, can be explained for low production rates due to forgetting – the loss of the labour knowledge and skills that delivered the cost improvements. The balance between learning and forgetting is discussed in detail by Benkard (2000) in the context of aircraft production, and succinctly illustrated by Figure 11; this shows not only the continuous cost reduction over the scale of 100 units, but also that as production rate falls, costs can start to increase again.

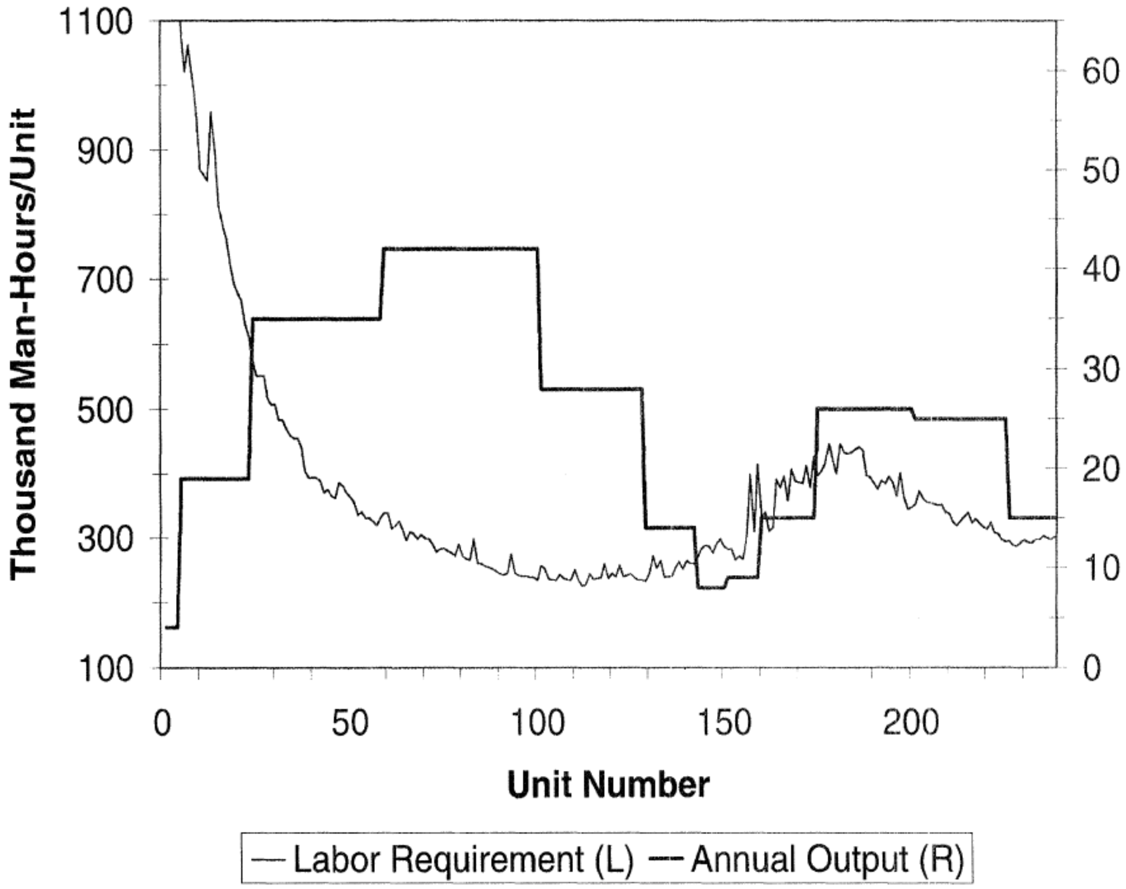

Figure 11: Labour requirement and production rate for Lockheed's L-1011 programme (Benkard, 2000, p. 1039)

Rosner and Goldberg (2011) envisaged continuous production in an SMR module manufacturing facility as yielding 12 units per year. McDonald & Schrattenholzer (2001) observed the mean learning rate for the production of energy technologies to be 15%; this was therefore taken to be the high learning rate associated with production of 12 units per year. Limited learning has been observed in large nuclear reactor construction, which has been partly attributed to low rates of construction (Roulstone, 2015b). The low learning rate associated with 1 unit per annum was therefore taken to be 2%.

A logarithmic relationship was used to connect these two data points. The opportunities for learning are more greatly increased when moving from 2 to 4 units per year than from 10 to 12; it was therefore judged that higher production rates had diminishing returns with regards to learning. The consequent relationship between learning rate and production rate used in this model is given in Equation 10 (Lyons & Roulstone, 2018).

$$Mean\ learning\ rate = (5.3467 \times \ln(production\ rate)) + 1.6944$$

Equation 10: Production rate – learning rate relationship

2.6.7. Interest during construction

The interest accrued during construction is calculated by assuming uniform spending throughout the construction period, and compounding the interest annually.

2.6.8. Operation and maintenance costs

The operation and maintenance (O&M) costs for an SMR are derived in this model from a set of reference costs provided by Lazard (2017). This report divides O&M costs into fixed and variable costs. Mott MacDonald (2010) explain that fixed O&M costs are made up of the following:

- ‘operating labour’;
- ‘planned and unplanned maintenance (additional labour, spares and consumables)’;
- ‘through life (time dependent) capital maintenance’;
- ‘property taxes (rates), insurance and network use of system charges’ (Mott MacDonald, 2010, p. 4).

To determine the fixed O&M costs for a 250MW SMR, it was assumed that non-labour contributions had the same specific costs (per MW) as the reference data from Lazard (2017), while the labour contribution was scaled. This was done to reflect the non-linear relationship between manning levels of reactor units and their power output. The specific labour cost for an SMR was determined using Equation 11, which is based on the manning-power relationship (Equation 4.3.12) provided by Rothwell (2016, p. 116). This relationship is the result of a 'semi-log' regression model, using data from operating plants in the US provided by the Idaho National Laboratory (INL, 2004, based on Rothwell, 2016).

$$\boldsymbol{Specific\ labour\ cost} = \frac{\boldsymbol{reference\ specific\ labour\ cost}\ (\$\ \boldsymbol{per\ MW})}{\boldsymbol{reference\ specific\ manning\ level}\ (\#\ \boldsymbol{per\ MW})} \times \frac{\boldsymbol{e}^{(\mathbf{5.547}+\ (\mathbf{0.870}\ \times \boldsymbol{unit\ size}(\boldsymbol{GW})))}}{\boldsymbol{unit\ size}\ (\boldsymbol{MW})}$$

Equation 11: Specific labour cost calculation

The variable O&M costs are mainly related to fuel and 'output related repair and maintenance' (Mott MacDonald, 2010, p. 4). In this model, the cost of decommissioning is turned into a generation charge, thus adding to the variable O&M cost. This reflects the practice in some markets whereby utilities make payments into a decommissioning fund during operation to cover the costs of plant dismantling and clean-up.

2.6.9. LCOE

The LCOE is determined by applying Equation 12 to Equation 14, which implement a pre-tax methodology based on that employed by the UK Department for Business, Energy & Industrial Strategy.

$$\boldsymbol{Net\ Present\ Value\ of\ Total\ Costs} = \sum_{\boldsymbol{t}} \frac{(\boldsymbol{Pre - development\ costs + construction\ costs})_{\boldsymbol{t}}}{(\mathbf{1}+\boldsymbol{r})^{(\boldsymbol{t}-\mathbf{1})}} + \sum_{\boldsymbol{t}} \frac{(\boldsymbol{Operation\ and\ maintenance\ costs})_{\boldsymbol{t}}}{(\mathbf{1}+\boldsymbol{r})^{\boldsymbol{t}}}$$

Equation 12: Discounting of lifetime costs (Department for Business, Energy & Industrial Strategy, 2016, p. 8)

$$\boldsymbol{Net\ Present\ Value\ of\ Electricity\ Generation} = \sum_t \frac{\boldsymbol{electricity\ generated_t}}{(\boldsymbol{1}+\boldsymbol{r})^{\boldsymbol{t}}}$$

Equation 13: Discounting of electricity generation (Department for Business, Energy & Industrial Strategy, 2016, p. 8)

$$\boldsymbol{LCOE} = \frac{\boldsymbol{Net\ Present\ Value\ of\ Total\ Costs}}{\boldsymbol{Net\ Present\ Value\ of\ Electricty\ Generation}}$$

Equation 14: LCOE calculation (Department for Business, Energy & Industrial Strategy, 2016, p. 8)

The funds to cover costs incurred during the development and construction phases of the plant lifecycle are assumed to be drawn down from the beginning of each year; consequently this costs are discounted from the start of the year they are incurred; all other costs and revenues are discounted from the end of the year in which they are incurred.

2.6.10. Model parameters and assumptions

Table 8 summarises the fixed parameters in the model; the sensitivities of the model outputs to these parameters are discussed in Section 2.8. Further to these, there are several assumptions that underpin the design and implementation of the cost model; these are summarised in Table 9.

Fixed Parameter	**Value**	**Source**
Cost-weighted scaling factor	0.65	(United Engineers & Constructors Inc., 1988a)
Owner's costs rate (%)	10	(US Department of Energy, 1988)
Contingency rate (%)	15	(US Department of Energy, 1988)
Cost-weighted modularisation percentage	76	(Lloyd, 2019)
Structural material module increase factor	1.05	(Economic Modeling Working Group, 2007)
Non-structural material module decrease factor	0.9	(Economic Modeling Working Group, 2007)

Fixed Parameter	Value	Source
Module shop productivity factor	0.3	(Economic Modeling Working Group, 2007)
Module shop labour rate factor	0.35	(Economic Modeling Working Group, 2007)
Shop overhead rate (%)	200	(Economic Modeling Working Group, 2007)
Module freight rate (%)	2	(Economic Modeling Working Group, 2007)
Module installation rate (%)	5	(Economic Modeling Working Group, 2007)
Standardisation (%)	80	(United Engineers & Constructors Inc., 1988a)
Interest rate (%)	9.6	(Lazard, 2017)
Build schedule (months)	51	(US Department of Energy, 1988); (Lloyd, 2019)
Pre-development period (years)	3.5	(United Engineers & Constructors Inc., 1988a)
Pre-development capital cost share (%)	0.79	(Department of Energy & Climate Change, 2013)
Plant operational lifetime (years)	60	(Lazard, 2017)
Staff fixed O&M cost share (%)	66.9	(Rothwell, 2016)
Variable O&M cost ($/MWh)	0.75	(Lazard, 2017)
Capacity factor (%)	90.2	(Lazard, 2017)
Fuel cost ($/MWh)	8.9	(Lazard, 2017)
Decommissioning cost ($/MWh)	2	(Department for Business, Energy & Industrial Strategy, 2016)

Table 8: Fixed parameter values

Model Assumption	Supported Model Element
SMR design/technology is largely similar to the reference design (i.e. dispersed PWR)	Scaling Fixed O&M costs
Costs/revenue accrue uniformly across the relevant lifecycle phase	LCOE calculation

Table 9: Model assumptions

2.7. **Demonstration Results**

In this section a set of calculated costs for a 250 MW SMR are presented to demonstrate the separate stages of the cost model. These results are based on the modelling assumptions detailed in Section 2.6.9, as well as a simplified supply chain model: one SMR vendor and module manufacturing facility are assumed; the manufacturing of all factory made components and modules is subject to the mean learning rate yielded from Equation 10.

2.7.1. First production unit

Table 10 gives the cost category breakdown of the OCC for the reference plant, along with the calculated OCC breakdown for the 250 MW SMR, both after scaling (representing a stick built plant) and after the effects of modularisation and standardisation. For each cost category, the specific capital cost is given, along with its percentage share of the OCC. As both the reference plant and scaled SMR are assumed to be stick built, no module shop costs are included.

The costs of the scaled SMR highlight why a small stick built plant is unlikely to be economically competitive; while the 250 MW SMR has a lower absolute capital cost than the reference large reactor (approximately \$2.6bn compared to \$7bn), this amounts to almost double the specific overnight capital cost. When factoring in interest during construction to give Total Capital Cost, the scaled SMR benefits from a shorter stick built construction schedule which moderates the increase in financing cost arising from the increase in underlying specific capital used.

When then considering the OCC breakdown of the modularised and standardised SMR, Table 10 highlights two points. Firstly, the overall cost reduction resulting from these construction changes makes the SMR competitive with the large reference plant. Secondly, while there is minimal change in the distribution of costs across the categories from the reference plant to the scaled SMR, there is a significant shift with the modularised and standardised SMR. Most notably, the factory share has nearly doubled, and by adding in the new module shop cost categories, nearly 45% of the OCC is subject to the conditions for high production learning. This emphasises how both modularisation and standardisation are enablers of learning: the former moving work from unproductive construction sites to the controlled conditions of a factory; the latter allowing for repetition.

Cost Category	**Reference (1,144 MW)**		**Scaled SMR (250MW)**		**Modularised & Standardised SMR (250MW)**	
	2017 $/kW	Share	2017 $/kW	Share	2017 $/kW	Share
Factory	1,014	17%	1,743	16%	1,743	30%
Site Labour	964	16%	1,752	17%	475	8%
Site Material	288	5%	536	5%	141	2%
Indirect Site Labour	367	6%	588	6%	369	6%
Indirect Services	2,195	36%	3,736	35%	1,108	19%
Module Shop Labour	n/a	n/a	n/a	n/a	141	2%
Module Shop Material	n/a	n/a	n/a	n/a	388	7%
Module Shop Overhead	n/a	n/a	n/a	n/a	282	5%
Owner's Costs	483	8%	835	8%	465	8%
Contingency	797	13%	1,378	13%	767	13%
Total OCC	6,108	100%	10,568	100%	5,878	100%

Table 10: OCC Breakdown for Reference Data, Scaled SMR, and Modularised & Standardised SMR (January 2017 $/kW)

Figure 12 shows the corresponding TCC values for the three notional plants, along with the share of the overall cost reduction that is directly attributable to standardisation, modularisation, and schedule reduction; it should be noted here that the schedule reduction is itself a result of modularisation, as the movement of specific activities off-site reduces the critical path of construction. Correspondingly, the cost reduction from modularisation thus refers specifically to the productivity and labour rate savings from moving labour off-site.

Taking the latter two effects as a pair, the dominance of the modularisation benefits is significant. Given that factory made component costs outweigh the module costs, standardisation is arguably the greater enabler of learning; however, it is clear that modularisation is crucial to bringing down the first unit costs, thus putting the SMR programme in a strong competitive position from the outset. Indeed, with IDC included, the cost advantage of the modularised and standardised SMR over the reference plant is more significant than just considering OCC. This result challenges the conventional thinking that smaller reactors will also be more expensive than large ones.

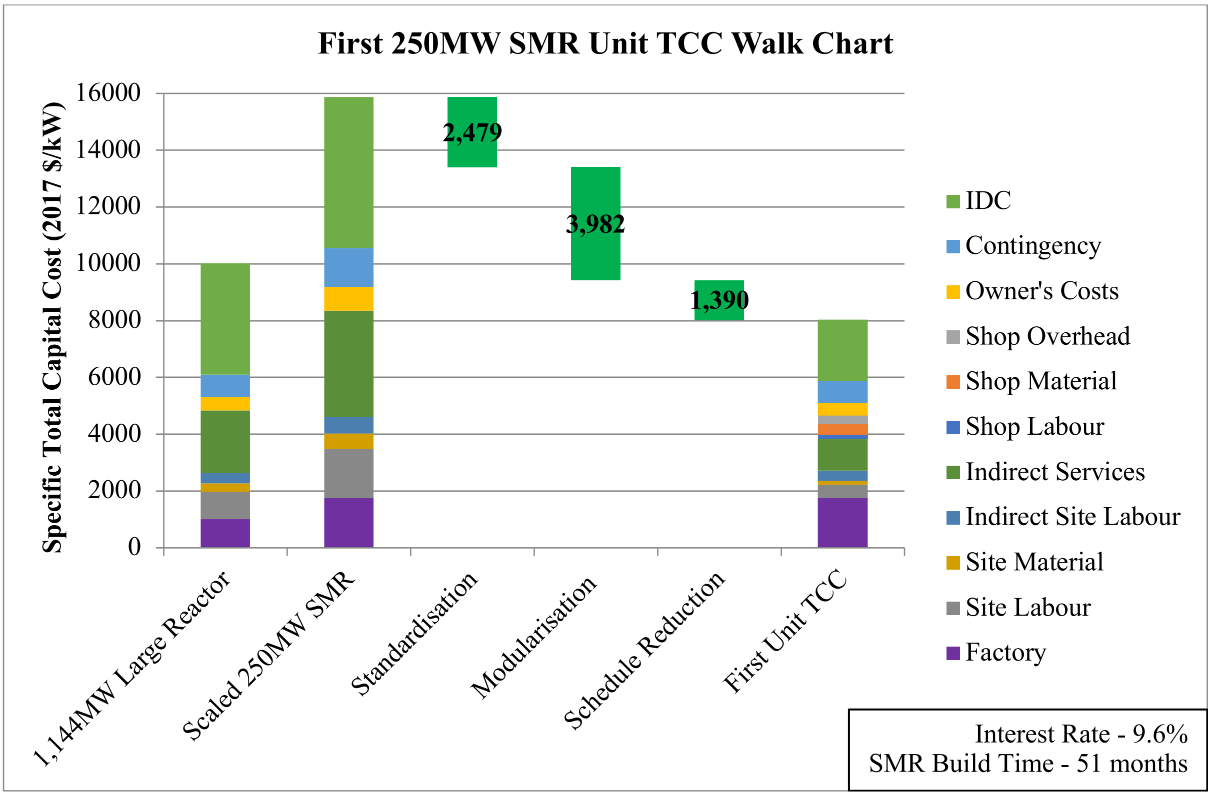

Figure 12: TCC walk chart from reference plant to first 250 MW SMR unit

When comparing the resultant LCOEs for the reference plant and first SMR unit shown in Figure 13, the effects of scale are again seen at play. While there is a reduction in levelised capital cost corresponding to the OCC and build schedule reductions, the scaling effect that governs the fixed operation and maintenance costs results in a near doubling of this cost component. Nevertheless, the first SMR unit improves on the LCOE of the reference plant by approximately \$40/MWh.

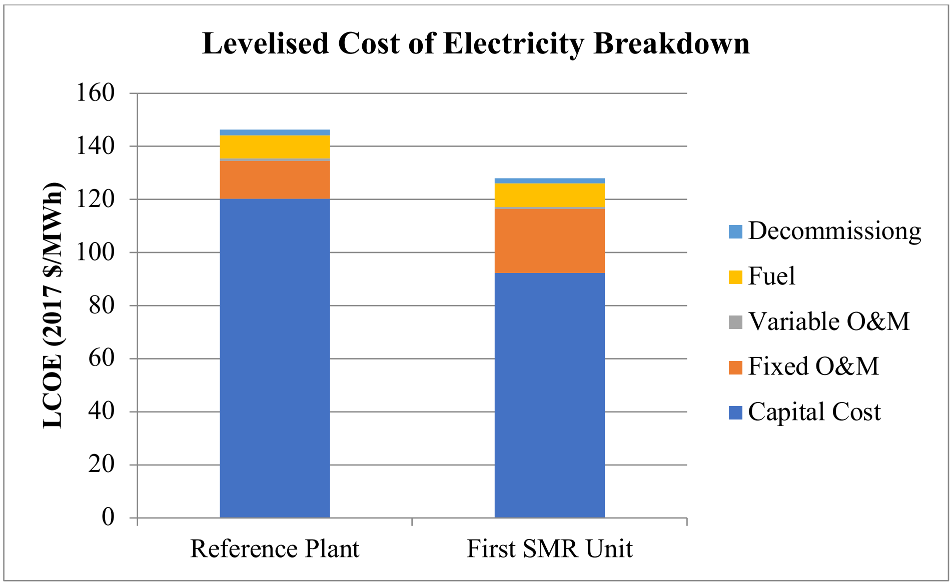

Figure 13: LCOE breakdown for reference plant and first SMR unit

2.7.2. Learning demonstration

Figure 14 shows the cost reduction achieved by learning over the course of a 10 year programme, in which plants are produced at a rate of 5 units per year. The cost reduction is separated out into that resulting from factory learning (i.e. learning by component suppliers), module shop learning, and on site learning. As expected, the factory learning provides the greatest cost reduction; this is due to two factors. Firstly, both the factory and module shop costs are subject to the higher learning rate of 10.3%, given by the production rate, compared to the fixed site learning rate of 2%. Secondly, as shown in Table 10 the factory share of the OCC of the first unit is more than double that of the module shop, meaning that there is a greater base cost to reduce.

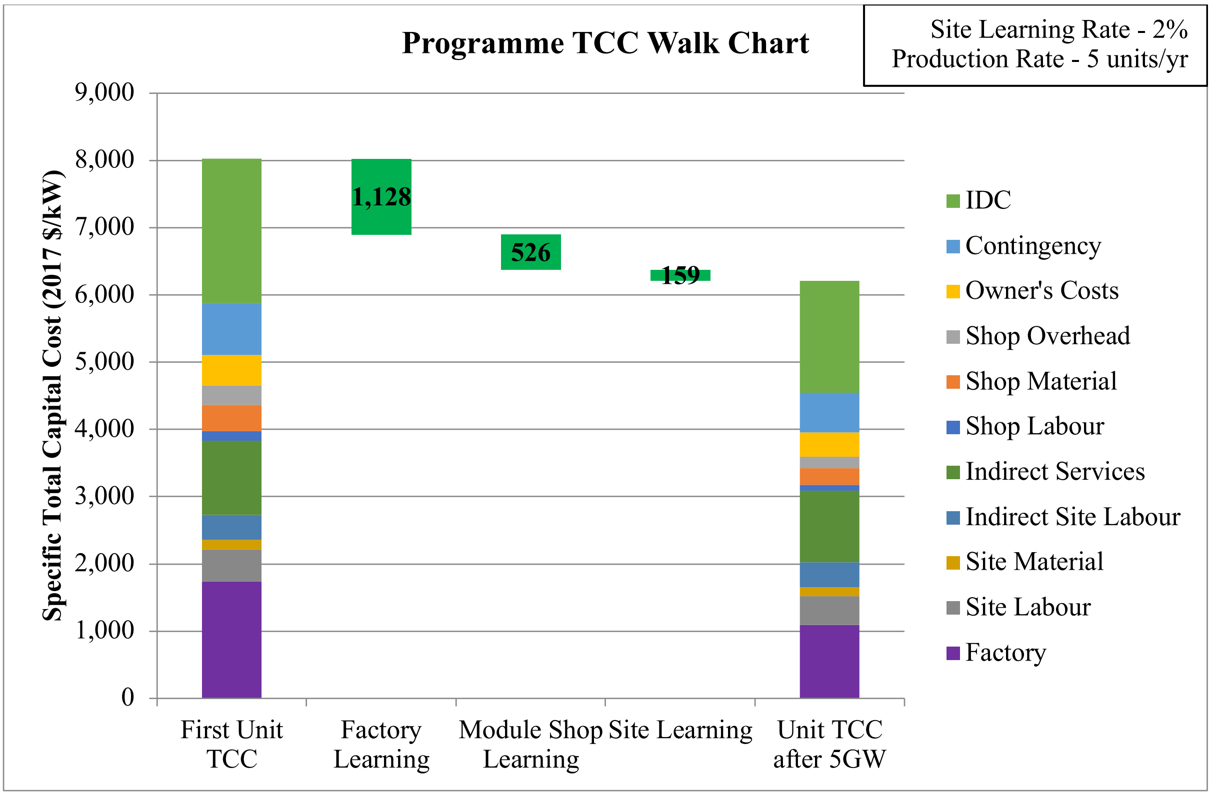

Figure 14: TCC walk chart over 10 year, 12.5GW programme

Figure 15 shows the effect on TCC reduction that comes from varying the production rate. Over the first 4 years of the programme in which 5 GW of plants are produced, only approximately 61% of the cost reduction achieved at 5 units per year is realised at 2 units per year. On the other hand, if the rate is increased to 8 units per year, the cost reduction achieved increases by approximately 18%. The apparent diminishing returns in terms of cost reduction against production rate is due to the logarithmic relationship between learning rate and production rate, as shown by Equation 10. This is further clarified by Table 11, which shows the individual learning rates used at the different production rates, and the resultant aggregate learning rates derived from the overall OCC reduction.

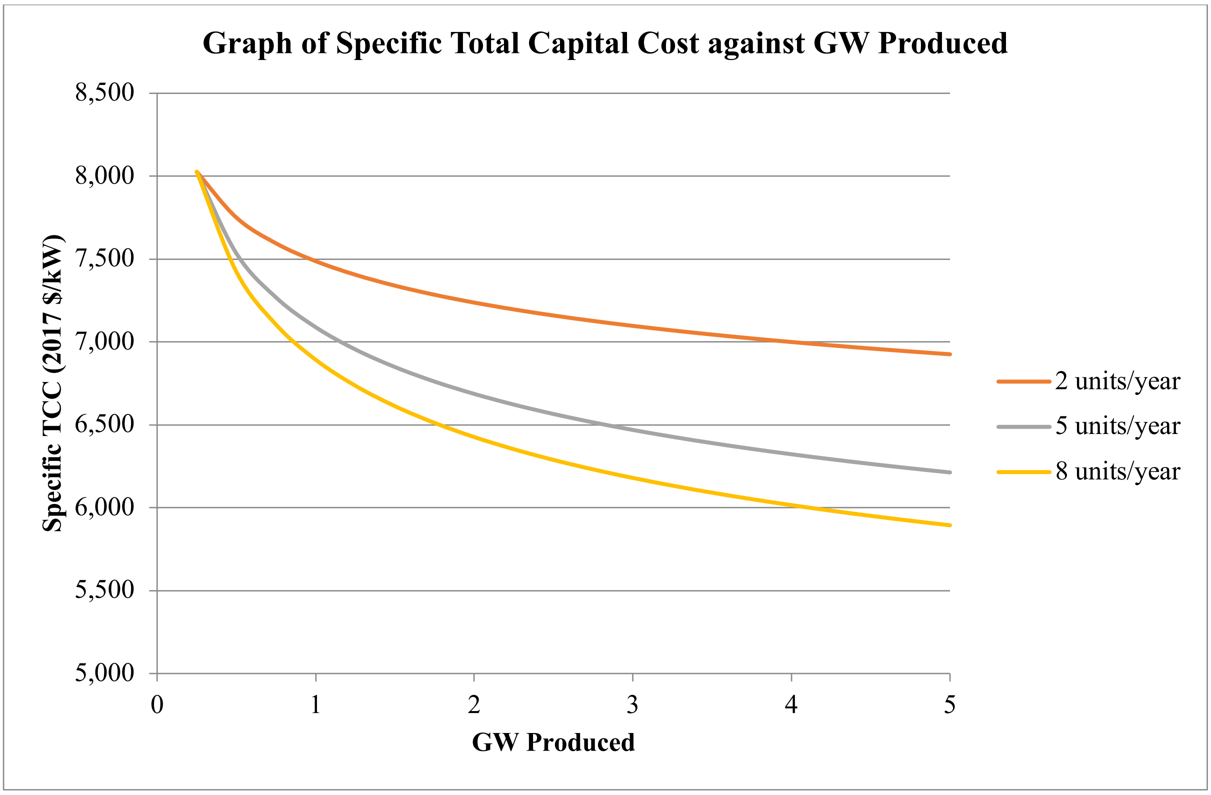

Figure 15: Resultant learning curves for different production rates

Production Rate	2 units/year	5 units/year	8 units/year
Factory Learning Rate	5.4%	10.3%	12.8%
Module Shop Learning Rate	5.4%	10.3%	12.8%
Site Learning Rate	2.0%	2.0%	2.0%
Aggregate OCC Learning Rate	**3.4%**	**5.6%**	**6.5%**

Table 11: Resultant learning rates for demonstration cases

2.8. Sensitivities

As discussed in Section 2.6.9, the cost model described in this chapter is built on a significant number of fixed parameters and assumptions. In order to understand the significance of these assumptions to the final cost produced, a set of sensitivity results are presented in this section. For each parameter, the assumed value shown in Table 8 was increased and decreased by 10% in isolation; the consequent variations in first unit TCC and LCOE were recorded.

It should be noted that the parameter values were varied in such a way as to reflect an increase/decrease in the effect of the parameter, rather than just the value itself. For example, the 10% increase in the standardisation factor represented a 10% increase in the effect of standardisation, which is to reduce cost; the actual value of the parameter was decreased from 0.2 to 0.12 in the model implementation. It should also be noted that both the scaling factors and modularisation percentages, while varying across the four digit accounts, were each changed by 10% individually to give a 10% variation in the cost-weighted averages of these parameters.

2.8.1. Total Capital Cost

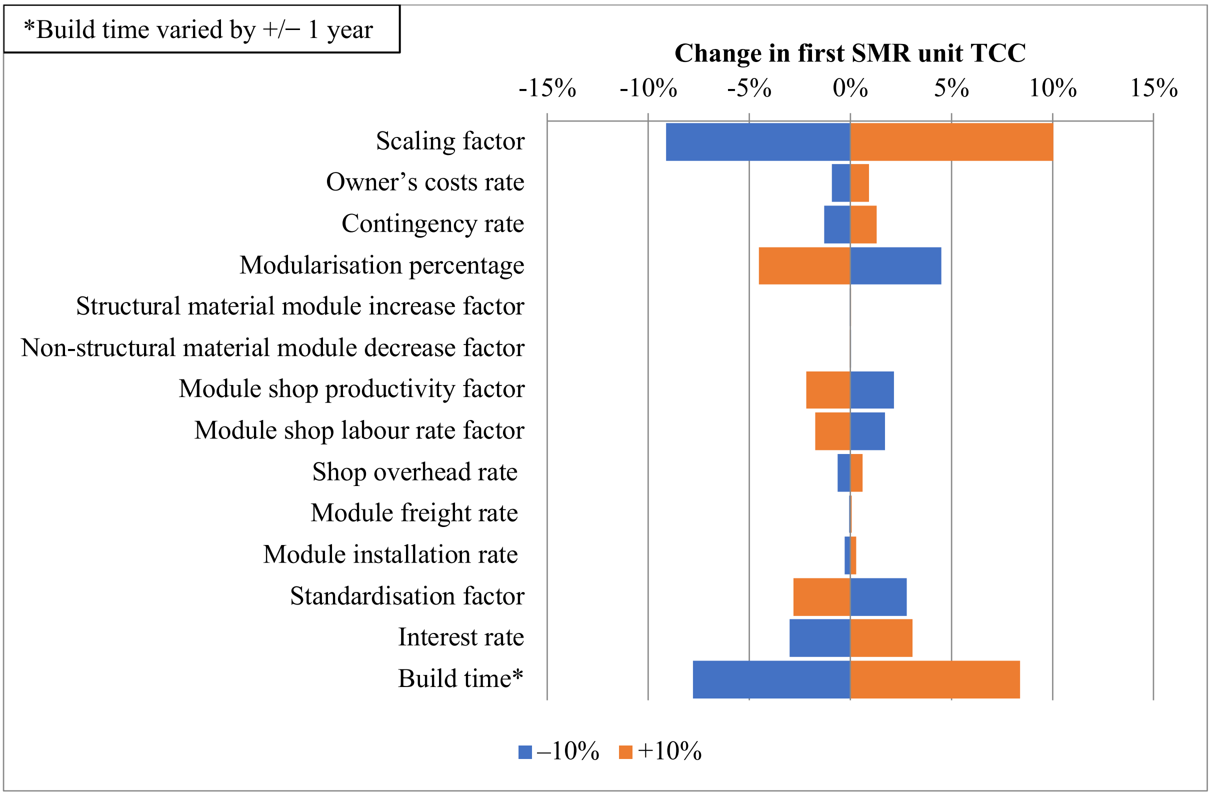

Figure 16: Sensitivity of TCC to parameter values

The sensitivity of the first unit TCC to the fixed parameters in the model is shown in Figure 16; parameters that had no bearing on TCC are not included. The TCC is most sensitive to the scaling factors, which highlights why the economies of scale have been seen as such a challenge to SMR economic competitiveness. The TCC is also particularly sensitive to the modularisation percentages, which can be explained by the multiple effects it has. By increasing the degree of modularisation, a larger portion of the direct costs is reduced by increased productivity and wage decreases; the associated indirect costs are also further reduced. While both affecting the IDC values, the build time has a greater influence on TCC than the interest rate, due to its influence on the time-based indirect site costs.

2.8.2. Levelised Cost of Electricity

The sensitivity of the first unit LCOE to the fixed parameters in the model is shown in Figure 17. Due to the inclusion of operation and maintenance, fuel, and decommissioning costs, variation of any of the parameters included in Figure 16 has less of an effect on the LCOE, except for the build time and interest rate. These latter two parameters have a direct bearing on the levelised value of the additional cost elements, as well as the capital cost. Any increase in the build time delays operation, and so reduces the value of the revenue accrued from electricity generation. Similarly, an increase in the interest rate decreases the value of all costs and revenues, and to a greater extent on later cash flows. Since the majority of costs are incurred earlier in the lifetime of a plant (i.e. during construction), the net effect of a higher interest rate is to decrease the value of revenues more than cost, and thus raise the LCOE.

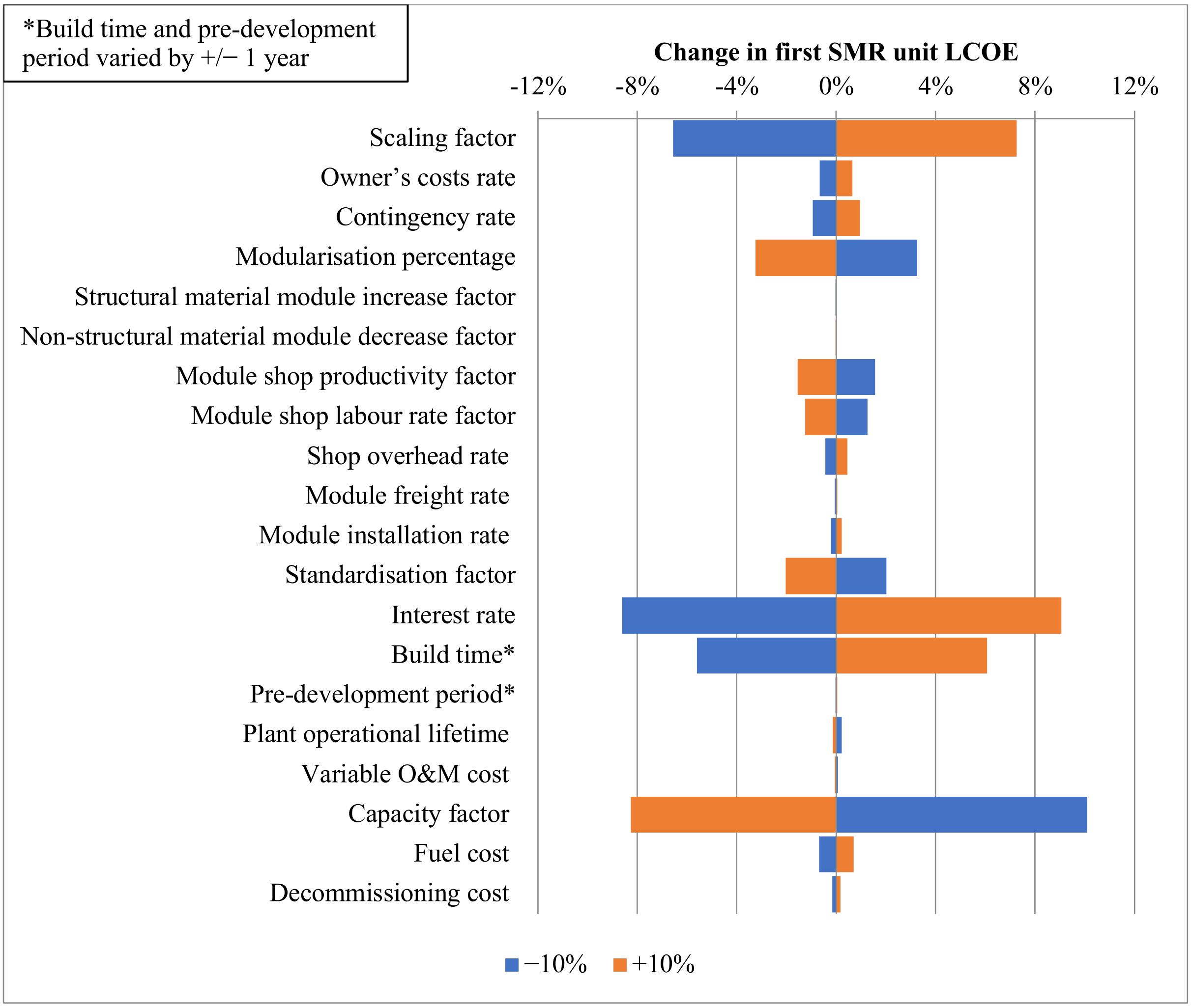

Figure 17: Sensitivity of LCOE to parameter values

The greater significance of early cash flows over late ones explains the high sensitivity of the LCOE to variations in the pre-development period, compared to that of the plant operational lifetime. As is shown in Figure 13, the sum of the variable operation and maintenance, fuel, and decommissioning costs amounts to only 9% of the first unit LCOE, thus giving relatively insignificant sensitivities. Moreover, the significant share of the LCOE coming from the fixed compared to variable operation and maintenance costs explains the high sensitivity to the capacity factor: the vast majority of costs are incurred regardless of how much electricity is generated, so capacity factor needs to be maximised to keep the LCOE down. Indeed, this is why nuclear power plants have conventionally served as baseload electricity providers.

2.8.3. Build time and pre-development period sensitivities

For both sets of sensitivities shown in the previous sections, the build time and pre-development period were varied by +/− 1 year, rather than 10% as done for the other parameters. This was done to avoid the misleading results that arise from the discounting method, highlighted by Figure 18.

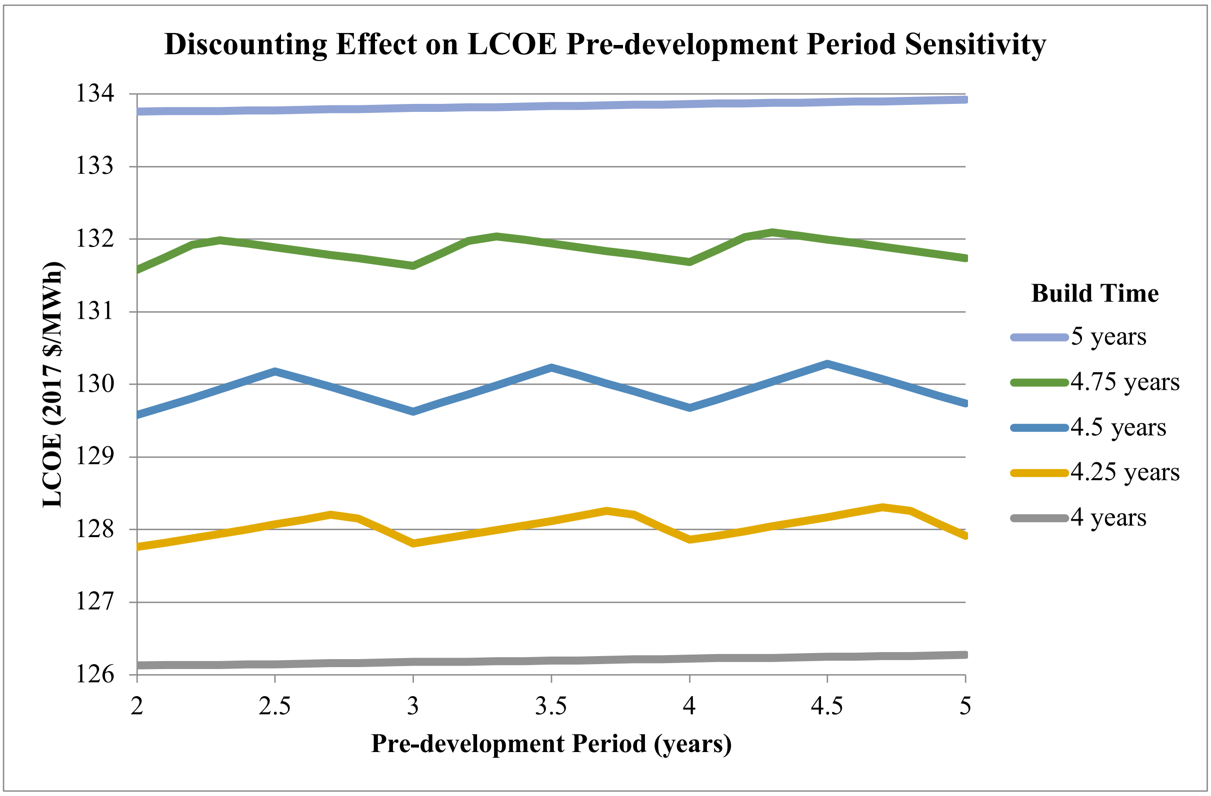

Figure 18: LCOE pre-development period sensitivity

An increase in the pre-development period is expected to result in a very minor increase in the LCOE, because the revenues from electricity generation are delayed just slightly more than the upfront costs. When the build time is an integer year length, this is the trend observed. However when the build time is not an integer year length, variations in the pre-development period can cause the build phase to vary in the number of discounting years it spans. This in turn causes a greater reduction in the discount factor applied to construction costs compared to other elements, most crucially the energy generation, thus resulting in decreasing rather than increasing LCOE.

2.9. **Cost model comparison**

As no real cost data is available for an established SMR production programme, in order to provide a degree of validation for the cost model, a comparison was made to other cost estimates in the literature. Specifically, the Energy Technologies Institute's nuclear cost drivers report (Energy Technologies Institute, 2018) provides a useful benchmark due to its use of reference data which is closely related to that of this model. The ETI references the EEDB's PWR12 Median Experience data, but uses the older Phase VIII update costs compared to the Phase IX cost employed in this model.

The objective of the ETI's project was to 'identify and quantify potential to deliver meaningful reductions in capital cost and levelised cost of energy (LCOE) in the UK' (Energy Technologies Institute, 2018, p. 2). To do this, the project team collated a set of cost estimates for past, in progress, and proposed nuclear plant projects, defined a set of key cost drivers, and then scored each project against these cost drivers based on interviews about the plant construction (Energy Technologies Institute, 2018, p. 3). This yielded a cost model which is able to quantify the cost reduction by varying the strength of the different cost drivers. The 8 key cost drivers and selected cost reduction strategies identified in the report are summarised in Table 12, along with the relevant component of this cost model.

A key conclusion of the report quantified the potential for cost reduction in the construction of conventional large reactors, using the aforementioned ETI cost model. Starting with the average costs of 'Gen III/III+ reactors in Europe and North America', with the worst scores for each cost driver, changing each score to the global average 'would result in a cost reduction of at least 35%' (Energy Technologies Institute, 2018, pp. 39-40). Given the similarity in the cost drivers considered by the two models, as well as the employment of closely related reference costs, this result serves as a relevant comparison to test the reasonableness of the cost reductions predicted in this study.

In order to compare the cost model from this study to the ETI study, cost reduction on the reference 1,144 MW plant was modelled; the reference cost data was not scaled. To reflect the decreased scope for modularisation and schedule reduction for this large plant compared to a 250 MW SMR, the corresponding modularisation percentages shown in Appendix A were used, as was the gigawatt scale schedule reduction factor shown in Table 6. The latter gave a modular construction build time of 92 months, compared to the stick built reference build time of 104 months. A 7% interest rate was used to match the ETI study; otherwise the parameters used were the same as in Table 8.

ETI Cost Driver	ETI Cost Reduction Strategy	Relevant Model Component
‘Project Governance and Project Development’	‘follow contracting best practices’	Supply chain design
‘Construction Execution’	‘leverage offsite fabrication’	Modularisation
‘Political and Regulatory Context’	‘design a UK program to maximise and incentivise learning’	Learning
‘Equipment and Materials’	‘follow best practices to reduce material use’	Modularisation
‘Supply Chain’	‘embrace a highly proactive approach to supply chain management and qualification’	Supply chain design
‘Vendor Plant Design’	‘complete design prior to starting construction’; ‘design for constructability’ ‘Increasing modularity in the design should be prioritised’ ‘Design for plant design reuse’	Standardisation Modularisation
‘Labour’	‘Improve labour productivity’	Modularisation
‘Operation’	‘Develop excellence in plant operations and maintenance’	n/a

Table 12: Summary of ETI Report cost reduction findings (Energy Technologies Institute, 2018, pp. 37-38)

The resultant first unit TCC cost reductions are shown in Figure 19. Given the lower specific cost compared to the scaled SMR, and the lesser scope for both modularisation and schedule reduction, the cost reductions achieved are unsurprisingly lower than those shown for the 250 MW SMR in Figure 12. The learning cost reductions over 10 units, based on a production rate of 5 units per year, are shown in Figure 20. After 10 units, the overall cost reduction from learning amounts to 13.12% of the first unit TCC. In contrast, for the 250 MW SMR produced at the same rate, the cost reduction after 10 units was 18.20% of the first unit TCC. This further emphasises the effect of modularisation on learning cost reduction; while the same learning rates were applied to the three settings in both cases, the reduced modularisation scope of the large reactor results in lower aggregate learning.

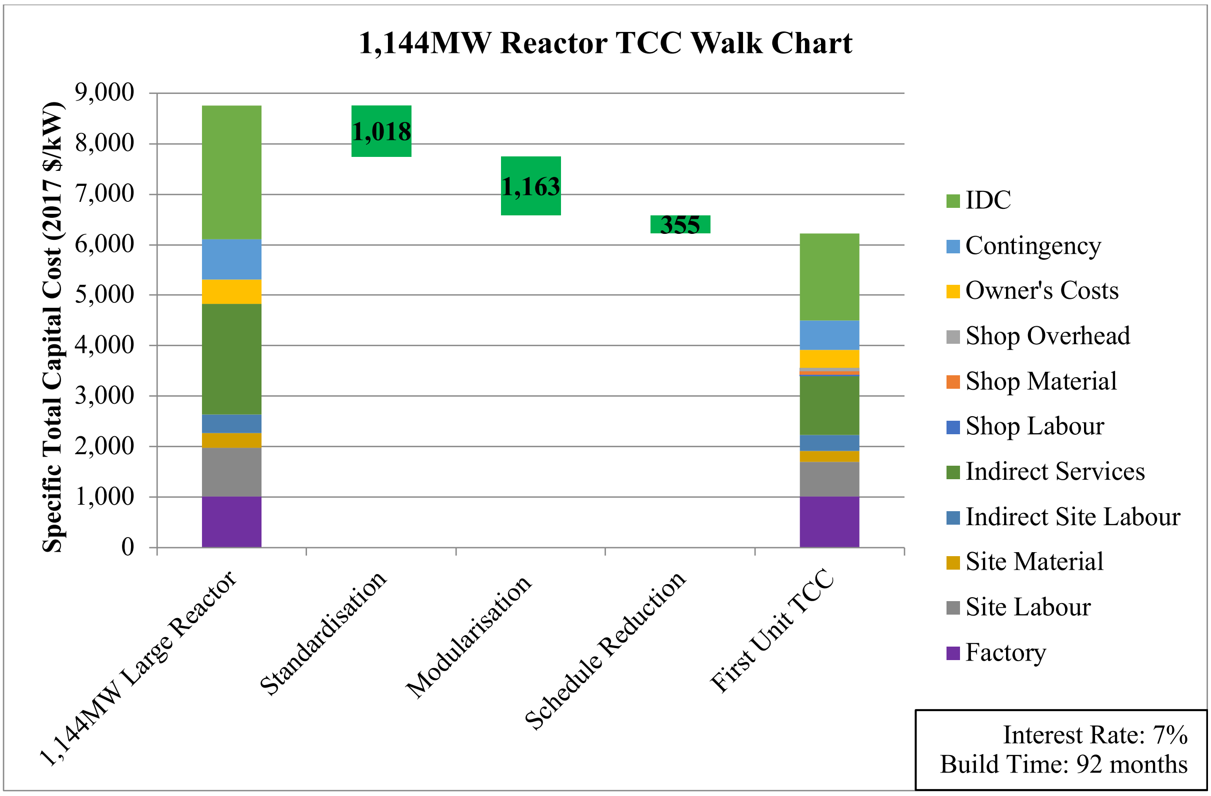

Figure 19: TCC walk chart for cost reduction of a 1,144MW plant

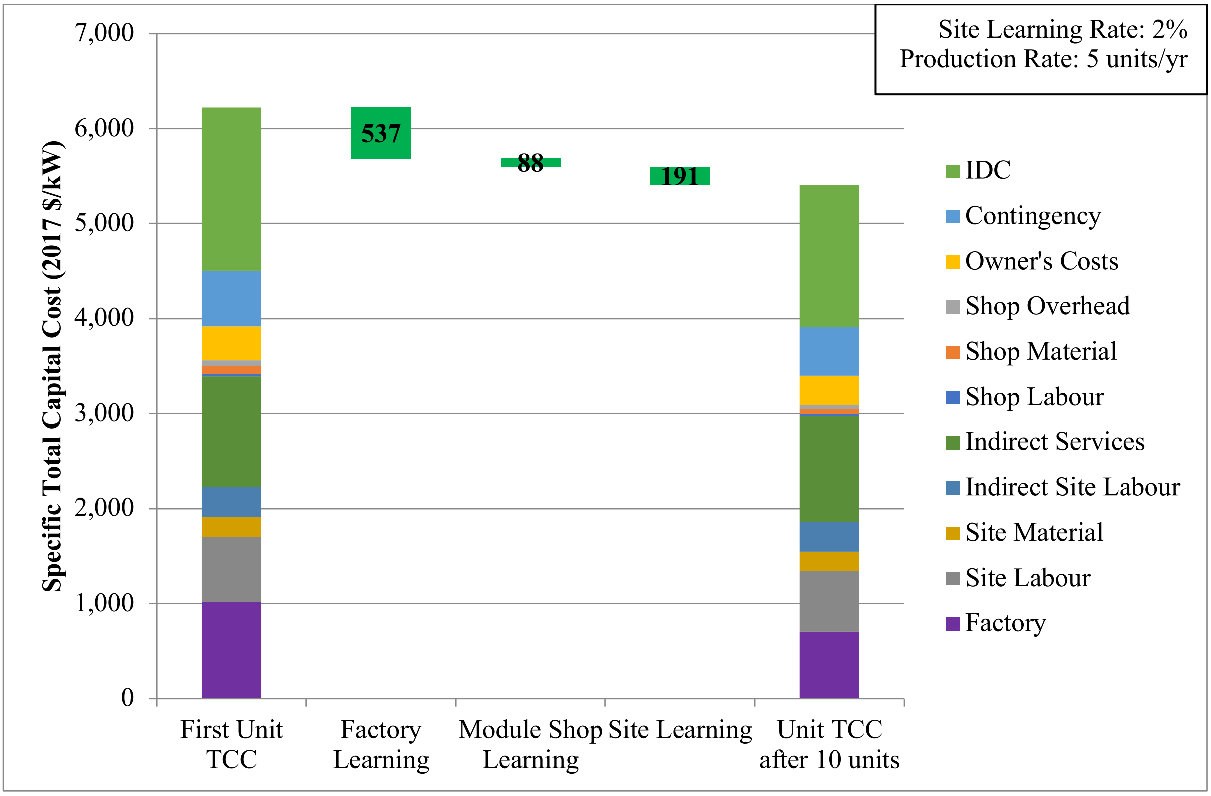

Figure 20: TCC walk chart over 10 units

Table 13 summarises the total cost reduction from the reference plant to the 10th production unit of the modularised and standardised 1,144MW plant, showing the individual contributions of the cost reduction methods and their cumulative effect. Before any learning, the cumulative cost reduction from improvements to the construction process amounts to 29%.

	TCC (2017 $/kW)	Reduction	Cumulative Reduction
Reference 1,144MW Plant	8,760	0%	0%
After Standardisation	7,742	-12%	-12%
After Modularisation	6,579	-13%	-25%
After Schedule Reduction	6,224	-4%	-29%
After 10 Units (5 units/year)	5,408	-9%	-38%

Table 13: TCC reduction for 1,144MW plant

At a production rate of 5 units per year, giving an aggregate OCC learning rate of 4.1%, the additional cost reduction brings the cumulative savings to 38%. If the production rate is dropped to just 2 units per year, giving an aggregate OCC learning rate of 2.7%, the cumulative cost reduction is reduced to 35%; the effect of further variation is shown in Table 14. These results are strikingly similar to those of the ETI.

Aggregate OCC Learning Rate	1%	2%	3%	4%	5%
Cumulative TCC Reduction	-31%	-34%	-36%	-38%	-40%

Table 14: Effect of aggregate OCC learning variation

2.10. Model limitations discussion

While the sensitivity analysis in Section 2.8 shows the influence of the assumptions and fixed parameters in the model, and the comparison with the ETI study in Section 2.9 gives confidence that the model results are reasonable, the model has limitations that need to be considered.

As already mentioned, the scaling factors used in this model are taken from the Nuclear Energy Cost Data Base of the US Department of Energy, and are provided at the two digit account level. While this provides more detail than a single cost-weight average aggregate scaling factor, it still requires uniform application across the four digit direct and three digit indirect accounts. The same applies to a lesser extent to the modularisation percentages, which are specified at the three digit account level. One must therefore be wary of looking at four digit account costs in isolation, as they may be distorted by the averaging of these parameters. Furthermore, learning is applied at the four digit level, and the resultant cost reduction is directly related to the factory and module cost share, which in turn is driven by the scaling factors and modularisation percentages; consequently, these distortions may be exacerbated further down the learning curve.

A further limitation deriving from the scaling factors relates to their applicability to different reactor sizes. As explained in Section 2.6.2, the Nuclear Energy Cost Data Base provides two sets of scaling factors to be used for different extents of reactor power variation. Again, the same applies to the modularisation percentages, as the greater physical dimensions and weights inherent in larger plants reduce the scope for modularisation (Lloyd, 2019). This limits the cost model's ability to project costs for a continuous range of reactor power; it is better suited for examination of particular cases.

In all cases, the first unit cost reductions produced by the model are separated out into those resulting from Standardisation, Modularisation, and Schedule Reduction. This would imply that these effects can be taken, and indeed varied in isolation. However, these effects are inherently coupled. In practical terms, the extent of standardisation will limit the modularisation scope, as it is only worthwhile to design and produce modules that will be repeated for multiple plants. It has previously been discussed how standardisation is an enabler of learning, in that it allows for repetition; however it also enables learning indirectly by creating the case for modularisation, which has also been shown as an enabler for learning. The consequence of this is that it would not be reasonable to apply the significant modularisation percentages without the high standardisation factor, even though these are operated as independent parameters in the model. Similarly, the assumed schedule reduction is a direct result of the impact of modularisation on the critical path of construction; while it would be possible to increase or decrease the extent of modularisation without affecting the schedule reduction, this would require detailed analysis as done by (Lloyd, 2019). Again, this limits the use of the model to specific cases of standardisation, modularisation, and schedule reduction, rather than continuous and independently varied ranges of each.

When considering the results of learning cost reduction, it is important to recognise that the observed learning rates that form the basis of the learning modelling are aggregate over production programmes. Moreover as a human activity, learning is inherently uncertain. Consequently, the projection of learning is better suited to estimation of long run cost reduction, rather than the specific savings realised over the first few units, and should be seen as the average reduction over a programme, rather than showing the specific reduction between each and every one of the units in the production run.

3. Supply Chain Theory and Practice

As demonstrated in Section 2, cost reduction for SMRs depends on: standardising work, transferring work from low productivity sites to production shops, and using the large volumes of units to make this work more efficient through learning. In this way nuclear construction is changed from project-by-project site construction to a series of common designs largely made in factories and assembled at site; site labour is largely limited to delivering that which requires local customisation, such as foundations and cooling systems. This transformation is from one-off site construction of projects to standard products delivered by a defined supply chain.

The focus of reducing cost is therefore on production efficiency, production rates and the progressive reduction of cost through learning, Therefore, the structure of the supply chain needs to be explored and how production rates affect cost reduction. As explained in Section 2.4.5, the learning rates applied to factory and module shop costs are determined by two factors: the production rate and the supply chain structure. While the influence of the production rate has already been discussed, this chapter explores the theoretical background to supply chain design, and how supply chain structure is parameterised in this study.

3.1. Supply Chain Design

Srai and Gregory (2008) define the configuration of a supply network (or supply chain) as the specific arrangements of its 'key elements', which are:

1. 'supply network structure';
2. 'flow of material and information';
3. 'role, inter-relationships, and governance between key network partners';
4. '"value-structure" of the product or service. (Srai & Gregory, 2008, p. 394)

These key elements can be condensed further into two complementary aspects of a supply chain: the physical logistics and the relationships between supply chain actors. With regards to physical logistics, supply chain design concerns 'the number and location of production facilities, the amount of capacity at each facility, the assignment of market region to one or more facilities, and supplier selection' (Meixell & Gargeya, 2005, p. 532). With regards to supply chain relationships, supply chain design is built on fundamental procurement decisions:

having broken down the product or service into components, how will each component be procured?

Both aspects of supply chain configuration are explored in this study. With the idealised supply chain map described in Section 2.5, the consideration of physical logistics is limited to the number and location of module manufacturing facilities, the number of component suppliers, and localisation of the supply chain.

The primary influence of these factors is on production rate and volume, as well as labour costs. Meanwhile supply chain relationships have a direct effect on the learning cost reduction applied in the cost model, as is explained in the following sections.

3.2. **Supplier Relationship Types**

Christy and Grout (1994) present a framework for understanding different supplier relationships and why they are chosen, which is summarised in Figure 21. This framework is driven by two characteristics of the product or service that is being traded: product specificity and process specificity.

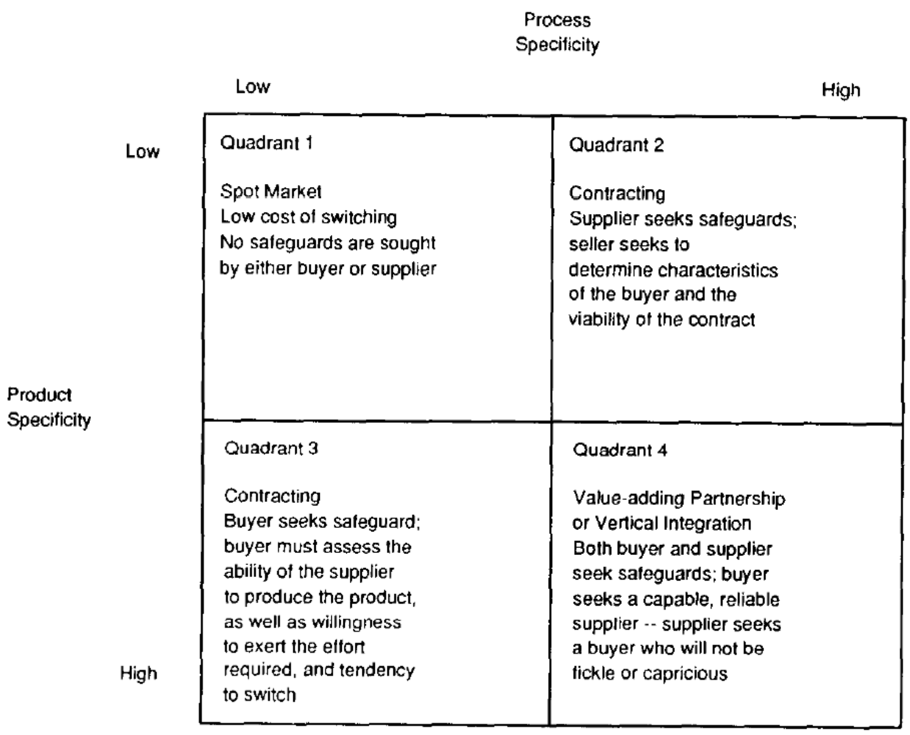

Figure 21: Supplier relationship framework (Christy & Grout, 1994, p. 237)

Product specificity relates to the needs of the buyer, deriving from the intended use of the product or service; the product specificity:

‘may be manifest in its design, material required, service mix requirements, conformance requirements, or timeliness measures’ (Christy & Grout, 1994, p. 236).

For example in the context of a nuclear power plant, the design and manufacturing characteristics of a steam generator would equate to high product specificity, whereas a chair in the plant control room would have relatively low product specificity. Process specificity relates to the needs of the supplier, deriving from the production process the supplier uses to provide the product or service. If the production process requires ‘specialised assets’, such as ‘unique tooling’, that would deliver a loss in value if redeployed for an alternate use, then process specificity is high (Christy & Grout, 1994, p. 236). On the other hand, if the production process only uses generic assets that have multiple uses, process specificity is low.

These two specificities create risk for the buyer and supplier respectively. For the buyer in a high product specificity transaction, the risk is the failure of the supplier to deliver, whether on time or to the required quality standard. For the supplier, the risk of high process specificity transaction is that the buyer will not ultimately make the full purchase, or go elsewhere entirely (Christy & Grout, 1994, p. 236). As shown in Figure 21, when either specificity is high, the party bearing the risk seeks contracting arrangements to act as a safeguard; these are the conditions that result in single, long term supply agreements. When both specificities are low, neither party needs the reassurance of a long term commitment, which creates the opportunity for multiple competing suppliers. On the other hand, if both specificities are high, the risk to both parties is high enough that a more engaged partnership model might be pursued, if not full vertical integration.

In many industries, the twin pressures of competition and globalisation have led to more complex supplier relationships. While selection of suppliers by competitive tender (lowest cost for the task) is still employed, the needs to: aggregate volumes, to progressively reduce product and interface cost and to be more responsive to customers - has led to new structures. This framework thus presents four supplier relationship types: an integrated supplier (or in-house production), a single source supplier, multiple competing suppliers, or a value-adding partnership. While the first three are simple to understand, it is worth considering how the relationship between a buyer and a supplier ‘partner’ differs from that with a standard single supplier.

3.2.1. Supplier partnerships

A 'strategic supplier partnership' is 'designed to leverage the strategic and operational capabilities of individual participating organizations to help them achieve significant ongoing benefits' (Li, et al., 2006, p. 110). This means that such suppliers not only participate in the engineering and design processes of the final product, but crucially are expected to 'contribute to continuous improvement' (Mahoney & Helper, 2017, p. 2). Stuart (1997) explains that 'such arrangements are based on influence, trust and mutual values' and require 'a more intensive governance approach than would be the case for the transactional and adversarial buying approach' (Stuart, 1997, p. 226).

Examination of a specific example of such a relationship further illustrates what differentiates this type of arrangement. Project 13 is an initiative launched by the Institution for Civil Engineers to promote a new business model for infrastructure projects, which it refers to as an enterprise; its purpose is to improve productivity, with an emphasis on innovation (Institution for Civil Engineers, 2018). The enterprise model encompasses all parties in an infrastructure project, as shown in Figure 22, and the roles described are specific to that industry; nevertheless the nature of the relationships between suppliers and the owner/integrator are relevant to the more generic concept of a supplier partner. Most notably, suppliers are not just providers of a particular component or material, but also subject matter experts who are responsible for the development and deployment of their specialist skills throughout the project. Moreover, they share in both the risk and rewards of the whole product, not just their specific component. It can thus be understood that unlike single suppliers in traditional transactional relationships, supplier partners join an integrated team with the buyer and work collaboratively. As discussed in the following sections, this causes significant differences in the potential for learning between such enterprise partners and traditional suppliers.

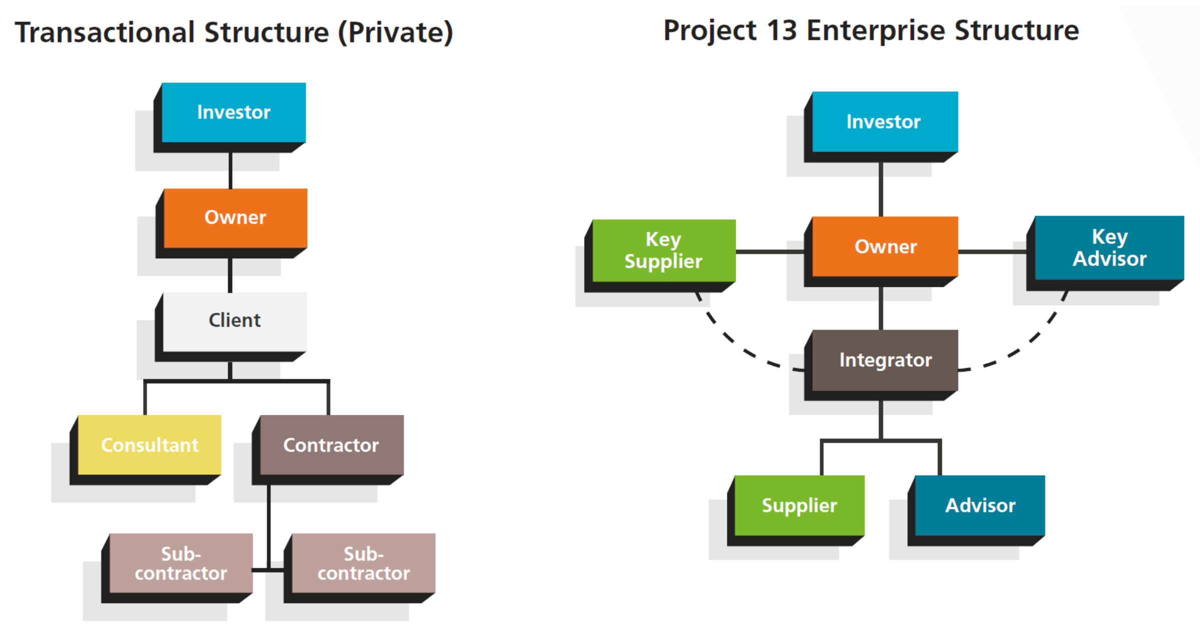

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Figure 22: Project 13 enterprise structure (Institution for Civil Engineers, 2018, p. 6)

3.3. **Supplier Learning**

In order to determine the net learning cost reduction delivered to the SMR vendor, it is necessary to consider the difference between the price and cost, as highlighted by the Boston Consulting Group (1968) in their discussion of learning. There are separate cost and price experience curves, and while the latter is 'coupled to the cost experience curve…it also reflects the sales and pricing strategies of the producers, the investors' bargaining power, and market reactions to public deployment policies' (International Energy Agency, 2000, p. 35). While broader factors might be worthy of inclusion when considering different market conditions, for the supply transactions in an SMR supply chain, three key factors were identified as most relevant to learning: innovation, the cost of interfaces, and value capture. Innovation relates directly to cost reduction, while the cost of interfaces and value capture influence the difference between cost and price.

3.3.1. Innovation

Innovation refers to the real changes that come out of learning, and reflects a supplier's incentive and ability to deliver these. Strategos (2014) lay out the factors that influence the learning that can be achieved:

- ‘management style and actions’;
- ‘corporate culture’;
- ‘organisation structure’;
- ‘technology’;
- ‘capital investment’;
- ‘engineering’ (Strategos, 2014).

For both a specialist integrated supplier and an enterprise partner, a high level of innovation would be expected. Both of these supplier types have the necessary expertise, and as their core business is in the production of the specific component, they have sufficient motivation to make the necessary investment, both financially and otherwise, to realise learning. For a non-specialist integrated supplier, while the motivation is present, the fact that the business is not set up specifically for the provision of this particular component means that it will struggle to produce at competitive costs. Indeed, the ‘Integrated (not specialist)’ supplier type can be seen as one that would not come out of competitive business design, but rather forced by external factors (such as political pressure from state actors). For external suppliers, a medium level of cost reduction would be expected. As specialists in a competitive market, these suppliers have both the motivation and ability to learn. However compared to integrated suppliers and enterprise partners, these suppliers cannot make improving performance for this particular component as high a priority, due to the need to balance investment between different products/customers.

3.3.2. Cost of interfaces

In any transaction, there will be costs associated with the interaction between the buyer and seller. Grover and Malhotra (2003) refer to these as coordination costs, and give by way of example ‘costs of exchanging information on products, price, availability, demand, as well as costs to exchange design changes rapidly with the supplier’ (Grover & Malhotra, 2003, p. 459). For an integrated supplier which is part of the vendor organisation, these costs do not exist by definition. As enterprise partners work with the vendor in an integrated team, the cost of interfaces would similarly be expected to be low. Otherwise, it is clear that these costs will be higher when working with multiple suppliers as opposed to one, as information sharing activities will have to be duplicated. These varying cost of interfaces are incorporated into the model as a reduction in the net learning yielded to the SMR vendor.

3.3.3. Value capture

After the extra costs inherent in supplier transactions are factored into learning cost reduction, there is still the potential for disparity between the actual cost incurred by the supplier and the price given to the buyer. This is the result of value capture, and is a reflection of the power of a supplier to command profit for their work. Value capture in the context of learning is thus not different from the generic profit making ability of any business or industry. Therefore, the Five Forces Model presented by Porter (1985) is relevant to understanding the potential for value capture.

Porter describes five competitive forces, summarised in Figure 23, that in combination determine how competitive an industry is, and thus how much profit actors in that market can retain; a greater degree of competition means that firms must yield more value to their customers if they are to compete. The five forces are:

1. 'the threat of new entrants' – if it is easy for new competitors to enter the market, competition is higher;
2. 'the threat of substitutes' – if customers can meet their needs easily with alternative (rather than directly competing) products/services, competition is higher;
3. 'the bargaining power of buyers' – the stronger the power of customers, the more value must be yielded to them;
4. 'the bargaining power of suppliers' – the stronger the power of suppliers, the less value is passed down the supply chain;
5. 'rivalry among the existing competitors' (Porter, 1985, pp. 4-5).

This model is presented as a framework for determining the attractiveness of entering a new market, and so the forces are presented from the perspective of a business making such a consideration. Nevertheless, the attractiveness in question ultimately equates to profitability and so can be translated to the issue of value capture.

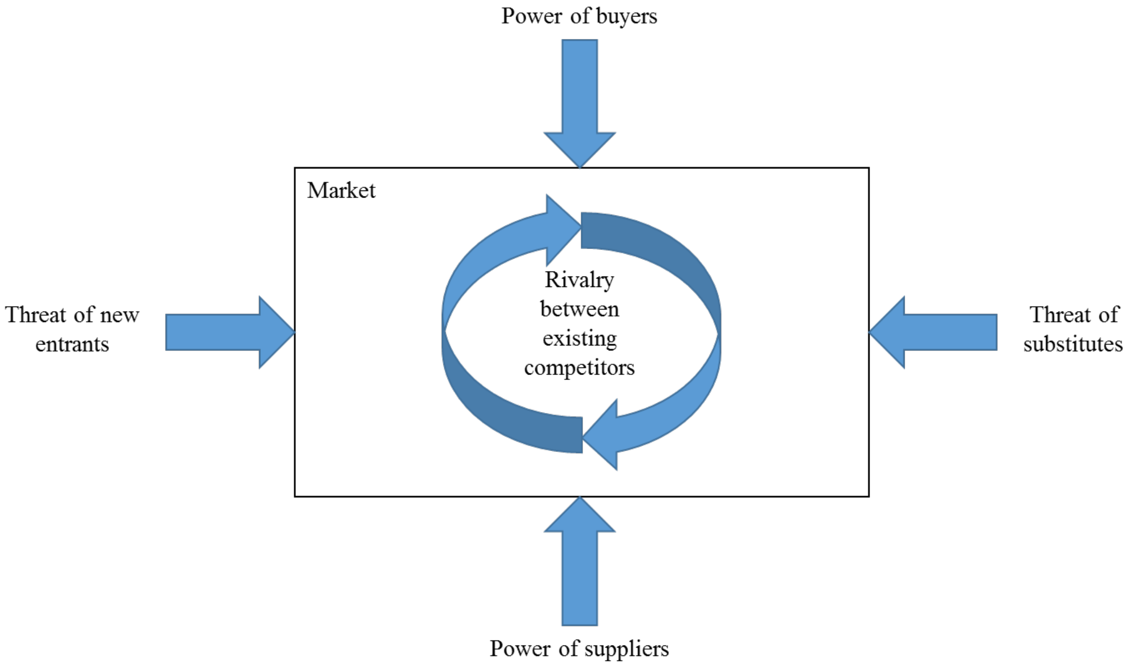

Figure 23: Porter's Five Forces Model (Porter, 1985, p. 6)

For integrated suppliers, there is inherently no value capture because they are part of the vendor organisation. For enterprise partners, a degree of value capture, or rather profit sharing, is expected as this is what is traded for the risk-sharing and innovation. For single traditional transactional suppliers, a distinction is drawn between relationships where the balance of supplier and buyer power falls to the buyer, and where it falls to the supplier; in the latter case, the supplier is expected uniquely to capture all of the cost savings realised from learning; in the former case, the degree of buyer power necessitates some savings being passed down the supply chain, but the level of value capture would still be high. While Porter provides an extensive list of factors that contribute to buyer and supplier power (Porter, 1985, p. 6), in this model the focus is on the significance of the buyer's purchase to the supplier's overall business; if the buyer is a major customer for the supplier, buyer power is stronger; if the buyer is a relatively minor customer to the supplier, than supplier power dominates.

In the case of multiple suppliers, the competitive rivalry between them reduces the value capture. This is further differentiated by the judgement that suppliers may still be able to capture some value when providing safety critical or otherwise complex components; in this case, value capture would expected to be at a medium level, compared to that for suppliers of relatively simple components, who would only be able to retain minimal value.

3.3.4. Net learning rate

The differentiation between single source suppliers in the presence of buyer or supplier power, and multiple suppliers providing either simple or complex components, results in a total of 7 supplier relationship types. Table 15 shows how each supplier relationship type was scored against the three factors described above. For each factor a score of 1, 2, or 3 was assigned, the sum of which was used to determine the relative net learning rate for the supplier type, as shown in Table 2. The mean learning rate, μ, is determined in the cost model by the production rate, as described in Section 2.6.6. The standard deviation, σ, is determined by Equation 15, which relates the standard deviation to the mean by a fixed Coefficient of Variation; this in turn was derived from a normal distribution of learning rates estimated from gas turbine investment cost data (McDonald & Schrattenholzer, 2001, p. 257). This is part of the same data used for the establishment of the learning rate – production rate relationship, but the gas turbine learning rates were isolated for three reasons. Firstly, by limiting the data to one technology, variations in cost structures and manufacturing processes are avoided. Secondly, compared to some other included technologies (such as full power plants), the gas turbine category was judged to be dominated by factory costs. Thirdly, the measure used to determine the learning rates was specifically investment cost, as opposed to price, which avoids the complicating factor of outside market forces skewing the measured learning.

Supplier Relationship Type	Description	Innovation	Cost of Interfaces	Value Capture	Net Learning Rate
Integrated (specialist)	In-house supplier	High (3)	None (3)	None (3)	**High (9)**
Integrated (not specialist)	In-house supplier	Low (1)	None (3)	None (3)	**Medium (7)**
Enterprise partner	Enterprise partner, engaged with vendor	High (3)	Low (3)	Medium (2)	**High (8)**
Multiple Source (simple component)	Competing suppliers	Medium (2)	High (1)	Low (3)	**Medium (6)**
Multiple Source (complex component)	Competing suppliers	Medium (2)	High (1)	Medium (2)	**Low (5)**
Single Source (buyer power)	Supplier for whom vendor is major customer	Medium (2)	Medium (2)	High (1)	**Low (5)**
Single Source (supplier power)	Supplier for whom vendor is minor customer	Medium (2)	Medium (2)	All	**None**

Table 15: Summary of supplier relationship types

Total Score	Net Learning Rate
8 – 9	High ($\mu + \sigma$)
6 – 7	Medium (μ)
3 – 5	Low ($\mu - \sigma$)

Table 16: Net learning rate allocation scheme

$$Standard\ deviation, \sigma = \left(\frac{5.1318}{14.9667}\right) * mean\ learning\ rate$$

Equation 15: Learning rate standard deviation calculation

3.4. **Overview of the Global Nuclear Supply Chain**

The nuclear industry has changed greatly during the last twenty years, driven by the hiatus in new plant ordering. Factories have been closed and engineering teams combined so that there is a small number of reactor vendors and component suppliers. These vendors and suppliers have become more international in pursuit of the limited number of orders and the centre of gravity of the industry has moved towards the Far East where the majority of new build has occurred in the last decade. The nuclear industry is seeking a better balance between national priorities, perceived nuclear safety constraints, and economics; this is reflected in the number of nuclear vendors and their supply chains. Economics will be the key driver for small modular reactors (SMRs), as their purpose is to overcome the cost problem that large nuclear plants face. This raises the question of how to best design a supply chain to deliver the much lower level of costs and shorter build timescale required to make SMRs competitive?

As the NEA explains, the importance of the supply chain to the ultimate economic competitiveness of nuclear power plants can be attributed to the high contribution of capital costs to the final levelised cost of electricity, and in turn 'the large share of capital costs that is accounted for by the supply chain' (Nuclear Energy Agency, 2015, p. 145). Large NPPs have traditionally been stick-built: the main structures are constructed from raw materials on site, with large components manufactured off-site in factories and shipped in. Figure 24 shows a percentage breakdown of the total overnight capital cost of building an NPP. 'Overnight' refers to the notion of building the plant essentially instantaneously; this ignores the significant cost of financing construction activities over the multi-year build times typical of nuclear power plants. It can be seen that the cost of procured equipment represents approximately 48% of the total build cost.

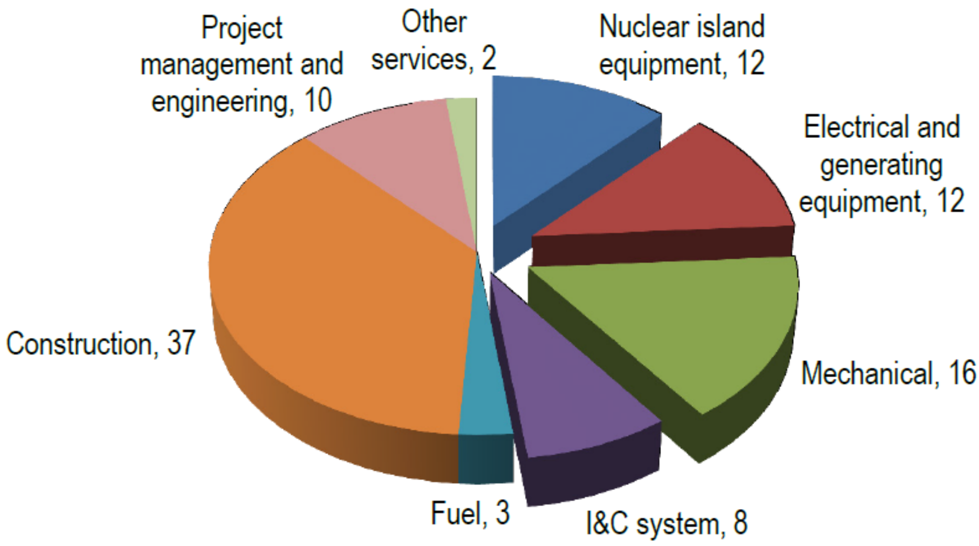

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Figure 24: NPP Cost Breakdown (Nuclear Energy Agency, 2015, p. 146)

Before considering the possible supply chain configurations that could be employed in the production of small modular reactor plants, it is important to understand the nature of the current nuclear supply chain used in the construction of conventional large reactor plants. There are a number of benefits to this:

1. Current supply chain configurations may reveal limits on what is possible in SMR production;
2. Strengths and weaknesses of particular configurations may be identifiable;
3. Particular areas may be highlighted where SMR production has the opportunity to introduce practice that is new to the nuclear industry.

The design of a supply chain traditionally revolves around 'decisions regarding the number and location of production facilities, the amount of capacity at each facility, the assignment of each market region to one or more locations, and supplier selection' (Meixell & Gargeya, 2005, p. 532). The nuclear industry has particular characteristics which complicate these decisions, such as the high degree of regulation, driving in particular high quality standards, and the political sensitivity of the technology, involving both public perception and national sovereignty. The relatively low volume of production and long build times are also important factors, and indeed these are ones SMRs are intended to disrupt.

The construction of nuclear power plants requires a reactor designer (vendor) who may make some key parts of the plant and a large number of contractors with varied skills, working together over many years. These companies together with the owner, who is usually the operator of the completed plant, are collectively considered to be the nuclear supply chain.

3.4.1. Organisational Structure of the Nuclear Supply Chain

Thomas (1988) provides descriptions and discussion of the nuclear industries in a number of countries: USA, FR Germany, France, and Canada. The focus is on the roles and relationships of the various players in the industries, thus providing insight into the overall structure of the nuclear supply chain. Thomas highlights five roles that vary in their distribution and relation across the different countries. These roles are as follows:

1. *Vendor* – the designer and proprietor, and to varying degrees manufacturer, of the nuclear reactor technology; in general, there will be a reactor vendor and a separate turbine generator/power conversion supplier;
2. *Architect-engineer* – the organisation that arranges the detail design and coordinates the project;
3. *Constructor* – the organisation responsible for the construction of the plant;
4. *Utility* – the owner and operator of the plant;
5. *Regulator* – the organisation responsible for the giving permission for the plant to be built and operated, enforcing regulations pertaining to the design, construction, and operation of the plant (Thomas, 1988, pp. 60-68).

In some cases the same organisation will discharge more than one of these roles. A sixth role can also be recognised, given the unique bearing it has on nuclear power: the State. The sensitivity of nuclear technology, public concerns about nuclear safety, and the scale of the investment mean that, even for privately owned and funded nuclear power plants, the State has an important role to play. Included in Thomas' observations of the different countries is the level of state support, financial or otherwise, that is provided to the nuclear power industry.

Taking these roles as a basis, Thomas provides a summary of the 'institutional structure of nuclear power', as shown in Table 17 (Thomas, 1988, p. 16).

	USA	FR Germany	France	Canada
Vendors #	3/4	1/2	1	1
Origins	Long-standing, diversified	Long-standing, diversified	Specifically created	Specifically created
Source of Technology	Indigenous	Imported	Imported	Indigenous
Manufacturing capability	Increasingly sub-contracted	Sub-contracted	In-house	Sub-contracted
State support	None direct	None direct	Underwritten by government	Owned by government
Architect-engineers	Specialist companies	Vendor	Utility	Utility
Constructors	Specialist companies	Specialist companies	Specialist companies	Utility
Utilities				
Number	Over 50	~10	1	3
Size	Wide range	Medium/Large	Very large	Large
Ownership	Generally investor-owned	Investor-owned	Publicly-owned	Publicly-owned
Catchment area	Variable	Generally regional	National	Provincial
Safety regulation				
Utility relations	Arm's length	Arm's length	Close, co-operative	Close, co-operative
Public disclosure	Very extensive	Extensive	Limited	Extensive
Methods	Active	Active	Reactive	Reactive
Centralisation	Partially devolved	Devolved	Centralised	Centralised

Table 17: National nuclear industry structures (Thomas, 1988, p. 16)

While not representing polar-opposite approaches to industry structure, it is useful to compare the USA and France as relative extremes, due at least in part to the different cultures of the two countries. With its preference for private sector competition, the US has maintained multiple reactor vendors who compete for each new build project individually. While historically these vendors had 'the capability to supply the major nuclear components', there is now a trend of procuring more components from specialist suppliers (Thomas, 1988, pp. 63-65). The lack of support from the government and decline in new orders has made it uneconomical for the vendors to keep such capability in-house. On the other hand, in France the single reactor vendor Areva has benefitted not only from the stability of a national nuclear build programme, producing 58 reactors, but also from the State's ambition to be an independent nuclear nation. Thus Areva has been able to maintain much more of its manufacturing capability.

The role of the architect-engineer has also been played out differently in the two countries. In the US it has been taken on by companies that often have experience of other construction sectors, offering expertise in project management that technology vendors do not have. The downside of this separate role is that it may 'make the logistics of constructing nuclear power stations more complex', 'by lengthening the lines of communication' (Thomas, 1988, p. 67). Moreover, the slowdown in new build projects has seen the loss of nuclear-specific knowledge from architect-engineer firms. In contrast, France has only one architect-engineer, which is also the only nuclear utility: EDF. Again, this can be attributed to the differences in culture between the two countries, and in particular France's state-driven national programme. Where the US and France do have common ground is the role of the constructors: in both countries local contractors have been charged with the construction of the nuclear plants.

While no details are provided, it can nevertheless be envisaged from the above descriptions that the supply network structure employed by vendors in the USA is more extensive than that of France. Indeed, Figure 25 and Figure 26 show the idealised structures of the NPP supply chains in the US and France, as described by Thomas.

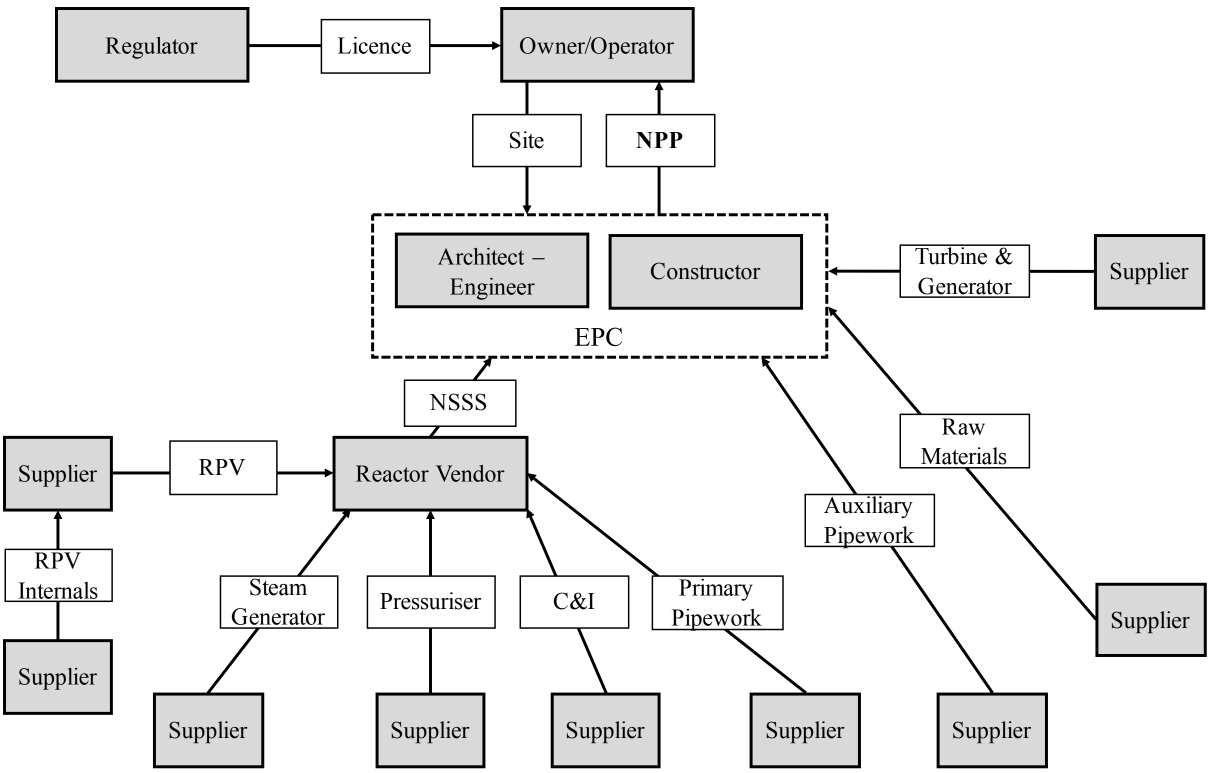

Figure 25: Idealised Map of Supply Chain Structure in US

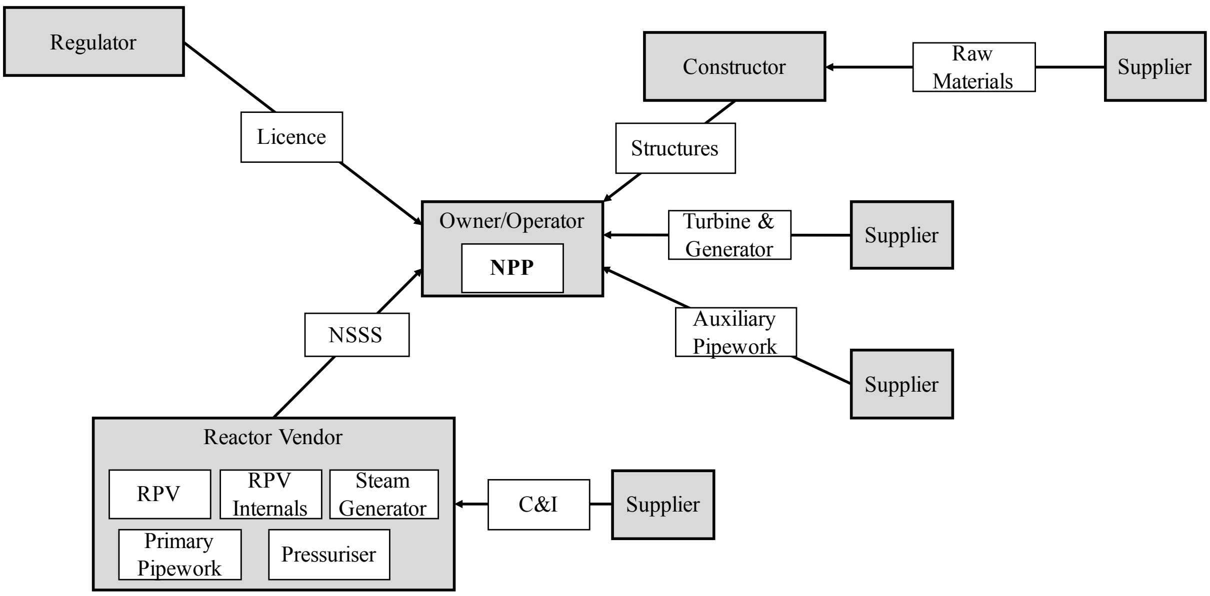

Figure 26: Idealised Map of Supply Chain Structure in France

One can draw comparisons between these two case studies and the organisational structures of the nuclear industries in the other major nuclear countries. China and Korea have followed France's example by establishing national build programmes, but with differences comparable to the US; China has two nuclear utilities as opposed to one, and Korea is more engaged with outside suppliers, though they are tightly integrated with the programme lead KEPCO. In Russia, the state-owned vendor represents one extreme by being completely vertically integrated.

3.4.2. Global Reactor Vendors

The NEA explains that in the past, 'the design and construction of NPPs was led by consortia in each country' (Nuclear Energy Agency, 2015, p. 160). The largely self-contained industry structures described by Thomas (1988) were born out of the era when nuclear power was an issue of national sovereignty, and indeed security. Now however, economic pressures have led the number of reactor vendors to fall significantly. Those that remain have reduced the scope of their technical capabilities to varying degrees, as shown in Table 18, and instead outsource to suppliers all over the world. Table 18 highlights further consolidation in the US industry beyond what is discussed by Thomas (1988); namely the reduction in reactor vendors from four to two as of 2015.

Vendor	**Country**	**Reactor**	**Capabilities**
AREVA NP	France	EPR	Manufacturing capability for reactor pressure vessel including the Le Creusot forgings facility and nuclear steam supply system components.
		ATMEA	Front end fuel supply and reprocessing facilities as well as decommissioning.
		KERENA ABWR	Co-operation agreement with Mitsubishi HI to develop ATMEA technology.
Candu Energy	Canada	ACR 1000	Design and construction of NPPs, supply of specialised equipment and plant life support.
GE Hitachi	US & Japan	ESBWR	Two subsidiary partnerships offer fuel cycle services.
		ABWR	Engineering, procurement and construction management of NPPs.
China National Nuclear Cooperation	China	CNP-1000 CAP 1400	Subsidiary companies covering nuclear construction, fuel supply and fabrication.

Vendor	Country	Reactor	Capabilities
Doosan (with KEPCO)	South Korea	APR-1000 APR-1400	Partnership with KEPCO to supply nuclear and turbine components and engineering, procurement and construction management.
Mitsubishi Heavy Industries	Japan	APWR	Joint venture with AREVA to develop ATMEA.
		ATMEA	Fuel fabrication. Manufacture of reactor pressure vessel and nuclear steam supply system components.
Nuclear Power Corporation of India	India	PHWR-220 PHWR-700	Reactor pressure vessel and turbogenerator manufacture (with Larsen & Toubro). Architect engineer and engineering, procurement and construction management.
Rosatom	Russia	VVER	
Toshiba/ Westinghouse	Japan/US	ABWR AP1000	Reactor pressure vessel internals; steam turbine generators; NPP modular construction; fuel fabrication; engineering, procurement, and construction management.

Table 18: List of nuclear reactor vendors, adapted from NEA (2015, p. 163)

Moreover, this list highlights the shift in technological dominance from the United States to Asia, where now the majority of vendors are based. The United Kingdom, where civil nuclear power generation was first realised, no longer has a native reactor vendor.

3.4.3. Key Component Suppliers

The NEA provides succinct descriptions of ‘the main components for an NPP, their performance characteristics and manufacturing requirements’, as well as where the main suppliers are located (Nuclear Energy Agency, 2015, p. 148). In order to appreciate the global fragmentation of the nuclear supply chain, the tables shown in Appendix C indicate the region where each supplier is based. The component descriptions and supplier information are taken from both the NEA (2015, pp. 148-153) and Nuclear Energy International (2012, pp. 46-87). The list shown in Appendix C is by no means exhaustive, but rather illustrative of the limitations in supply of critical components.

4. Single Programme Analysis

Having developed a model to estimate the construction costs of SMRs over the course of a production programme, in this chapter the model is employed to investigate the economic effect of supply chain configuration on a single production programme. The range of supply chain configurations considered is defined by the type of SMR vendor, and the relationships it has with its supporting supply chain. A total of 8 configurations are examined, based on three vendor types and variations in supplier relationships.

4.1. Supply Chain Scenarios

4.1.1. Baseline vendor types

The baseline vendor types adopted in this study are based on observations of the practice and limitations of the nuclear industry, as discussed in Section 3:

1. Integrated Vendor – this is a fully vertically integrated vendor, comparable to the Rosatom State Nuclear Energy Corporation, which supplies all the factory made components internally;
2. Design & Make Vendor – this is a reactor vendor which designs and manufactures reactor components, comparable to EDF;
3. Design & Buy Vendor – this is a reactor vendor that has no internal manufacturing capability, such that all reactor components and subsystems must be procured; this is representative of a new reactor design with no production experience.

4.1.2. Detailed configurations

The baseline vendor types described above are further differentiated by detailed configurations, which are defined by the supplier relationship types assigned to each account. The supplier types and the corresponding learning rate are listed in Table 19 – the explanation for the net learning rate distributions can be found in Section 3.3.4. The detailed configurations are summarised in Table 20.

Supplier Relationship Type	Net Learning Rate
Integrated (specialist)	**High (μ + σ)**
Integrated (not specialist)	**Medium (μ)**
Enterprise partner	**High (μ + σ)**
Multiple Source (simple component)	**Medium (μ)**
Multiple Source (complex component)	**Low (μ - σ)**
Single Source (buyer power)	**Low (μ - σ)**
Single Source (supplier power)	**None**

Table 19: Supplier type net learning rates

Scenario	Vendor Type	Reactor Plant Equipment	Turbine Plant Equipment	All Other Equipment	Modules
SC1	Integrated	Integrated (specialist)	Integrated (not specialist)	Integrated (not specialist)	Integrated (not specialist)
SC2	Design & Make	Integrated (specialist)	Single (supplier power)	Four Box Assignment	Integrated (not specialist)
SC3	Design & Buy	Single (buyer power)	Single (supplier power)	Four Box Assignment	Integrated (not specialist)
SC4	Design & Make	Integrated (specialist)	Single (supplier power)	Four Box Assignment	Single (buyer power)
SC5	Design & Buy	Single (buyer power)	Single (supplier power)	Four Box Assignment	Single (buyer power)
SC6	Enterprise	Enterprise Partner	Enterprise Partner	Four Box Assignment	Enterprise Partner
SC7	Design & Make	Integrated (specialist)	Single (supplier power)	Four Box Assignment (reduced competition)	Integrated (not specialist)
SC8	Design & Buy	Single (buyer power)	Single (supplier power)	Four Box Assignment (reduced competition)	Integrated (not specialist)

Table 20: Supply Chain Configurations

Across all configurations, a number of constraints were applied. By definition for an Integrated Vendor, all reactor plant equipment was assigned to integrated (specialist) suppliers, while all other accounts were assigned to Integrated (not specialist) suppliers. By definition for a Design & Make Vendor, all reactor plant equipment was assigned to integrated (specialist) suppliers. For a Design & Buy Vendor, all reactor plant equipment was assigned to single (buyer power) suppliers; this was to reflect the judgement that such a vendor would be a major customer for a third party reactor component producer, which would afford the vendor some buyer power.

Turbine plant equipment was always assumed to come from a single supplier; the turbines and generators used in nuclear power plants have technical requirements that differentiate them from those used in other thermal plants; consequently their specification is tightly coupled to the reactor design (Nuclear Energy Agency, 2015, pp. 152-153). Under normal contracting conditions, the turbine plant equipment was therefore assigned to single (supplier power) suppliers; this was to reflect the judgement that a turbine-generator supplier would have a broad customer base.

Beyond these constraints, all other equipment was assigned a supplier relationship type by applying a four-box methodology, which is explained in Section 4.1.3. In short, the four-box methodology reflects the standard procurement decision making process, and thus gives credible supplier type assignments based on the supply market conditions.

From the combination of the three baseline vendor types and the above constraints, eight detailed configurations were devised as credible supply chain structures to be considered. SC1, SC2, and SC3 are considered the benchmark configurations, as each represents one of the baseline vendor types. Each of these three assume that module production is done in-house by the SMR vendor. SMR vendors would likely have the motivation for this decision, given the importance of their delivery (both in terms of time and quality) to the achievement of the intended build schedule. However, the vendors may not have the skills and knowledge to design and make modules efficiently. Variations in the module supplier type are thus one of the supply chain decisions examined in this analysis.

The subsequent configurations are then used to explore specific supply chain decisions that could credibly be considered. SC4 and SC5 have the modules produced by a single external supplier. SC6 replaces single contractual suppliers with enterprise partners. SC7 and SC8 reduce the competition between multiple suppliers compared to the benchmark scenarios; while SC2 and SC3 assume four suppliers wherever multiple are used, SC7 and SC8 assume only two. The relevance of these supply chain configuration decisions is explained during the results discussion in Section 4.

4.1.3. Four-box methodology

The methodology for assigning supplier relationships types in summarised in Figure 27, which is an adaptation of the four box model discussed in Section 3.2. Each component account was scored on a 1 – 3 scale for two properties:

1. The risk and quality requirements associated with the component;
2. The number of suppliers available for the component.

The first is a proxy for 'product specificity', as a measure of the buyer's requirements for the component. The second is a proxy for the 'process specificity', predicated on the assumption that there is a strong relationship between the two; specifically, for a given product demand, a smaller number of suppliers will be able to support the investment in more specialised assets than would for generic ones. Consequently, a low number of suppliers equates to high process specificity, and vice versa. The choice of these two metrics was driven by the availability of data for the nuclear supply chain, and indeed various alternative four box methods can be found in the literature.

The risk and quality requirement scores were based on information from a supply chain map produced by the Nuclear Energy Institute (n.d.) for the US, being the largest nuclear market in the world.. This document lists the standard components in a nuclear power plant; given that this is based on the US operating fleet, it is assumed that this reflects LWR technology. Each component is classified as one of the following by its manufacturing and quality assurance requirements:

1. 'Standard quality products' – no quality assurance required;
2. 'Supplemental quality products' – specified quality requirements;
3. 'Safety-related products' – a fully quality assurance programme is required (Nuclear Energy Institute, n.d., p. 3)

By comparing the components in the supply chain map with the EEDB accounts, each of the former was scored in ascending order of quality and safety requirements: 1 for standard quality, 2 for supplemental quality, or 3 for safety-related.

The number of suppliers for each account was based on information from the Nuclear News Buyers Guide 2016 (American Nuclear Society, 2016), which contains a directory of suppliers organised by the component(s) they supply. A set of benchmark components were selected to determine the score given based on the number of suppliers list; these are shown in Table 21 and Table 22. The benchmark components were selected to cover the range of component specificities: fuel elements are highly specialised components, both in their design and fabrication processes, and are tightly regulated; switchboards on the other hand can be taken as relatively standard electrical components. The scoring system shown in Table 22 was employed to create simple, unambiguous groupings of the components.

Buyers Guide Component	Number of Suppliers
Fuel Elements, Fabricated	4
Turbine-Generators	13
Switchboards	14
Fuel Storage Racks	26

Table 21: Benchmark components (American Nuclear Society, 2016)

Number of Suppliers	Score
n < 10	Low
10 <= n < 20	Medium
20 <= n	High

Table 22: Scoring for Number of Suppliers

Where a direct match between an account and supply chain component was not available, a similar account was used based on the type of reactor system or function in which it is used. However if no comparable alternative was identified, then the score for 'Number of Suppliers' was assumed based on the 'Risk & Quality Requirements score', In the absence of supply chain data, a high score for Risk & Quality Requirements was assumed to equate to a low number of suppliers, and vice versa. This is built on the judgement that high quality components are more likely to require specialised production assets, and as previously discussed this in turn is likely to lead to a smaller pool of suppliers. There is a degree of support for this trend in the available data, as shown by Figure 28. This four box diagram maps the distribution of components for which independent scores were assessed. The majority of components with a high score for Risk & Quality Requirements have a low score for Number of Suppliers, with a minor tendency for a greater number of suppliers for low risk components. Appendix B contains the scores for each individual account, as well as the details of which accounts were taken as proxies, and which were assumed to follow the discussed trend.

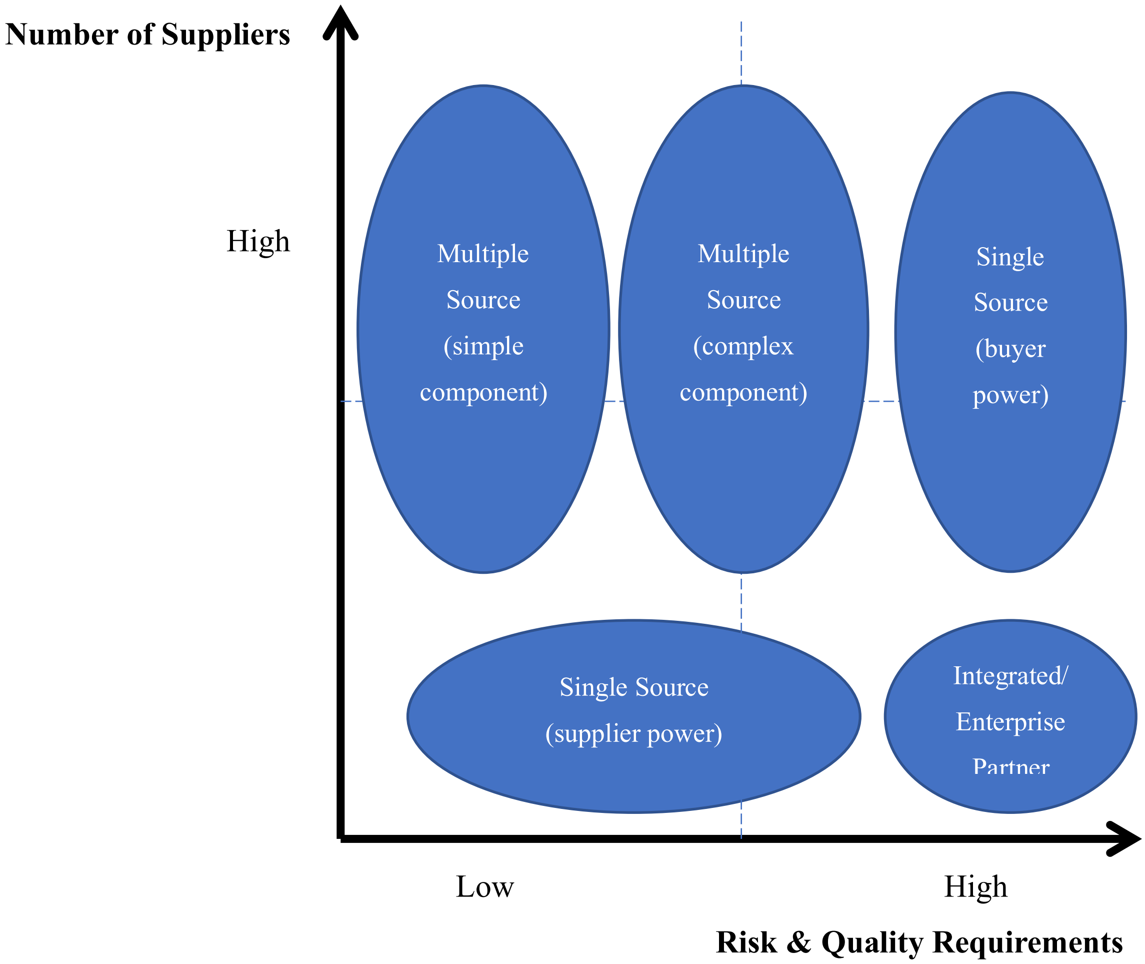

Figure 27: Four-box supplier relationship type assignments

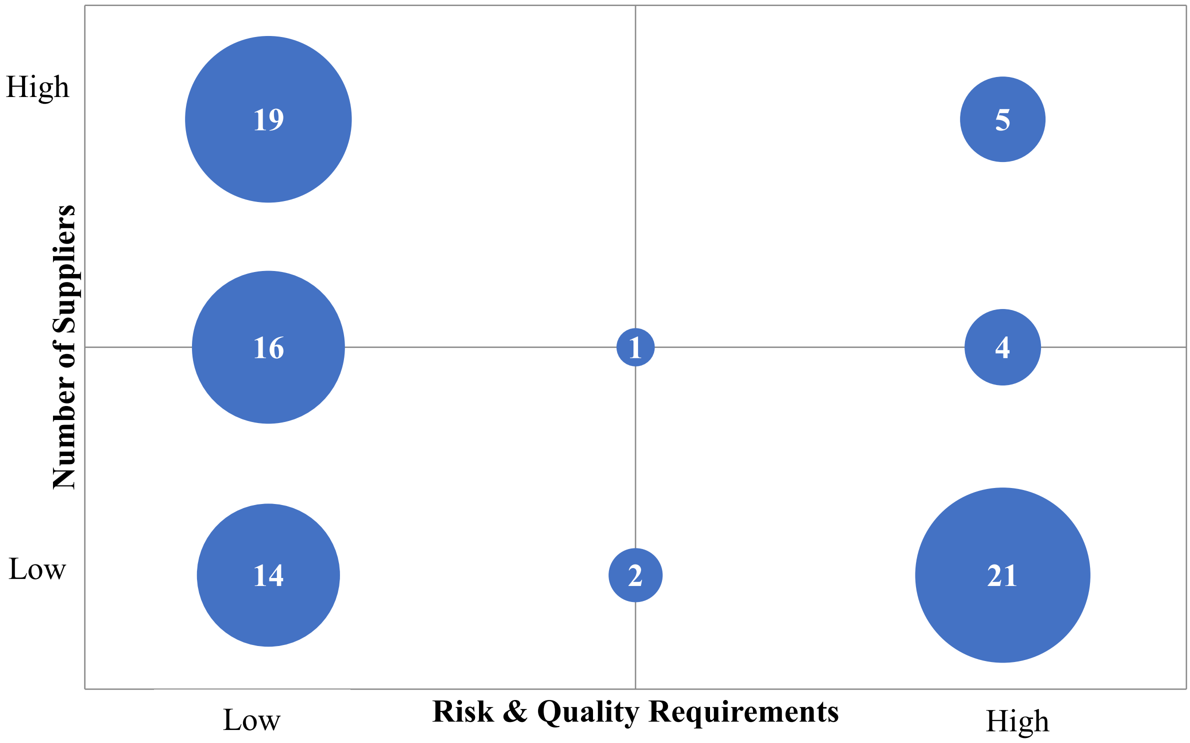

Figure 28: Distribution of four box scores

4.2. SMR Programme Parameters

Beyond the defined supply chain scenarios, a number of reactor and programme parameters were selected to explore the importance of supply chain variations under different programme conditions:

1. Reactor power;
2. Programme size;
3. Production rate;
4. Number of module shops;
5. Interest rate.

Reactor unit power is relevant because the combination of cost scaling, scope for modularisation and production volume has a significant impact on cost distributions within the supply chain.

Programme size and number of module shops both determine the production volume throughout the supply chain, which has a bearing on the learning cost reduction achieved. As discussed in Section 3.3, production rate is a key determinant of the learning rate achieved in production.

Finally, while not having a direct relation to configuration of the logistical supply chain, the interest rate does have multiple indirect connections. Firstly, the interest rate demanded by investors and creditors is indicative of the perceived risk in the delivery of the plant. An established supply chain, with consistent constructors and proven performance of delivering a standardised design, could arguably attract cheaper capital than is typical for nuclear plant projects. Secondly, the extent of government involvement would affect the interest rate. Thirdly, the high capital cost of nuclear power plants means that their economics are very dependent on the cost of borrowing.

The interest rates chosen are close to those employed by the International Energy Agency and Nuclear Energy Agency in their electricity generating cost analysis (International Energy Agency, 2015): 3% represents the 'social cost of capital' available to governments; 7% is reflective of the market rate in a competitive sector; and 9.6% is the return demanded for high risk projects (International Energy Agency, 2015, p. 27). The chosen values for the other parameters are shown in Table 23.

Parameter	Values
Reactor Power (MW)	100, 250, 500
Supply Chain Scenarios	1 – 8 (see Table 20)
Programme Size (GW)	5, 10, 25
Production Rate (units/year)	1, 2, 4, 5, 10, 25
Number of Module Shops	1, 2, 4, 8
Interest Rate (%)	3, 7, 9.6

Table 23: Programme parameters

4.3. **Results**

In order to condense the results produced from surveying the whole parameter space, two metrics were defined: the parity unit and the final TCC. The parity unit is the unit in the production run that has achieved sufficient learning cost reduction to reach the benchmark LCOE for nuclear power. The benchmark used was $112/MWh, being the bottom of the range for large reactors, provided by Lazard (2017). Thus it is indicative of being cost competitive with conventional nuclear plants. The final TCC is the total capital cost of the final SMR unit in the production run. This is indicative of the potential for being competitive with other low-carbon sources of electricity.

4.3.1. Benchmark configurations

Figure 29, Figure 30, and Figure 31 show the progressive reduction in TCC of a 250 MW SMR for three different programme sizes and the three benchmark supply chain configurations, in all cases over 10 years and at a 9.6% interest rate. The parity TCC line indicates the TCC required for the SMR to achieve the benchmark LCOE of $112/MWh, meaning that the parity unit is the unit number at which the TCC curve crosses this line. The parity unit and final TCC for each of the nine scenarios are shown in Table 24.

The most prominent feature of these results is the dominant influence of production volume and rate. For all three supply chain configurations, the 5 GW programmes do not achieve enough learning cost reduction to be competitive with large nuclear power. For the larger programmes, there is a significant range in the length of production required to become competitive, and this is also reflected in the range of final TCC values achieved. From these results, it can also be understood that while the final TCC metric serves as a measure of the long-term benefits achieved by certain programme conditions and supply chain design, the parity unit is a measure of the short-term benefits.

It is also clear from the figures that the supply chain configuration has a major effect on the learning cost reduction that is achieved. In all cases, the Integrated Vendor achieved the greatest reduction, while the Design & Buy Vendor achieved the least; the final unit TCC for the former reduced beyond that of the latter by approximately 6.9% for the 5 GW programme, 13.2% for the 10 GW programme, and 20.9% for the 25GW programme. The strength of the Integrated Vendor shows the benefits of concentrating production volume and rate, as well as reducing the cost of interfaces between suppliers; the weakness of the Design & Buy Vendor highlights the significance of the reactor plant equipment, which makes up approximately 55% of the factory made components.

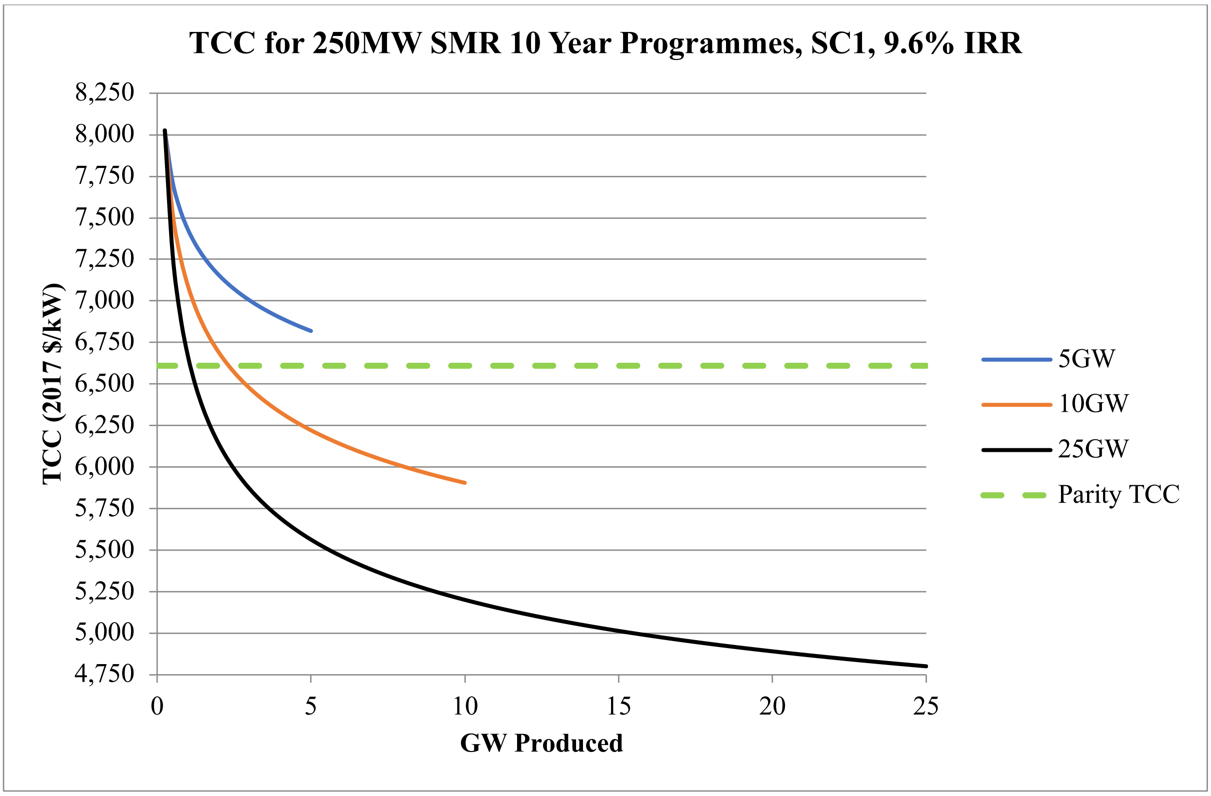

Figure 29: TCC learning curves for SC1

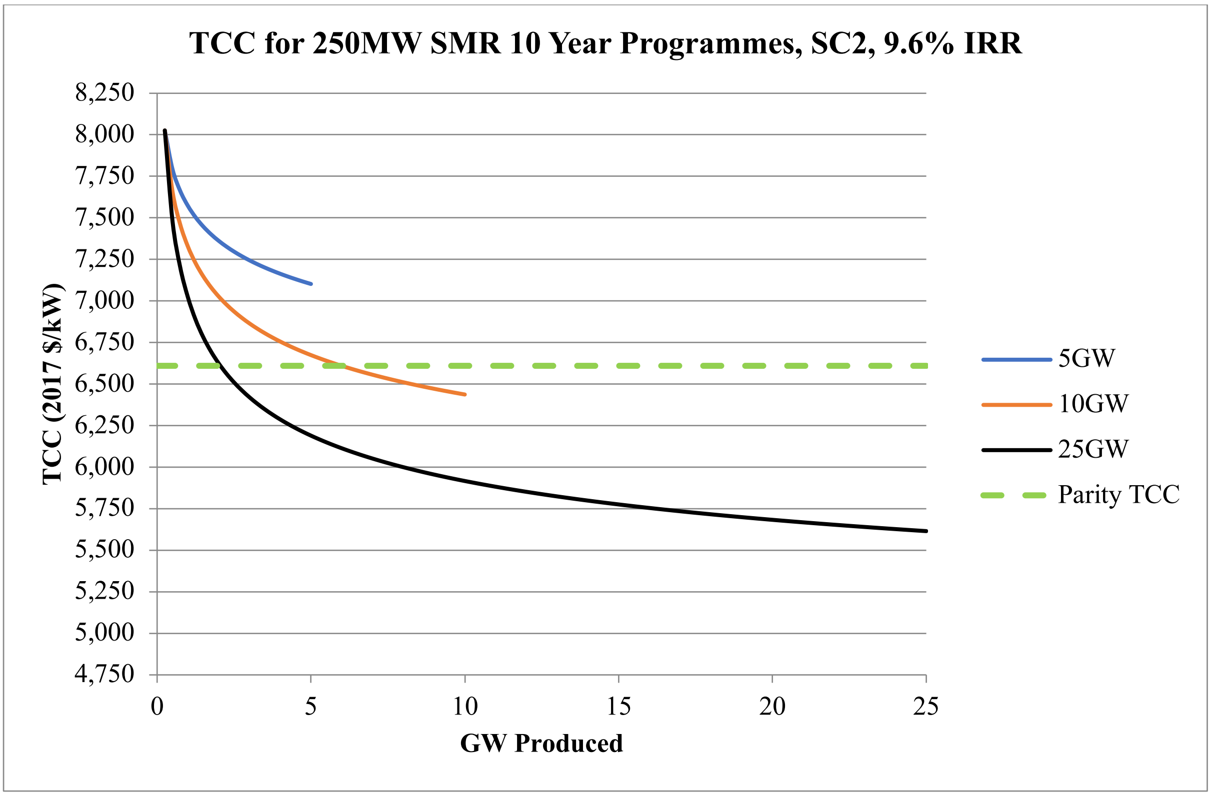

Figure 30: TCC learning curves for SC2

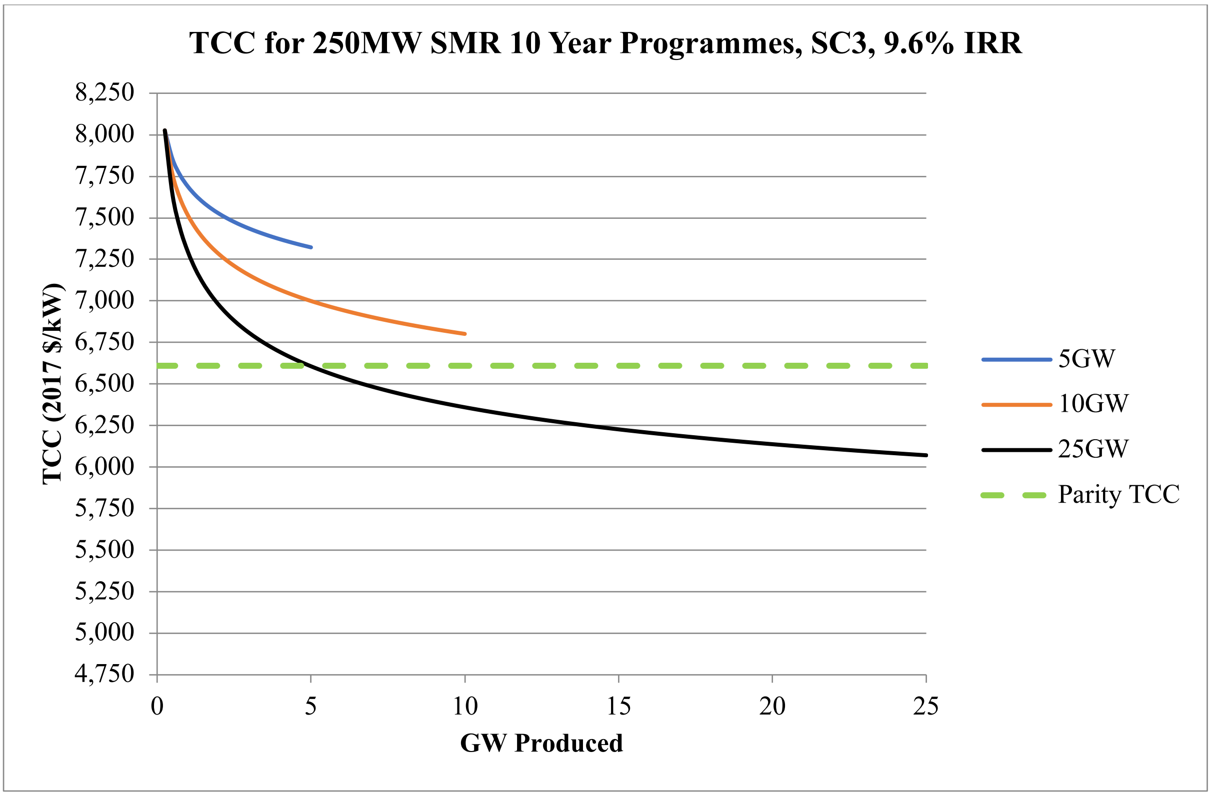

Figure 31: TCC learning curves for SC3

Supply Chain Configuration	Programme Size (GW)	Parity Unit	Final TCC ($/kW)
SC1	5	-	6,819
	10	10	5,906
	25	5	4,801
SC2	5	-	7,103
	10	23	6,437
	25	8	5,615
SC3	5	-	7,323
	10	-	6,802
	25	20	6,071

Table 24: Benchmark configuration metrics

4.3.2. Production rate and volume

To further explore the importance of production consolidation, the three benchmark configurations were evaluated across the full ranges of programme size, production rate, and module shop number. Figure 32 through Figure 37 show the resulting parity unit and final unit TCC values.

The parity unit plots highlight the importance of production rate, regardless of the programme size. Figure 32 emphasises the short run advantage yielded from high learning rates: SC1 achieves single digit parity unit values, so long as the number of module shops is kept low. In contrast Figure 36 has very few data points at all, only those with large programmes and production rates, thus showing the particularly limited scope the Design & Buy Vendor has for cost competitiveness. This is also reflected in the almost uniformly high final TCC values shown Figure 37.

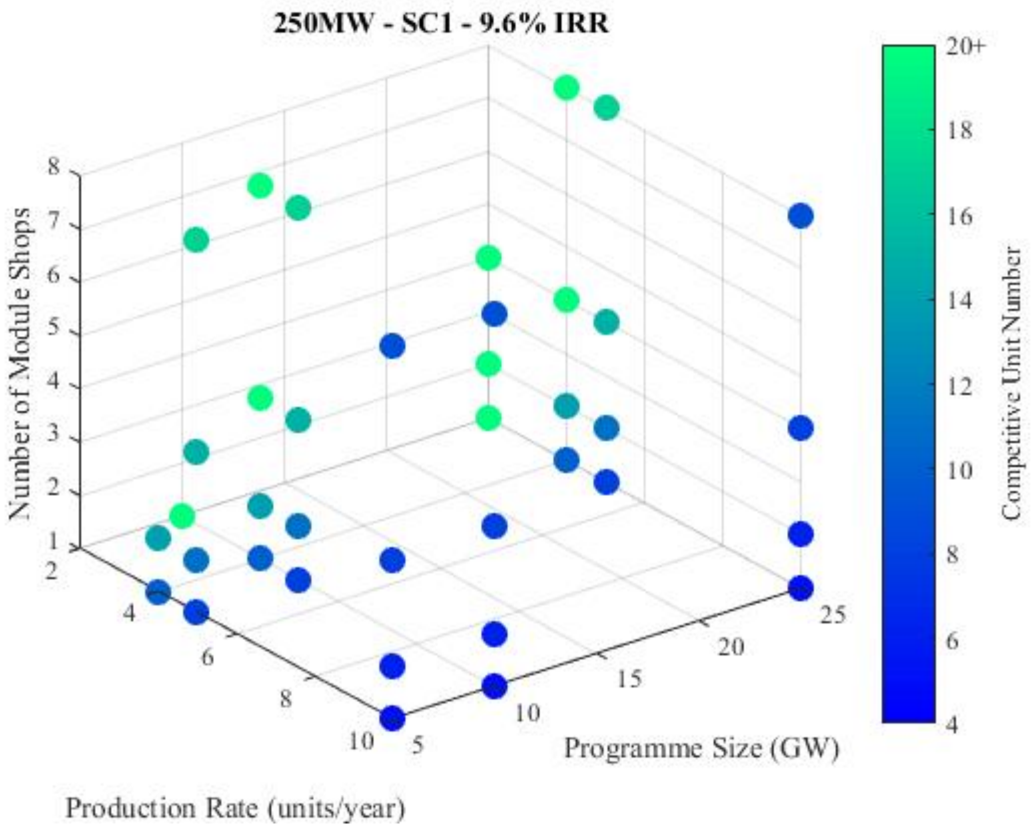

Figure 32: Parity unit plot for 250MW SMR, SC1, 9.6% IRR

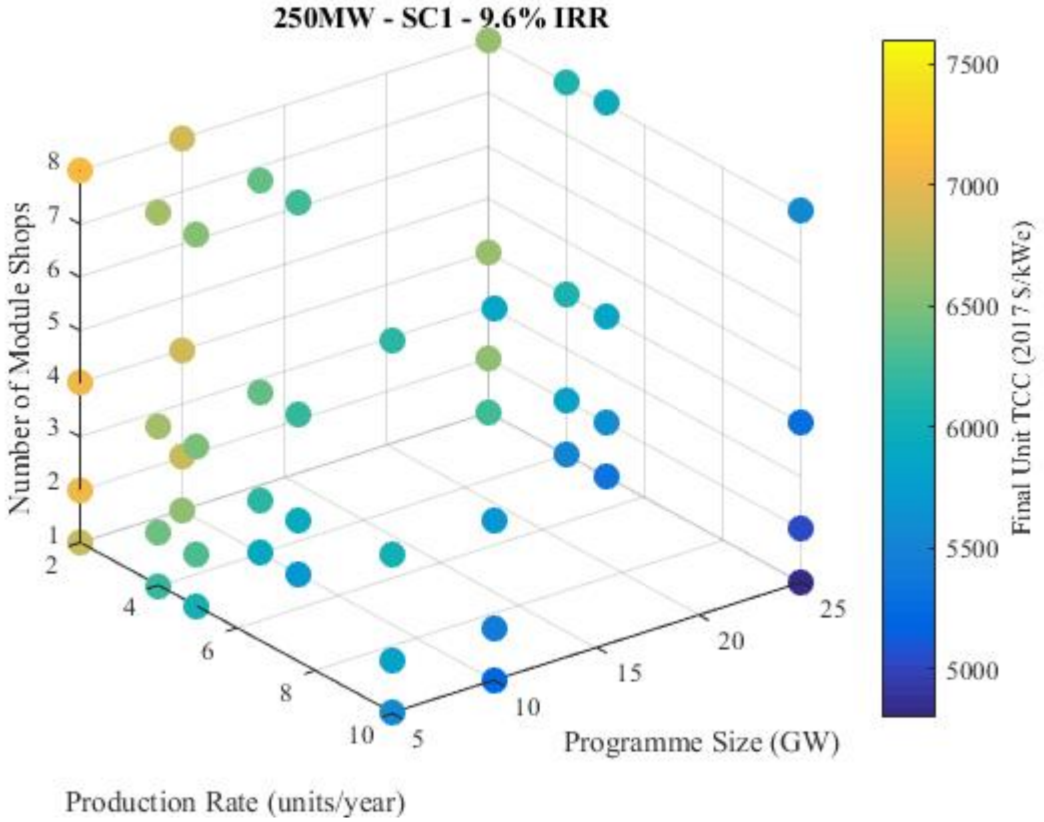

Figure 33: Final unit TCC plot for 250MW SMR, SC1, 9.6% IRR

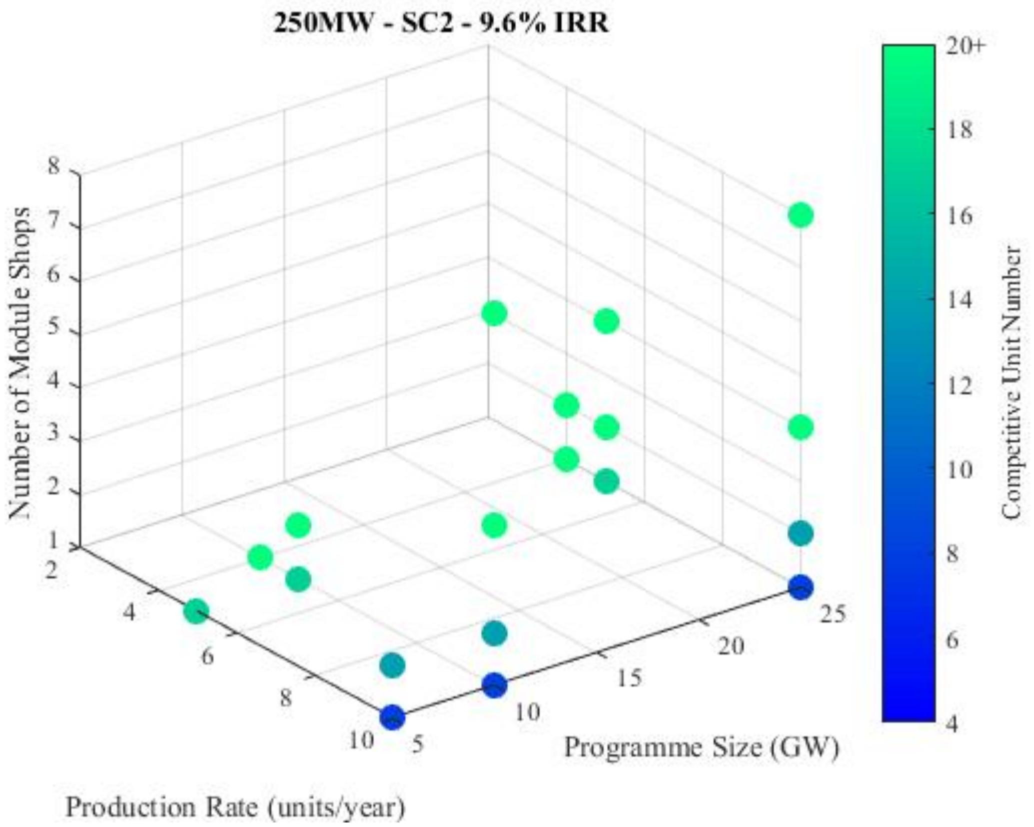

Figure 34: Parity unit plot for 250MW SMR, SC2, 9.6% IRR

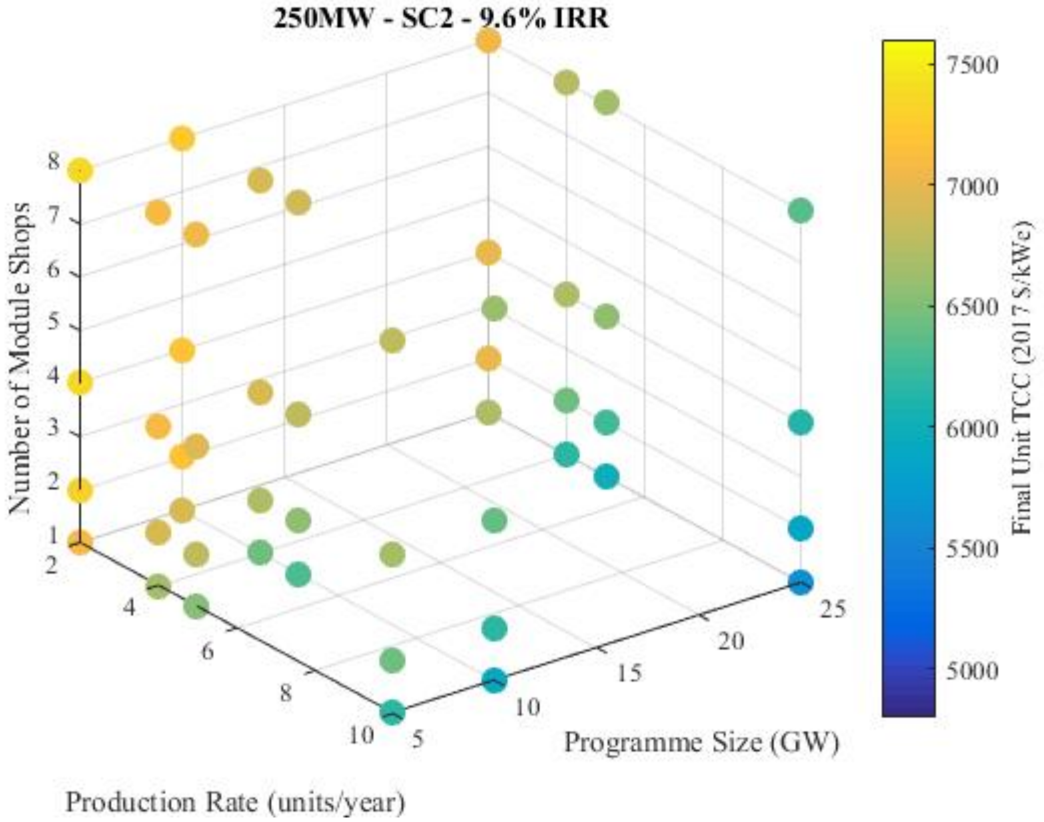

Figure 35: Final unit TCC plot for 250MW SMR, SC2, 9.6% IRR

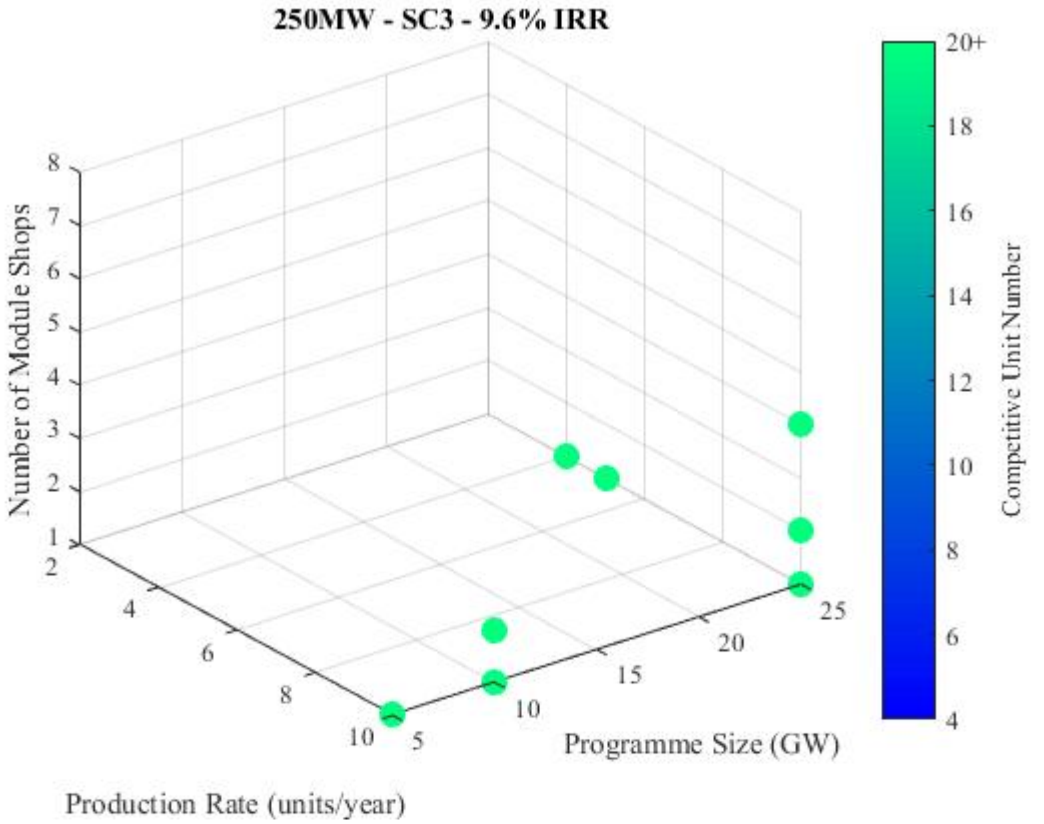

Figure 36: Parity unit plot for 250MW SMR, SC3, 9.6% IRR

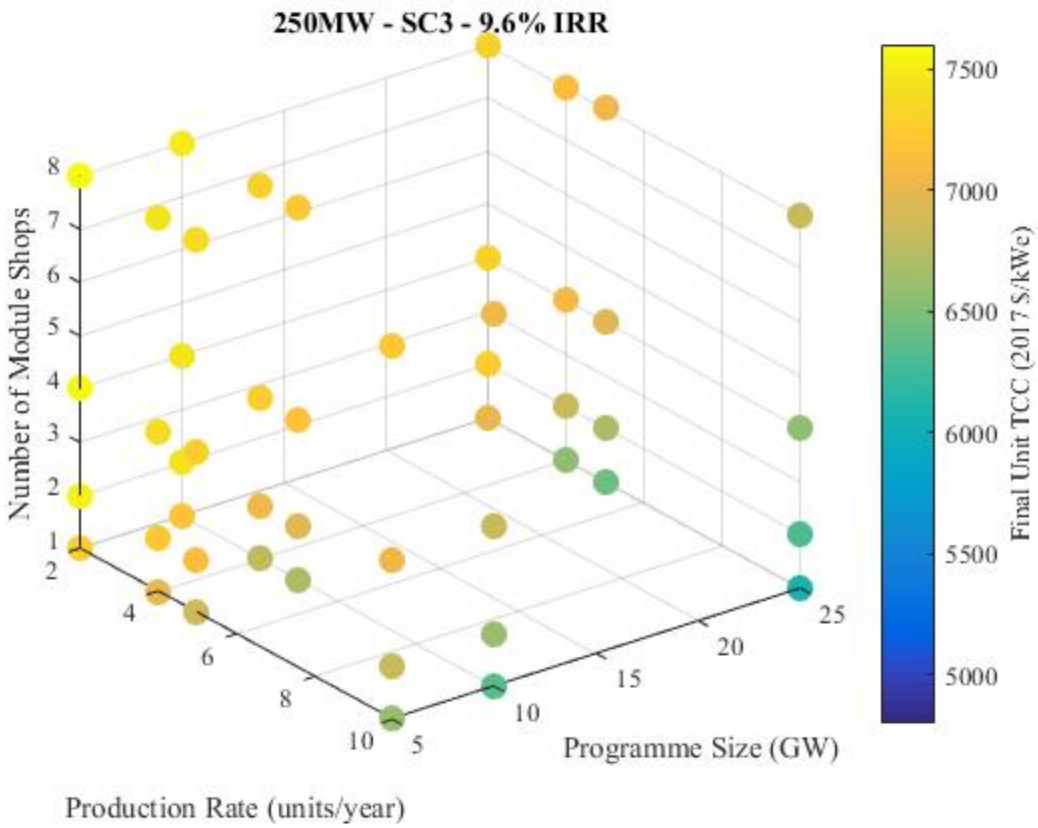

Figure 37: Final unit TCC plot for 250MW SMR, SC3, 9.6% IRR

4.3.3. Single suppliers and enterprise partners

An important lesson from the experience of other industries is the importance of the relationships between vendors and their single-source suppliers. Configurations SC4 and SC5 show the effect of outsourcing the module manufacturing to a single supplier, using traditional contracting arrangements. The increased interface costs and value capture by the supplier cause a discernible reduction in learning, as shown in Figure 38. For both the Design & Buy and Design & Make Vendors, the final unit TCC is increased by nearly 4% due to this procurement variation. However, if all the traditional single source suppliers are replaced with enterprise partners as in SC6, the resultant increase in learning makes such a market-based supply chain competitive with the fully integrated vendor case.

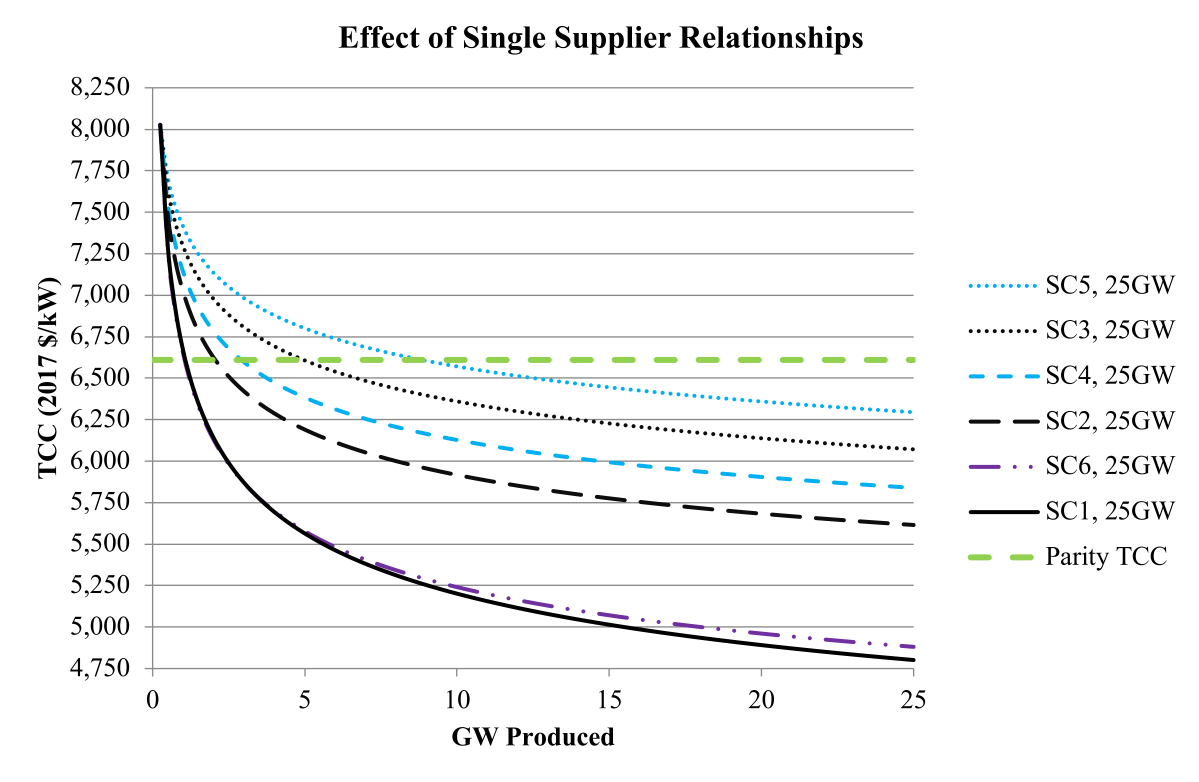

Figure 38: Single supplier relationship effect on learning

4.3.4. Reduced competition

In the case of components for which multiple suppliers have been chosen, the benchmark configurations assume that 4 suppliers are used, with production volume and rate distributed evenly across them. SC7 and SC8 consider the effect of consolidating this supply base to just 2 suppliers for each, in pursuit of a balance of benefits between production concentration and competition. Figure 39 shows that this configuration variation actually has a minimal impact on learning cost reduction. This can be explained by the fact that the total value of the components assigned to multiple suppliers is already a small share to begin with; the factory and module shop costs are instead dominated by single source components.

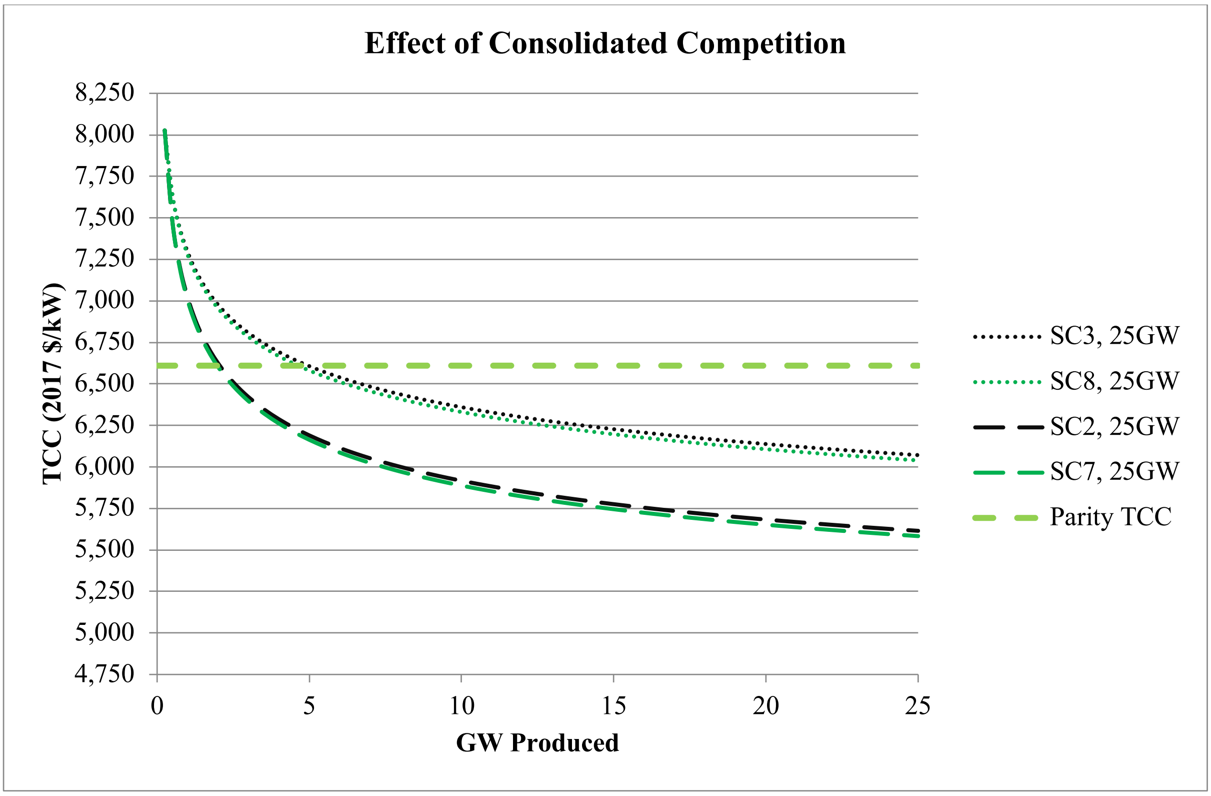

Figure 39: Consolidated competition effect on learning

4.3.5. Reactor power and interest rate

Alongside the supply chain configuration parameters, the effect of reactor power with variants of 100 and 500 MW and interest rates over the range 3-10% were also analysed. Variations in the latter have a predictable and consistent influence: a higher interest rate raises the cost (TCC) of all production units. However, variations in reactor power put competing pressures on cost. When reactor power is increased, economies of scale reduce the capital costs. At the same time the scope for modularisation, and in turn schedule reduction, is also reduced (as examined in detail by Lloyd (2019)). Furthermore the reduced number of units produced, and perhaps more importantly the lower production rate required to achieve a fixed programme capacity, both reduce learning rates. Increasing reactor size from 250 MW decreases the effect of all of these cost reduction measures.

The net result of these effects is shown in Figure 40, Figure 41, and Figure 42 for each of the benchmark supply chain configurations; each figure shows a quadratic polynomial surface fitted to the 9 evaluated data points. With each supply chain configuration, the 250 MW SMR achieves lower final unit TCCs than both the 100 MW and 500 MW SMRs; for the former, this is because the scaling effect overwhelms the cost reduction efforts; for the latter, the benefits of scale are undone by the reduced learning potential. However, for SC2 and SC3 the balance of these effects across the reactor power range is different; with these configurations achieving less learning cost reduction, economies of scale becomes more important. Consequently the cost advantage of the 250 MW unit size over 100 MW is increased, while that over the 500 MW is decreased. At the same time, variations in interest rate have a greater effect for larger units, due to their longer build schedules.

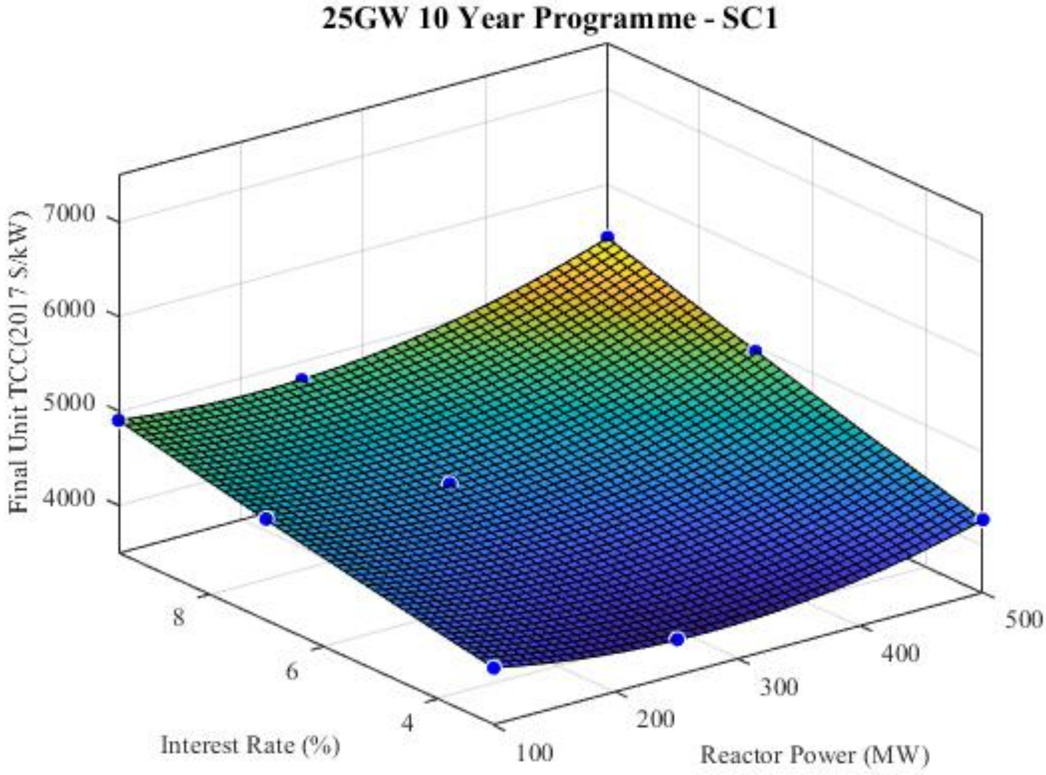

Figure 40: Effect of interest rate and reactor size variations (SC1, 25GW 10 year programme)

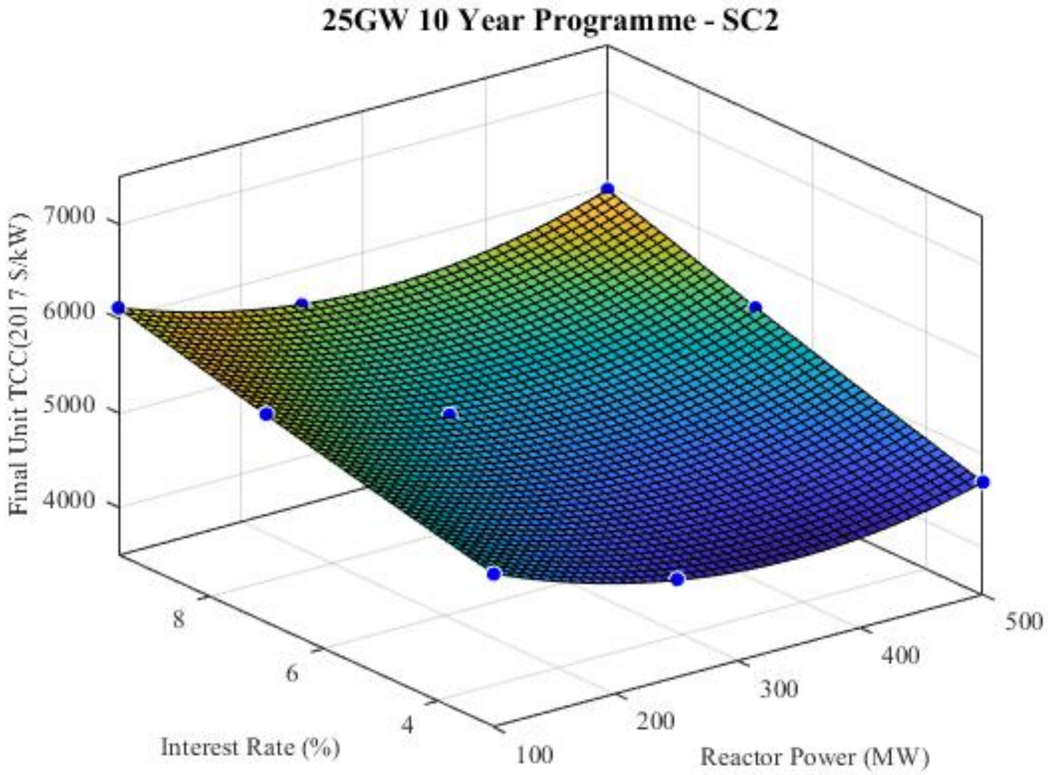

Figure 41: Effect of interest rate and reactor size variations (SC2, 25GW 10 year programme)

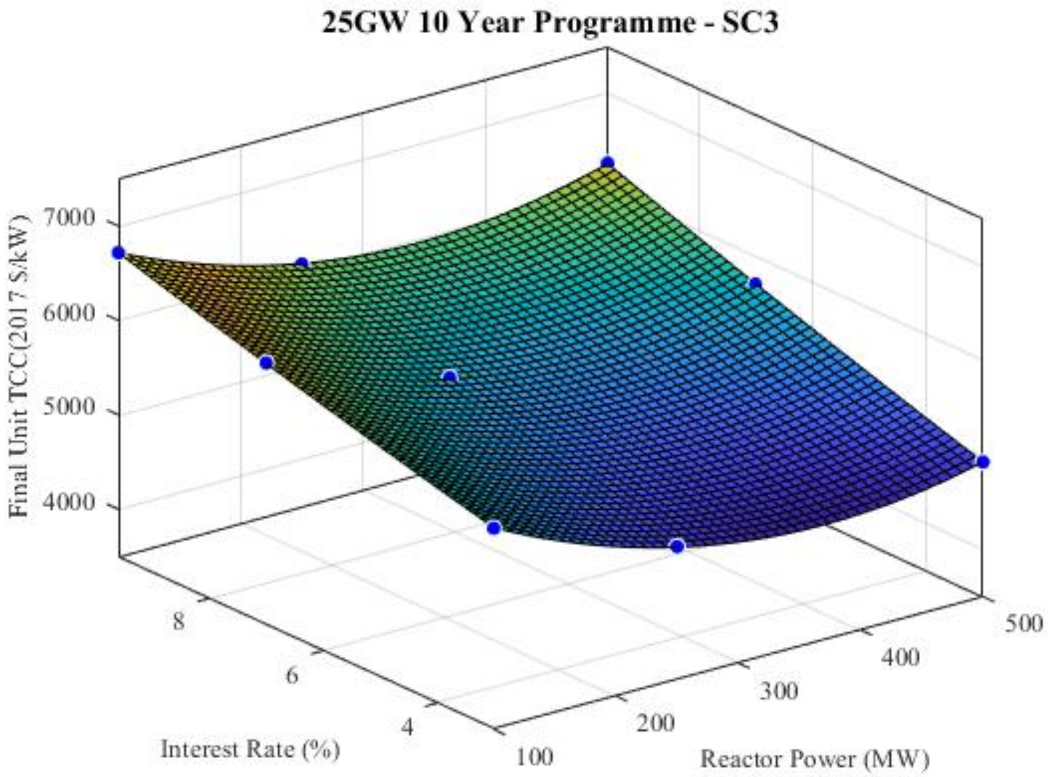

Figure 42: Effect of interest rate and reactor size variations (SC3, 25GW 10 year programme)

4.4. **Summary of performance**

Table 25 summarises the performance of the 8 supply chain configurations. It makes clear that in order to achieve competitiveness against large nuclear power, an SMR programme must produce at least 10 GW. Moreover, with the best performing configuration and programme conditions combinations highlighted in green, the importance of supplier relationships is emphasised. For markets where a fully integrated SMR vendor would not be possible, strategic partnerships between a vendor and key component suppliers can make for a competitive supply chain; such a collaborative enterprise could achieve sufficient innovation and keep interface costs down in order to achieve high learning cost reduction. Both a collaborative enterprise and an integrated vendor can achieve LCOE parity with large nuclear after ~1.25 GW (equivalent to one large reactor), and after a 10 year 25 GW production run, bring Total Capital Cost below $5,000/kW. Moreover, with a high learning supply chain configuration, a SMR size in the region of 250 MW is best; this strikes the balance between economies of scale and scope for modularisation, which enables learning.

Configuration	10 Year Programme Size (GW)	Parity Unit	Final TCC ($/kW)
SC1	5	-	6,819
	10	10	5,906
	25	5	4,801
SC2	5	-	7,103
	10	23	6,437
	25	8	5,615
SC3	5	-	7,323
	10	-	6,802
	25	20	6,071
SC4	5	-	7,199
	10	38	6,603
	25	12	5,839
SC5	5	-	7,419
	10	-	6,968
	25	34	6,295
SC6	5	-	6,801
	10	9	5,913
	25	5	4,881
SC7	5	-	7,100
	10	22	6,410
	25	8	5,583
SC8	5	-	7,320
	10	-	6,775
	25	18	6,039

Table 25: Summary of supply chain configuration performance

5. Global Programme Analysis

Having established that a programme size of 10 GW over 10 years is required to make SMRs cost competitive with current large nuclear power, consideration must be given to whether such demand is likely to exist, and how practical supply chain design might constrain access to it. The specific factors to be investigated can be grouped into two categories:

1. Country conditions;
2. Logistics and localisation.

While the preceding analysis has assumed competitive markets based on the scale and the economics of the United States and similar Western states, other less developed countries will offer different market conditions. Because of the large labour content of nuclear construction the variations in labour rates will have a significant bearing on construction costs. Also, differences in the cost of capital, due to varying extents of government support or participation, will also play a role.

In terms of logistics and localisation, not only could physical transport constraints limit global supply, but the need to adopt local supply, local design and local safety standards in exchange for market access will likely also need to be considered.

The analysis in this chapter has the following structure: firstly, credible scenarios for aggregate global SMR demand are defined, which are then used to determine how many global SMR programmes, or supply chains could be supported. The aforementioned constraints are then factored in to define segmented market scenarios, which are then assessed for their potential to deliver cost competitive SMRs.

5.1. Aggregate Global Demand Scenarios

In this study, it is assumed that the key differentiator between SMRs and conventional large LWRs is their economics. Consequently, while other studies have used bottom-up analysis of the total available market and the economics of nuclear versus other sources of electricity to arrive at specific market sizes for SMRs, in this analysis the demand for SMRs is based on that of conventional nuclear power. Moreover, while similar market studies can be found in the literature for nuclear power more broadly, in this study the view is taken that the overriding driver behind demand for nuclear power is policy: the deployment of nuclear power is particularly sensitive to political and public support or opposition.

Consequently, the demand projections adopted in this study are taken from the World Energy Outlook 2015 produced by the International Energy Agency (2015). The specific data used is based on the report's central scenario, the New Policies Scenario, which reflects energy market 'policies and implementing measures…adopted as of mid-2015…together with relevant declared policy intentions' (International Energy Agency, 2015, p. 31). It provides global gross electricity generating capacity additions, segmented by region and certain states, for the periods 2015 – 2025 and 2026 – 2040; the values for the latter period are used. To provide a range of possible aggregate demand, the WEO 2015 data is taken as a conservative estimate, and paired with the ambitious Harmony goal promoted by the World Nuclear Association (2018). This sets the target for nuclear power to deliver 25% of global electricity by 2050, and projects that this would require a build rate of 33GW/year of installed capacity in the period 2026-2050. The two aggregate projections are married by converting them both to 10 year demand for capacity addition. To arrive at SMR specific demand values, these nuclear demand projections are overlaid with low, medium, and high market share projections for SMRs. The resulting six aggregate SMR demand scenarios are shown in Table 26.

		10 Year Global Nuclear New Build (2020s - 2030s)	
		Low Demand (145 GW) IEA WEO 2015	**High Demand (330 GW)** WNA Harmony Goal
SMR Market Share	**Low (20%)**	29 GW	66 GW
	Medium (50%)	72.5 GW	165 GW
	High (80%)	116 GW	264 GW

Table 26: Aggregate global SMR demand scenarios

5.1.1. LCOE benchmark

Construction and operating costs for nuclear power plants unsurprisingly vary globally, which gives a wide range of resultant LCOE values. Therefore a competitive LCOE band was identified in lieu of a single benchmark figure as used in the single programme analysis. Table 27 shows the reference LCOEs used in the IEA's development of their global capacity addition estimates (International Energy Agency, 2015). Based on the accompanying statistics, the competitive LCOE band was set as $80/MWh - $100/MWh (assuming a 7% interest rate). The disparity in global LCOEs for nuclear can be attributed both to variations in local labour costs and different programme conditions: China in particular has benefited from recent build experience, enabling the supply chain, constructors, and programme managers to apply learning to bring down cost; Western countries on the other hand has had little new build plants, with a lack of standardisation and regulatory intervention driving up cost (Energy Technologies Institute, 2018, p. 21).

Nuclear Plant Location	Nuclear Plant LCOE (2017 $/MWh)
Belgium	88.76
Finland	81.87
France	87.14
Hungary	94.84
Japan	92.34
Korea	42.62
Slovak Republic	88.52
UK	106.24
USA	81.94
China (Plant 1)	50.20
China (Plant 2)	39.26
Mean	**77.61**
Standard Deviation	**22.70**

Table 27: IEA reference nuclear LCOE values, inflated to 2017 dollars (International Energy Agency, 2015, pp. 48-49)

5.1.2. SMR programme performance

Figure 43 shows the cost reduction performance of SMR programmes against the largest and smallest aggregate demand scenarios given in Table 26. A Design & Make Vendor

(SC2) was assumed, being the median learning performer of the three baseline configurations, and a 7% interest rate was applied. The potential for multiple SMR vendors was considered, with the results for a maximum of 8 vendors shown.

In the extremely optimistic scenario of a high demand for nuclear power, in line with the Harmony goal, and a dominating preference for SMRs over large reactors, SMRs would quickly become competitive power generators. In the extreme case of one vendor and supply chain delivering against all global demand, the SMRs produced could compete with the cheapest large reactors; this is assuming US-based costs in the SMR programme, which have to compete with cheaper labour abroad. Perhaps more importantly however, in the extreme high demand scenario, the volume could be split amongst up to 8 vendors, and significant cost reduction would still be realised, bringing the SMR LCOE to the bottom of the benchmark range. On the other hand, in the extreme low demand scenario, dividing the volume between 8 vendors dilutes the potential for learning, such that little cost reduction is realised. However if production is concentrated in one vendor, sufficient volume would be produced to bring the SMR LCOE down again to the bottom of the benchmark range.

Overall when considered in aggregate, one can conclude that there will be sufficient global demand to support multiple competitive SMR programmes between the 2020s and 2030s. However, if SMRs are to deliver significant cost improvement over conventional nuclear power plants, and thus compete with other technologies, except in the most optimistic scenarios production should be consolidated amongst a small pool of vendors.

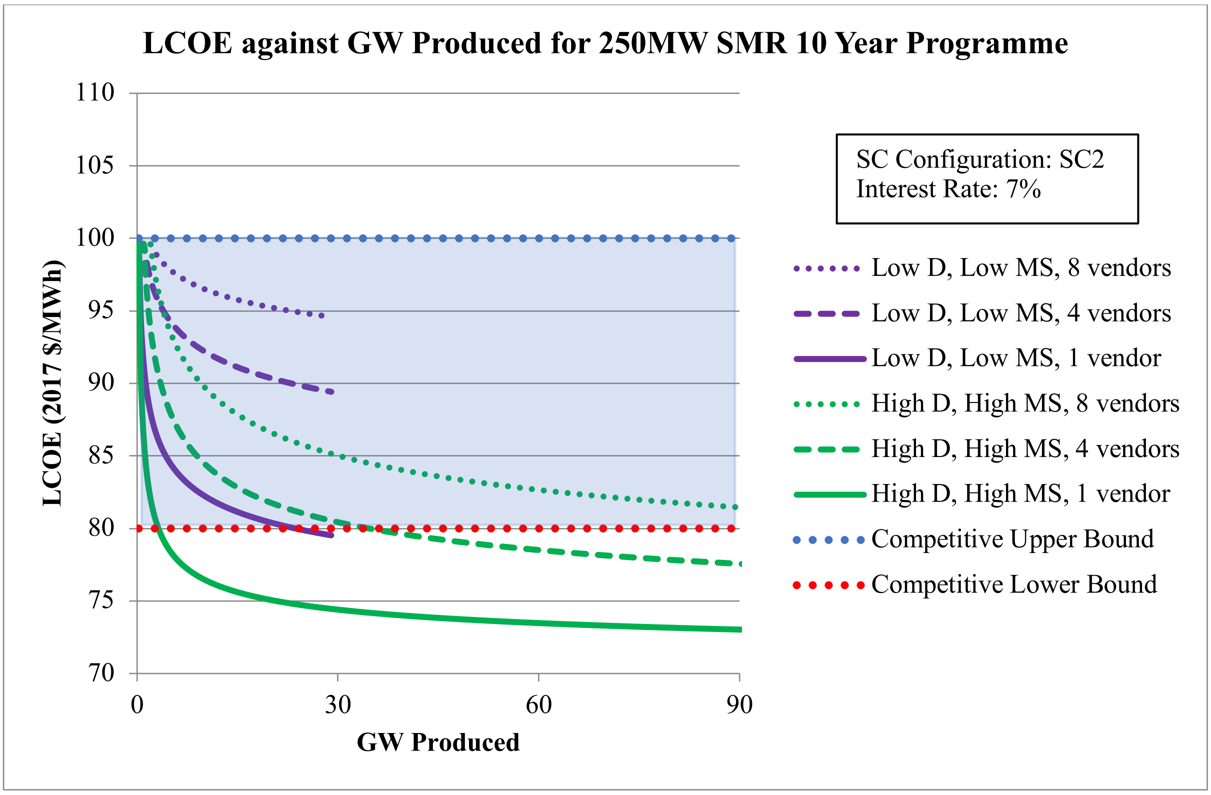

Figure 43: Bounding cases of 250MW SMR programme performance against aggregate global demand

5.1.3. Role of reactor power

As previously discussed, variations in reactor power change the balance between scaling and the cost reduction methods applied to SMRs. Figure 44 and Figure 45 show the same bounding cases of aggregate demand for 500 MW and 100 MW SMR programmes respectively.

These results indicate that the scaling effect for 100 MW plants is such that they would struggle to be cost competitive even with in the extremely high volume scenarios. Moreover, the results suggest that while having a cost advantage in the short run, with a modest volume the 500 MW plants are only slightly more competitive than 250 MW plants in the long-run, but only for the case of a single reactor vendor supplying the whole (260 GW) market. It should be highlighted that these results are for a 7% interest rate and a Design & Make Vendor; both higher interest rates and a supply chain configuration delivering better learning performance both tilt the balance more in favour of the 250 MW plant.

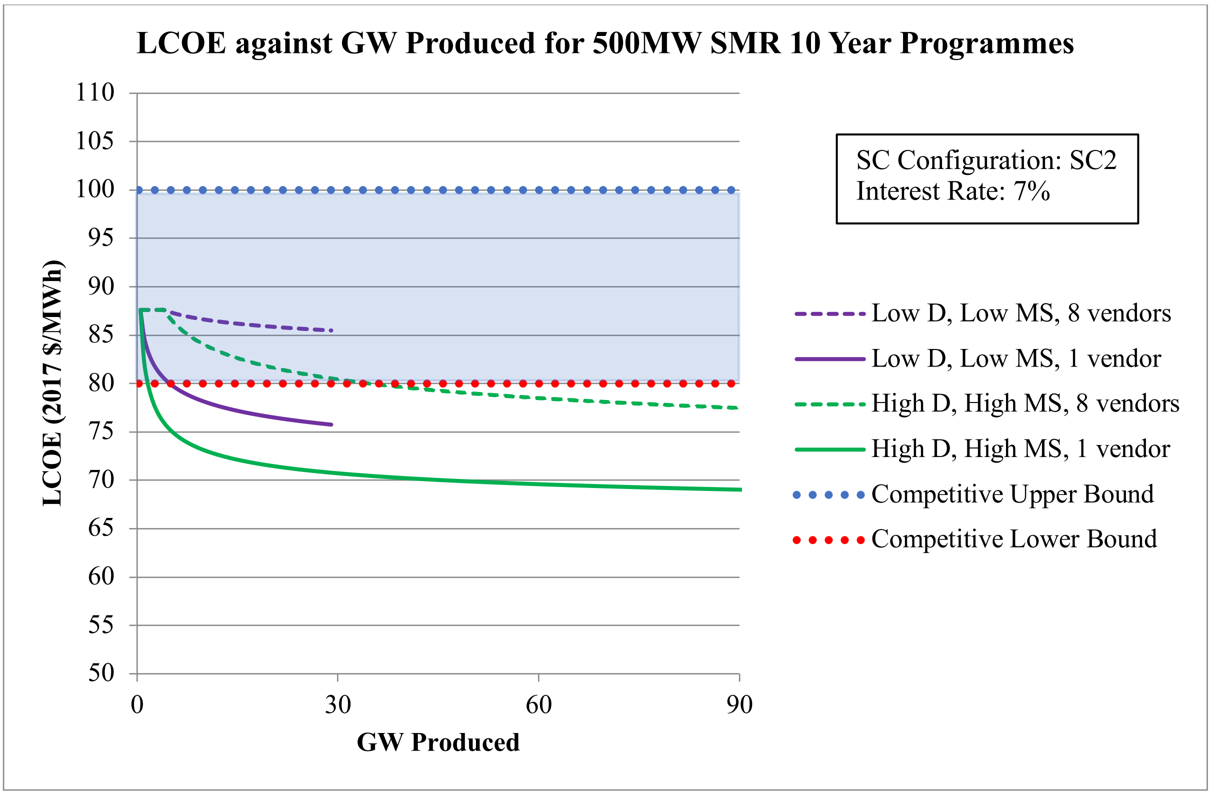

Figure 44: Bounding cases of 500MW SMR programme performance against aggregate global demand

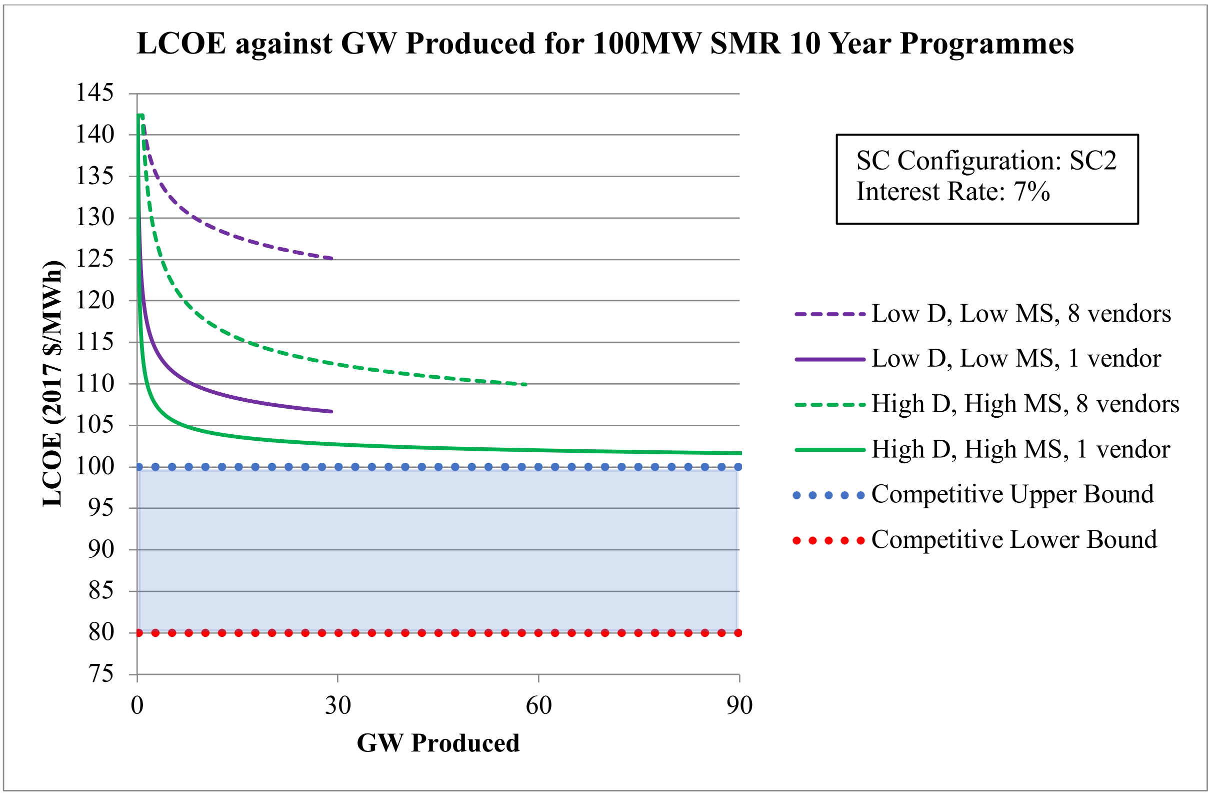

Figure 45: Bounding cases of 100MW SMR programme performance against aggregate global demand

5.2. **Segmented Market Scenarios**

While the analysis in the preceding section indicates that sufficient global demand exists to support multiple SMR programmes, considering this demand in aggregate is misleading. The ability of a single vendor and supply chain to deliver SMRs to the whole global market is likely to be constrained by:

- Market access – given the geopolitical nature of nuclear technology, certain national markets may be closed completely to foreign vendors, or to certain nationalities based on strategic partnering and rivalry;
- Technical and safety standards – a lack of regulatory harmonisation between markets creates barriers to entry;
- Localisation – often related to market access, the desire for local economic benefit from the significant investment required for a nuclear power plant leads to demands for local component supply;
- Logistics – physical transport constraints can similarly necessitate localisation of manufacturing.

Harmonisation of technical and safety standards can be singled out as potential barriers to both standardisation and production learning. Current methods in the nuclear industry employ technical standards which vary from country to country. For example a reactor design of US origin would have its component and construction drawings in US imperial units, whereas UK construction uses SI metric units. Therefore all such drawings would need to be converted.

Safety regulators around the world have regulatory systems that operate to the same IAEA safety principles. However, the way in which these operate are different, reflecting different legal histories and industry experience. The clearest example of this difference is between the US and UK regulatory approaches: the former's Nuclear Regulatory Commission employs prescriptive technical standards, while the latter's Office for Nuclear Regulation sets overall safety goals. While these two systems have the same purpose and principles as their basis, the different processes lead to different requirements and potentially different designs.

Unless there is substantial progress in harmonisation of both technical standards and safety regulation, if not across the whole world then at least in key markets, the economic potential of SMRs will be impaired.

To generate segmented market scenarios, the following constraints are applied to the more conservative global demand estimates taken from the IEA's WEO 2015:

1. Due to the existing nuclear industries and size of their domestic demand, the US, China, and Russia are considered base markets that are closed to each other; if sufficient demand exists each will have their own SMR programme(s);
2. Based on past nuclear exports (World Nuclear Association, 2019), each of the base markets is assignment possible export markets, shown in Table 28;
3. As a logistics and localisation constraint, each major region must have a dedicated module manufacturing facility; the asterisks in Table 28 indicate markets requiring their own such facility.

Base Market	**Potential Export Markets**
US	Americas, Europe*
China	Asia, Europe*, Middle East*
Russia	Eastern Europe/Eurasia, Asia*, Middle East*

Table 28: Export market assignments

Table 29 shows the estimated SMR market sizes for each of the segmented markets. While each of the base markets has the potential to support a single programme, there is sufficient potential demand to incentivise export (~20 GW for the USA, ~39 GW for China, and ~27 GW for Russia). In order to adjust the SMR capital costs to evaluate SMR programmes in these different markets, the labour rate factors shown in Table 30 are applied. They are derived from the ratio of average salaries (Parent, 2008) for the manufacturing and construction industries. For broad regions, the countries in brackets are the source of the relevant salary data. This approach is similar to that employed by MIT (2018) and the ETI (2018) in their own analysis.

The final set of constraints applied to the different market scenarios relate to supply chain configuration and interest rates. Based on the differences in the existing nuclear industries in the different countries, for Chinese and Russian SMR programmes, Integrated Vendors are assumed (SC1); this reflects the existence of their state-owned reactor vendors. Similarly, as SMR vendors in these countries would likely have access to government finance, a 3% interest rate is assumed. For US SMR programmes, a Design & Make Vendor is assumed, due to the presence of multiple established reactor vendors; a 7% interest rate is employed to reflect the need for private finance, tempered with some assumed government support.

State	**10 Year Nuclear Capacity Additions (GW)** (International Energy Agency, 2015)	**Market Size (GW) (with 80% share)**
USA	16.7	13.3
China	39.3	31.5
Russia	14.7	11.7
Americas (w/o USA)	1.3	1.1
Asia (w/o China)	19.3	15.5
Eastern Europe/Eurasia (w/o Russia)	8.7	6.9
Europe	23.3	18.7
Middle East	6.0	4.8

Table 29: Segmented market sizes

State	Module Shop Labour (Manufacturing)	Site Labour (Construction)
US	1.00	1.00
China	0.05	0.04
Russia	0.10	0.20
Europe (France)	0.55	0.43
Asia (Philippines)	0.07	0.05
Middle East (Kuwait/Israel)	0.35	0.42
Eastern Europe/Eurasia (Romania)	0.08	0.07

Table 30: Labour rate factors

The net effect of these constraints is illustrated in Figure 46, which shows the progressive reduction in LCOE of SMRs produced in four independent programmes: domestic programmes in the US and China, and mutually exclusive export programmes in Europe by a single US and single Chinese vendor. The large differences in first unit costs between each vendor's domestic and export programmes reflects the significance of labour cost variations between the countries. Moreover, the difference between the two European programmes is largely attributable to the different costs of capital available to the two vendors; the vendor type and consequent learning rate differences are reflected in the minor gradient differences.

The independent treatment of these four programmes has two implications related to learning. Firstly, the production volumes of factory made components would in reality be consolidated, either in part or completely; the former is more likely due to the aforementioned pressures for localisation of supply to acquire market access. Nevertheless, given that factory equipment makes the dominant contribution to learning cost reduction, any degree of consolidation would give significant benefit. Secondly, the possibility of technology and knowledge transfer means that export programmes need not start at the top of their learning curves. Technology transfer models, such as that employed by Haug (1992), suggest that a proportion of learning benefits can be credited to a new production facility; this reflects the benefits of replicating existing facility designs and tooling in new locations. In fact this process could be used to justify pursuing export in advance of a domestic programme; initial learning could be done with production in markets with cheaper labour, allowing the subsequent domestic programme to start some way down the learning curve.

Conversely, the model's assumptions regarding standardisation and modularisation are open to challenge when considering global demand. If export markets require design changes to reflect their particular technical standards or other regulatory requirements, costs will not only be incurred in making the changes themselves, but also in the effective loss of learning if manufacturing and build processes are affected. Similarly, the modularisation scheme investigated by Lloyd (2019), which is implied in the modularisation percentages in the cost model, is based on road transport envelopes; it is therefore assumed that modules can be easily transported from module facilities to plant sites, irrespective of where they are located. The same rationale is assumed for factory made components, meaning that transport costs are assumed to be negligible. However, if component and module transport is more constrained, not only would these costs need to be factored into supplier and module shop location selection, but also market access. Thus all the cost reduction principles pursued by SMRs – standardisation, modularisation, and learning – are relevant considerations when planning a global SMR production programme.

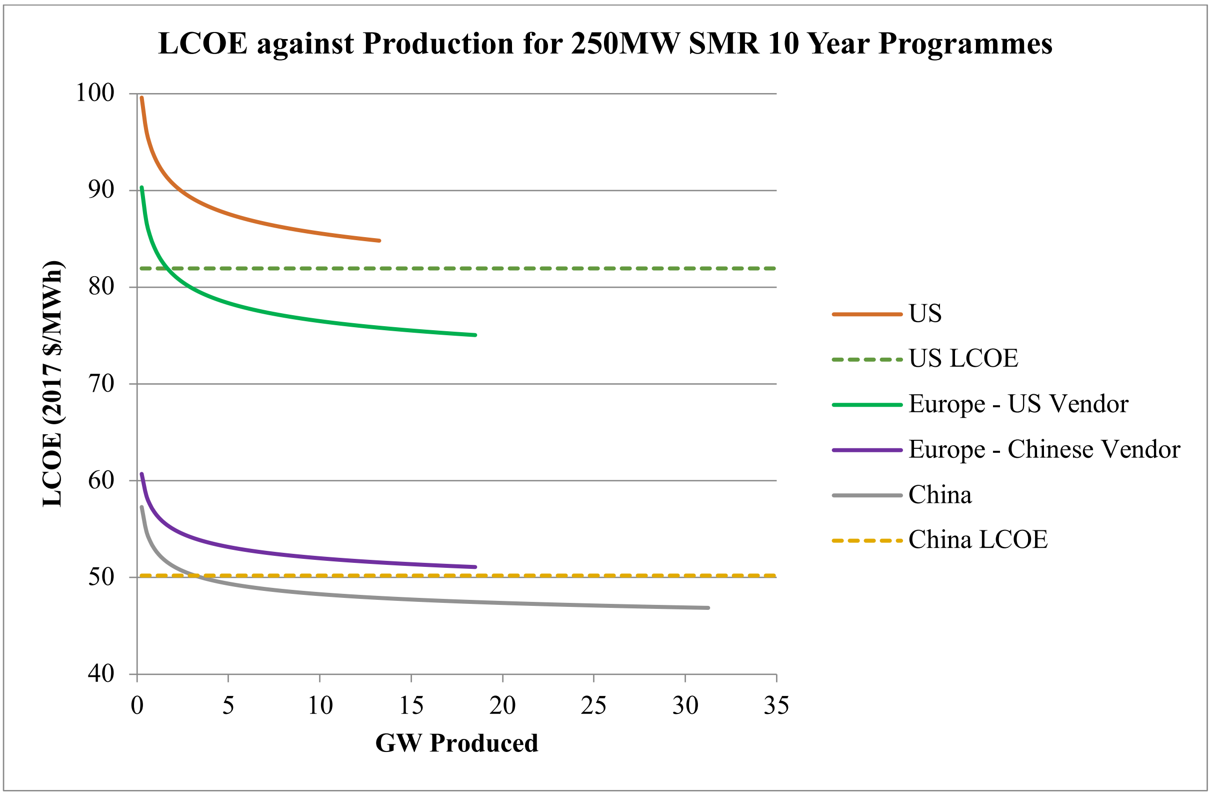

Figure 46: Comparison of US and China SMR programmes

5.3. **Key Findings**

Projections of aggregate global demand for nuclear power, based on current national policies, suggest that multiple SMR supply chains could be supported. If SMRs are only able to take a small share of the market, 1 or 2 SMR programmes could still bring costs down to a competitive level. However, if more ambitious nuclear capacity additions are pursued, multiple SMR supply chains could serve the expected demand. In reality though, nearly half of nuclear new build will be within the closed markets of the US, Russia, and China, where only domestic SMR programmes would have a presence.

Under the conservative demand estimates, each of these countries could support a single competitive SMR programme, with significant export opportunity available. Furthermore, variations in labour rates could make export programmes cheaper (particularly for a US vendor), such that experience could be gained to enable learning benefits before the start of a domestic programme. However, this is dependent on the harmonisation of technical standards and regulation such that standardised designs can be deployed globally, and development of easily transportable modules.

6. Programme Costs

The costs of individual SMR plants from the first-of–a-series to the nth production unit within a possible SMR production programme have been examined in detail. The costs of establishing such a programme and how they could be recovered must also be considered. These one-off costs incurred by the SMR vendor or consortium would have to be recovered over the course of the production programme. The vendor would therefore need to be confident that a sufficient volume of units would be produced, and an appropriate design fee recovered on each, to justify the upfront investment.

The analysis in this section takes the following steps: firstly, the structure of a possible project to develop an SMR production programme is described; secondly, credible costs are posited for such a project; thirdly, the aggregate investment costs and accrued interest at the start of production are compared with the net present value of design fees charged throughout the programme. This allows a determination to be made as to the required production volume and design fee to make a programme economically viable.

6.1. Development Project Structure

Both the project structure and associated costs for the development of a SMR programme are based on data presented in a discussion of nuclear technology development projects from MIT (2018). This report has as its focus an advanced reactor with new technology that has not been demonstrated or built at scale. It provides a structure for new reactor development and deployment and a transparent set of up-to-date costs. The use of this data for the somewhat different case of a light-water based SMR needs to be considered in this context; the reactor technology would not be new, but the design and production process would be.

As the report explains, the steps required to bring a new reactor to market include 'R&D, full detailed engineering design work, development of fuel and provisions for fuel disposition, construction and testing of a prototype, and licensing' (Massachusetts Institute of Technology, 2018, p. 106). Figure 47 shows a summary of such a development project for both a higher and lower maturity technology; the costs are based on detailed studies produced by the US Department of Energy and associated national laboratories (Massachusetts Institute of Technology, 2018, p. 107).

The three stages of technology development as described in the report are:

1. Early development – research and development, design development, and readying of the supply chain;
2. Performance demonstration – proving of the technology;
3. Commercial demonstration – proving the commercial viability.

One of the key assumptions bounding the scope of this thesis is that an SMR design would be based on light water reactor technology which can be considered highly mature technology, with an established fuel cycle and many thousands of reactor years of operational experience. Consequently, a SMR should not require a reactor performance demonstrator, such that a development project could proceed directly from the early development stage to a commercial demonstrator. This commercial demonstrator would fulfil the role of the LEAD plant as described by Rosner & Goldberg (2011), which 'likely would be custom-built, but based on the design that ultimately would be built in a factory' (Rosner & Goldberg, 2011, p. 17). This would facilitate the testing and refinement of the modules and on-site assembly process. A final step beyond the plan laid out in Figure 47 would be the construction of the module manufacturing facility, once confidence in the build process had been reached.

			Higher Maturity Technology	Lower Maturity Technology
Early Development	Years		3	8
	Expenses, $ million	R&D	50	300
		Design Development	100	200
		Supply Chain	100	200
Performance Demonstration	Years	Pre-build		2
		Build		7
		Operational Testing		5
	Plant	Capacity, MW_e		250
		Unit cost, $/kW		9,200
	Expenses, $ million	Design Completion		300
		Licensing		200
		Construction		2,300
		Operational Testing		400
Commercial Demonstration	Years	Pre-build	2	2
		Build	5	5
		Operational Testing	2	2
	Plant	Capacity, MW_e	250	250
		Unit cost, $/kW	6,900	7,100
	Expenses, $ million	Design Completion	100	100
		Licensing	200	100
		Construction	1,725	1,775
		Operational Testing	200	200
Total Expense of Development			**2,475**	**6,075**

[Republished with permission of MIT]

Figure 47: Development Project Summary (Massachusetts Institute of Technology, 2018, p. 107)

6.2. **Development Project Costs**

A summary of the development stages for an SMR programme and associated costs is shown in Table 31, and as is based on the higher maturity technology project described by MIT (2018). However, as discussed at length in the previous sections, the construction methodology for an SMR is intended to be significantly different from past practice. Moreover the desire to achieve standardisation, schedule reduction, and ultimately cost savings necessitates upfront design and development of the build process. Therefore the costs associated with the lower maturity technology in the MIT report were taken for R&D, design development, and the supply chain. The costs for design completion and licensing, as well as for the operational testing of the commercial demonstrator, were taken from the higher maturity technology plan. The aggregate $1 billion cost for developing and licensing the design seems reasonable; the same cost is cited for R&D and design of a HTGR reactor (Massachusetts Institute of Technology, 2018, p. 106), as well as for the detailed design and engineering for an LWR SMR (Rosner & Goldberg, 2011, p. 18).

The construction cost of the commercial demonstrator was determined by applying the same 50% increase to the first production unit OCC as done in the MIT report. For a 250MW SMR, the first unit specific OCC of $5,878/kW equates to approximately $1.47 billion; this gives an OCC for a commercial demonstrator of approximately $2.2 billion. The extra construction cost for the demonstrator ($735 million) reflects the need to refine the build process, and accounts for other first-of-a-kind costs. Finally, Rosner & Goldberg estimate that a module manufacturing facility would cost $300 million; as their model was based on a single module type being produced in this facility, this cost was increased to $400 million to account for the added complexity of manufacturing multiple module types.

Project Stage	Activity	Cost ($ million)	Time (years)
Develop and licence design	R&D	300	5
	Design Development	200	
	Supply Chain	200	
	Design Completion	100	
	Licensing	200	
Commercial Demonstrator	Construction	2,204	7
	Operational Testing	200	
Module Manufacturing Facility	Construction	400	2

Table 31: SMR Programme Development

6.3. **Programme Setup Cost Recovery**

While the total development cost for an SMR programme is approximately $3.8 billion, a significant proportion of this amount would already be recovered in the revenue from sales. The cost of the module manufacturing facility is already assumed to be amortised over the modules produced, and thus included in the module shop overhead costs (Economic Modeling Working Group, 2007, p. 111). The majority of the construction cost of the commercial demonstrator can be recovered from the revenues accrued from its electricity sales, just as for a production unit. One would expect a somewhat lower initial availability from this demonstration plant, reducing the capacity factor, which in turn would require a higher electricity price. However, if the additional first-of-a-kind construction costs (approximately $735 million) are separated out, the demonstrator's LCOE could be close to that of the first production unit and hence mostly covered by the revenue from electricity sales.

By removing the module facility cost, and only counting the first-of-a-kind share of the demonstrator construction cost, the programme setup costs are reduced to approximately $1.94 billion. Figure 48 shows the schedule for the development activities; it is assumed that the costs are spread uniformly across the relevant periods. If a 7% interest rate is assumed, the total setup costs accrued at the end of the development project are approximately $3.17 billion. This is the cost that must be recovered by the design fees.

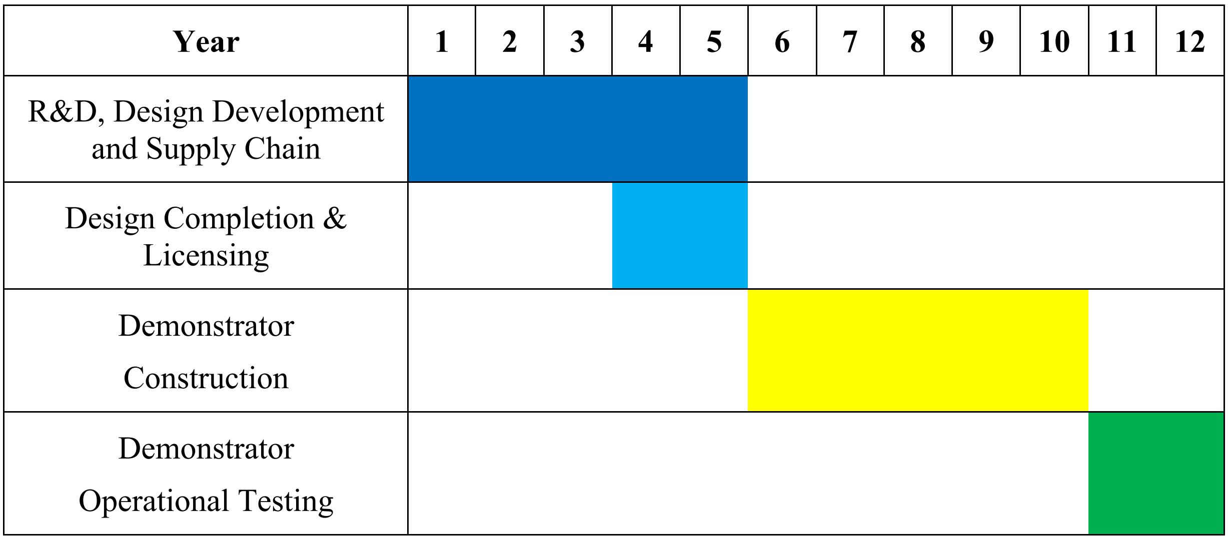

Figure 48: Programme Development Schedule

In the case of a 10GW, 10 year production programme, resulting in a production rate of 4 units per year, a design fee of approximately $113 million would be required. When discounting the annual cash flow of these design fees over the 10 year programme using a 7% discount rate, the net present value of the cash flows equals the $3.17 billion total setup costs. This design fee equates to approximately 7.7% of the OCC of the first production unit.

The effects of varying the production volume and interest rate on the required design fee are shown in Table 32; the percentage of the first SMR unit OCC that the design fees equate to are shown in brackets. These results show that a production volume of 10 GW (40 units) or more can bring the design fee down to a relatively small (5-10%) increase beyond the capital cost of the units themselves. Conversely, high interests and low production volumes results in higher design fees, reaching up to nearly 21% of OCC in the case of a 5 GW programme with an IRR of 9.6%.

Design Fee ($ million per unit)		**Interest Rate**		
		3%	**7%**	**9.6%**
10 Year Programme Volume	5 GW	140 (9.5%)	226 (15.4%)	306 (20.8%)
	10 GW	70 (4.8%)	113 (7.7%)	153 (10.4%)
	20 GW	35 (2.4%)	56 (3.8%)	76 (5.2%)

Table 32: Design fee variation with production volume and interest rate

While the lower interest rates are indicative of public financing rather than private costs of capital, there are a number of specific steps which state actors could take to reduce the hurdle posed by these programme setup costs, such as:

- providing grants or loans for early development;
- match funding private investor contributions;
- providing a physical site for a commercial demonstrator.

In summary, the total projected development costs of approximately \$3.8bn do not significantly change the economics of SMR production units, if amortized over a sufficient programme volume (10 GW+). However, the total is large enough compared to the balance sheets of potential private vendors that it could be a barrier to investment; there is consequently a need for a large and relatively certain launch market and/or some level of government support. In countries where the initial developments costs are funded or co-funded by the government, vendors will have a significant advantage in being able to launch a programme; not because of inherent lower costs, but because the risk associated with such a large investment will be reduced.

7. Uncertainties

While the results in the preceding sections are based on reasoned assumptions built into the cost model, significant uncertainty is present in the parameter values; parameters that in some way reflect human performance are particularly uncertain. As it would be impractical to consider the uncertainty in every individual parameter in the cost model, the analysis in this section focusses on the key areas of cost reduction: standardisation, modularisation, schedule reduction, and learning. The effect of uncertainty in these areas was assessed by employing a Monte Carlo method.

7.1. **Selected Parameters**

Table 33 presents the parameters selected for uncertainty analysis, with their fixed values used in the preceding sections, and the probability distribution applied in the following uncertainty analysis. The uncertainty in the standardisation factor reflects the variability in possible SMR plant site conditions, which has a bearing on the amount of the plant design that has to be customised. The uncertainties in the modularisation cost factors and learning rates are due to human performance: directly with regards to labour productivity and learning, and indirectly with regards to material cost changes, as this reflects the performance of module and build process designers. Similarly, the build time is uncertain due to its dependence on the performance of the on-site module assemblers, as well as again on the build process designers.

In the absence of uncertainty data, symmetric triangular distributions of the form shown in Figure 49 were applied. This allowed probability distributions to be formed by using the previously assumed value as the most likely value, and making a judgement about either a probable lower or upper limiting value. The resulting triangular distribution factors are shown in Table 34 and Table 35.

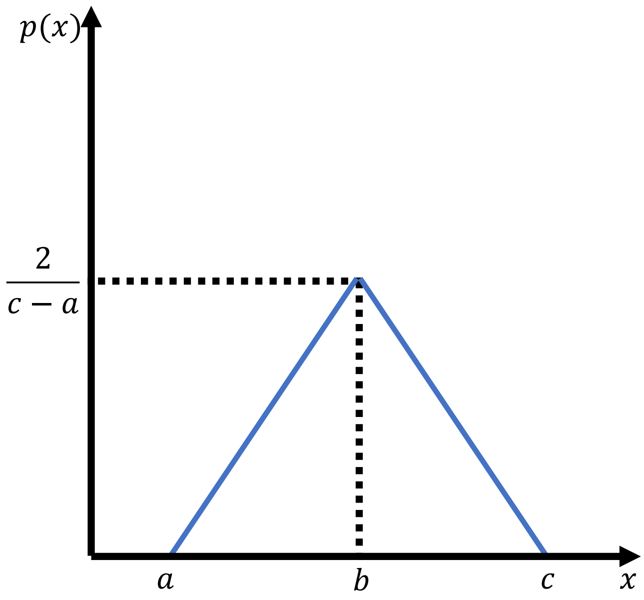

Figure 49: Triangular Distribution

Cost Reduction Method	Parameter	Fixed Value in the Cost Model	Distribution Applied
Scaling	Scaling Factors	*See Table 35*	Triangular
Standardisation	Standardisation Factor	0.2	Triangular
Modularisation	Labour Productivity Factor	0.3	Triangular
	Structural Material Increase Factor	1.05	Triangular
	Non-Structural Material Decrease Factor	0.9	Triangular
Schedule Reduction	Build Time	51 months	Triangular
Learning	Learning Rate	*Based on production rate and supplier type*	Normal

Table 33: Parameters selected for uncertainty analysis

Parameter	Lower Limit, a	Most Likely, b	Upper Limit, c
Standardisation Factor	0.1	0.2	0.3
Labour Productivity Factor	0.2	0.3	0.4
Structural Material Increase Factor	1	1.05	1.1
Non-Structural Material Decrease Factor	0.8	0.9	1
Build Time (months)	42	51	60

Table 34: Triangular distribution factors

Account	Lower Limit, a	Most Likely, b	Upper Limit, c
Structures & Improvements	0.18	0.59	1.0
Reactor Plant Equipment	0.06	0.53	1.0
Turbine Plant Equipment	0.66	0.83	1.0
Electrical Plant Equipment	-0.02	0.49	1.0
Miscellaneous Plant Equipment	0.18	0.59	1.0
Main Condenser and Heat Rejection System	1.0	1.06	1.12
Construction Services	0.38	0.69	1.0
Engineering & Home Office Services	0.2	0.60	1.0
Field Supervision & Field Office Services	0.38	0.69	1.0

Table 35: Scaling factor triangular distribution factors

A limit of 90% of an SMR plant being standardised was judged appropriate, equating to a lower limit for the standardisation factor of 0.1. With regards to modularisation, an 80% cost reduction from increased labour productivity when moving from site to factory conditions was judged to be the maximum achievable. The lower limit of the structural material increase factor was set at 1, equating to no increase at all; the same rationale gave the upper limit of 1 for the non-structural material decrease factor. A lower limit on the build time of a 250 MW SMR was taken to be 3.5 years. Finally, the relevant upper/lower limit for the scaling factors was set to 1.0, meaning no scaling.

To consider the effect of uncertainty in the achievement of learning cost reduction, the cost modelling approach was altered. As before, a normal distribution of learning rates for each account was determined from the production rate. The deterministic learning rate determined as described in Section 2.6.6 was instead taken as the new mean of the normal distribution, with the same standard deviation. The effect of this was that the supplier type shifted the entire distribution by a multiple of the standard deviation, rather than selecting a single rate. This normal distribution served as the learning rate probability distribution. In each simulation, the learning rate was sampled separately for each factory and module shop account.

7.2. **Results**

The results presented in this section were generated by using the fixed parameter values shown in Table 36. A high interest rate, production volume and production rate were chosen as these conditions would be more sensitive to variations in the selected parameters. Similarly, the integrated vendor type was selected as it gave the greatest learning cost reduction in the deterministic analysis, and thus would be the most sensitive to variations in the learning rate.

Figure 52 through Figure 59 are histograms of the resultant output costs from the Monte Carlo simulations. For each of the input uncertainties, variations in the final SMR unit TCC and LCOE were measured, as well as the parity unit for learning uncertainty; the measured TCC values for schedule reduction are not shown, due to the spurious distribution arising from the phenomenon explained in Section 2.8.3. Each uncertainty was considered in isolation. However the modularisation uncertainty is the aggregate of the three relevant parameters. Similarly, the learning uncertainty is the aggregate of separate factory and module shop learning uncertainties in each account, and the scaling uncertainty the aggregate of uncertainties in each two digit account scaling factor.

Parameter	Value
Power	250MW
Interest Rate	9.6%
Programme Size	20GW
Production Rate	8 units per year
Number of Module Shops	1
SMR Vendor Type	Integrated (SC1)
Number of Simulations	10,000

Table 36: Uncertainty analysis fixed parameters

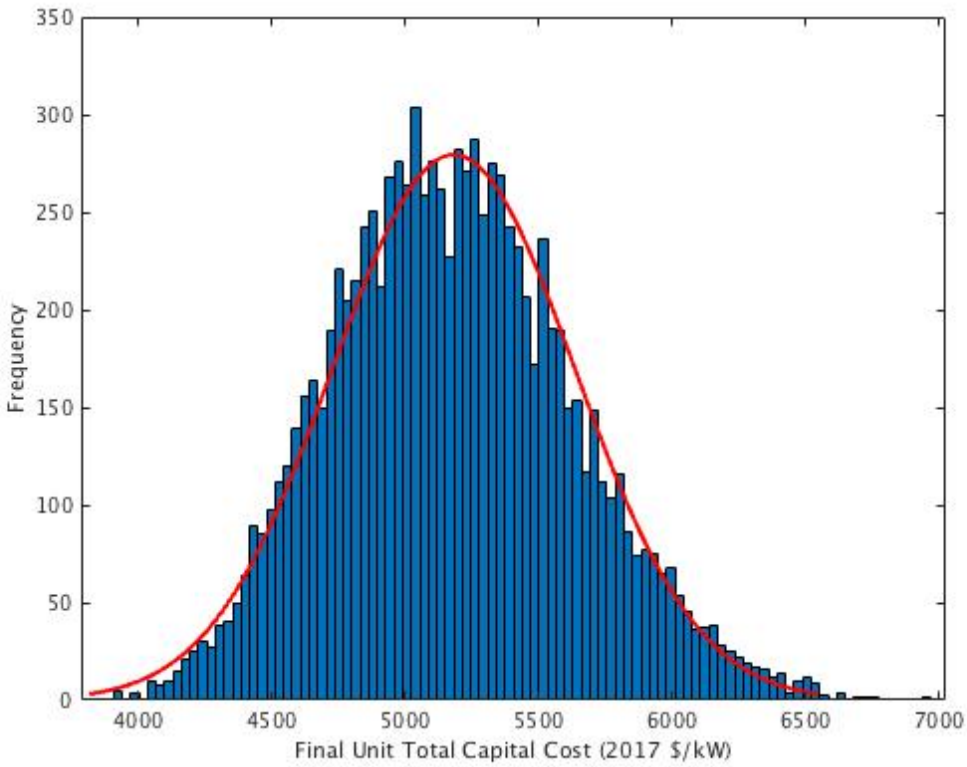

Figure 50: Final unit TCC distribution due to scaling uncertainty

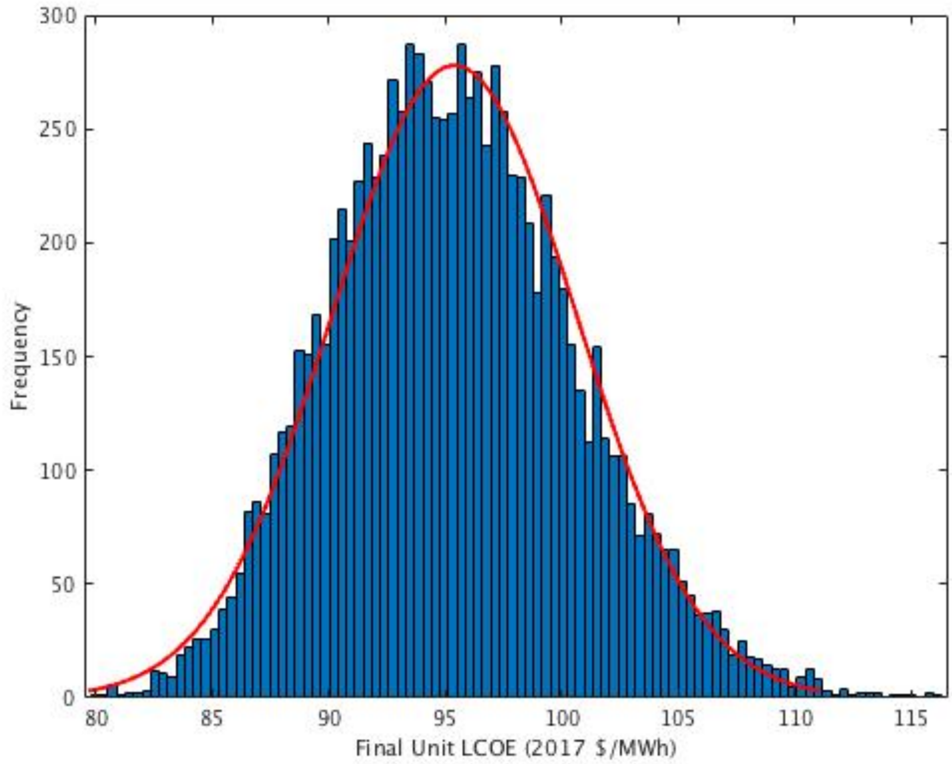

Figure 51: Final unit LCOE distribution due to scaling uncertainty

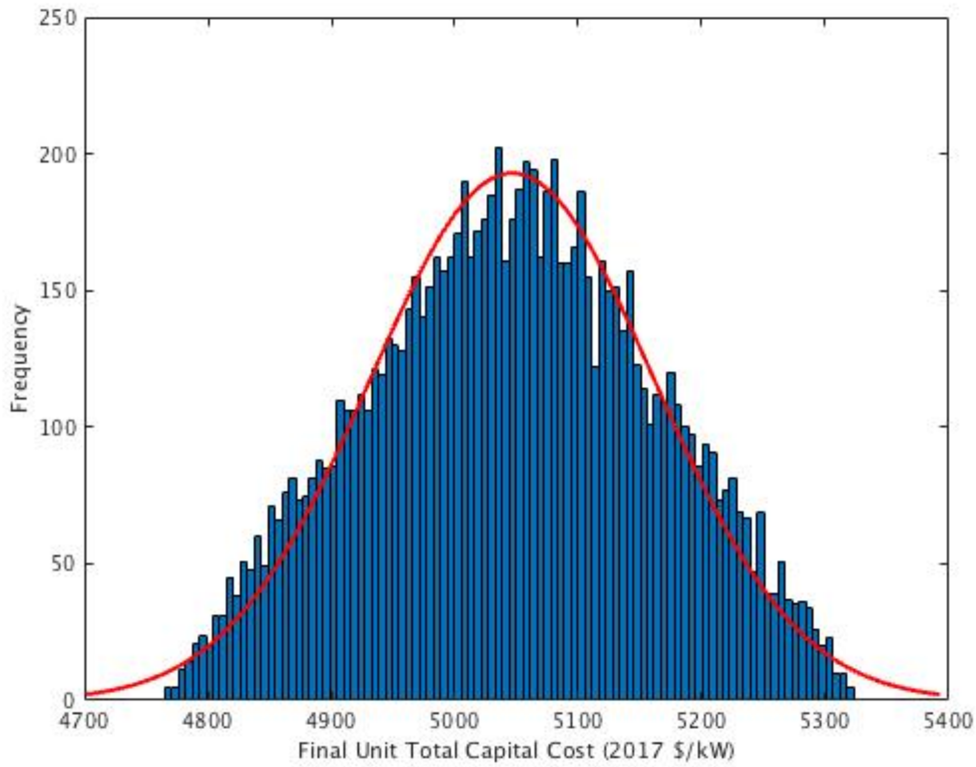

Figure 52: Final unit TCC distribution due to standardisation uncertainty

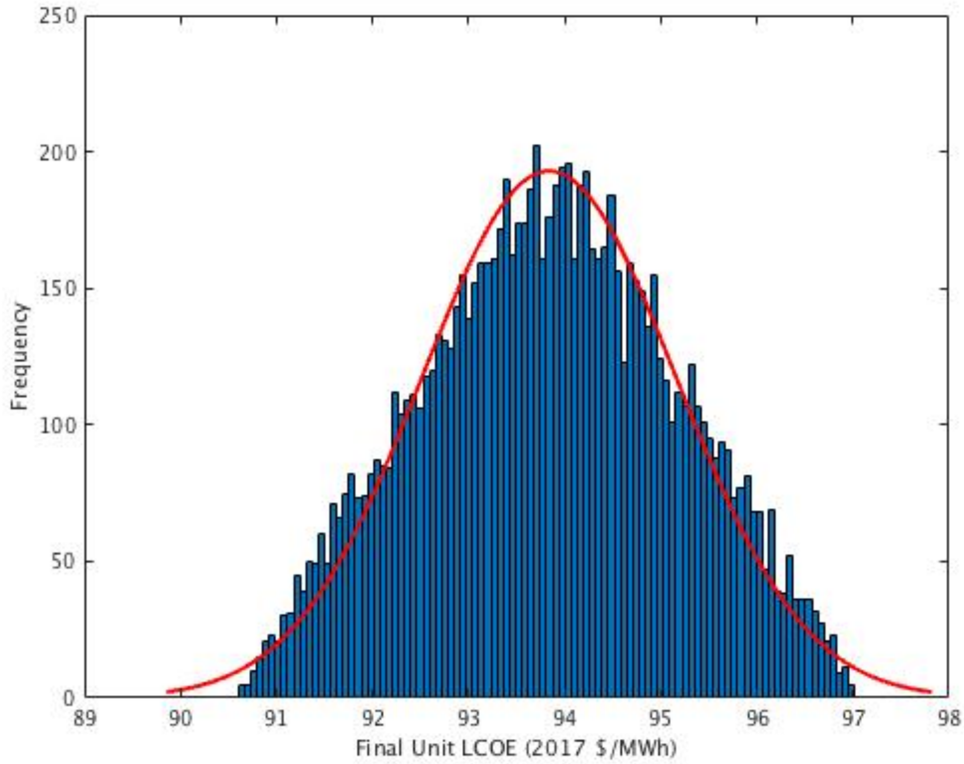

Figure 53: Final unit LCOE distribution due to standardisation uncertainty

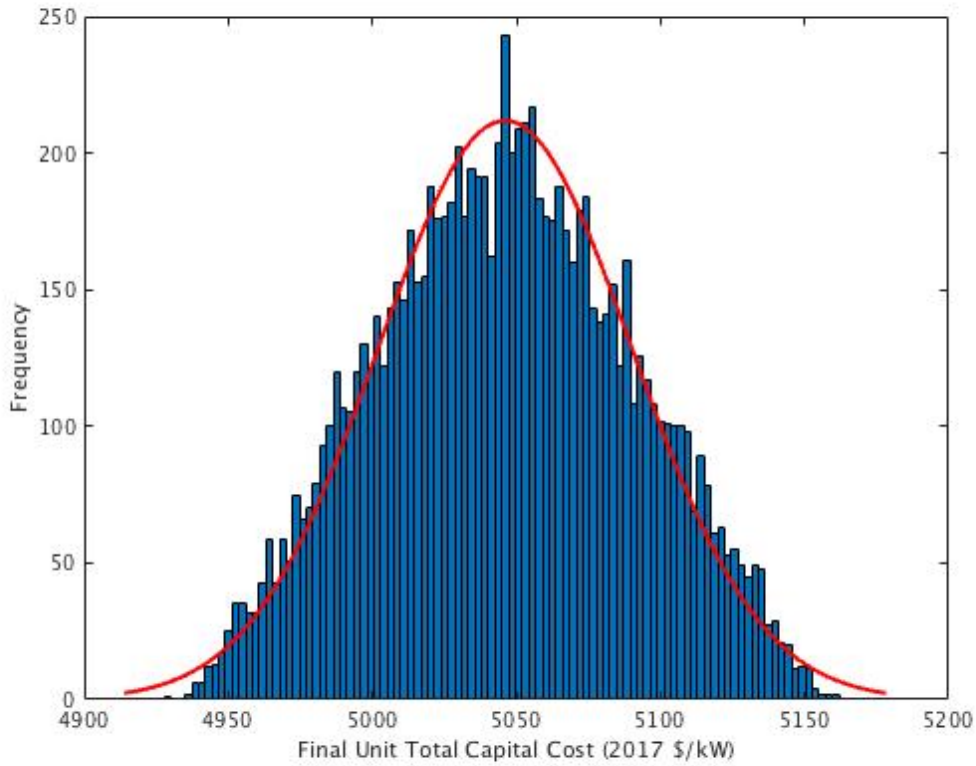

Figure 54: Final unit TCC distribution due to modularisation uncertainty

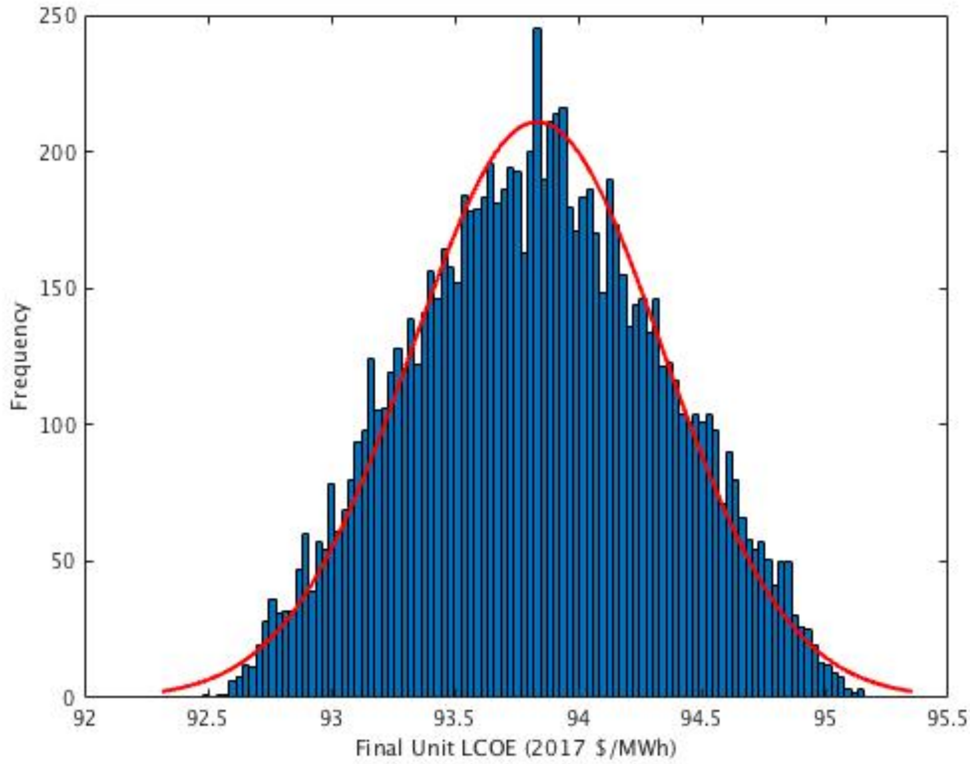

Figure 55: Final unit LCOE distribution due to modularisation uncertainty

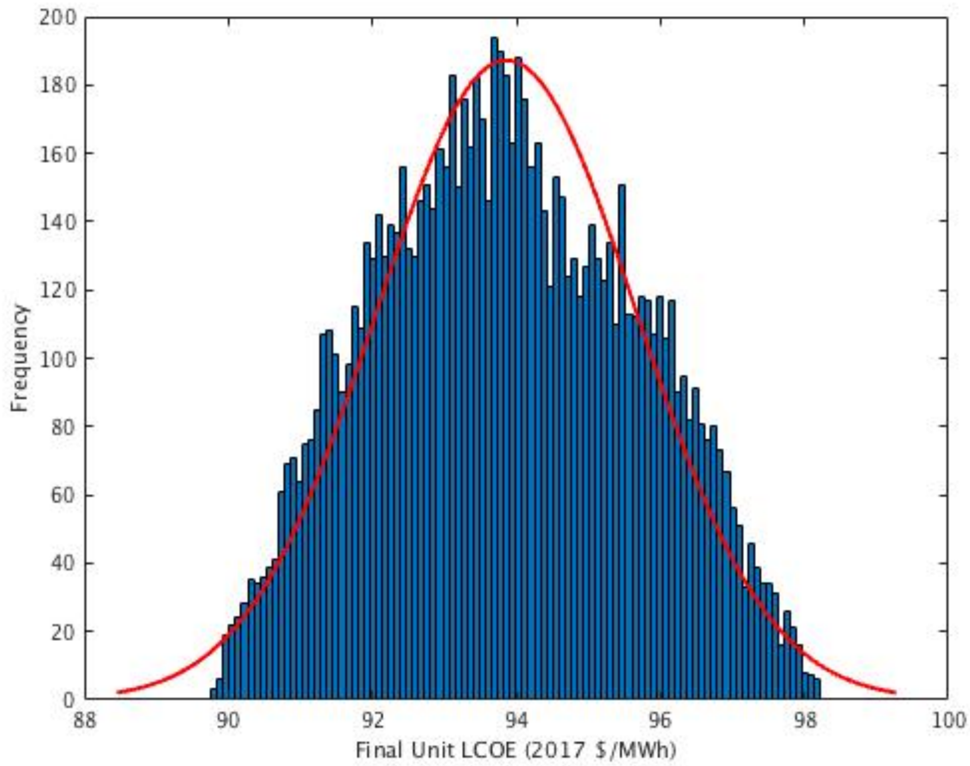

Figure 56: Final unit LCOE distribution due to build time uncertainty

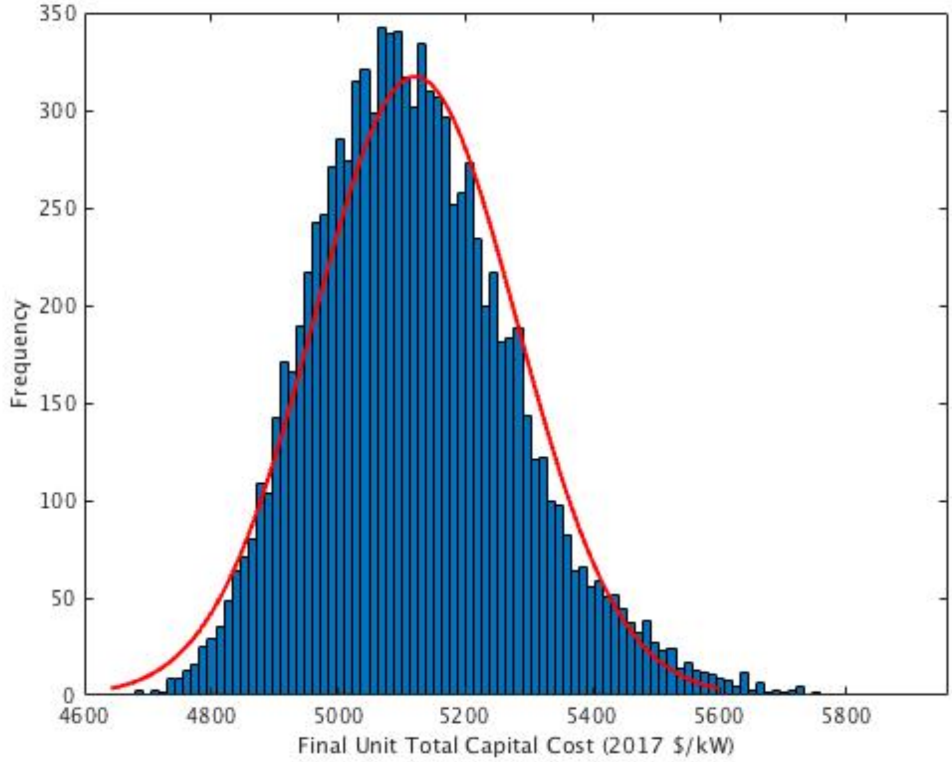

Figure 57: Final unit TCC distribution due to learning uncertainty

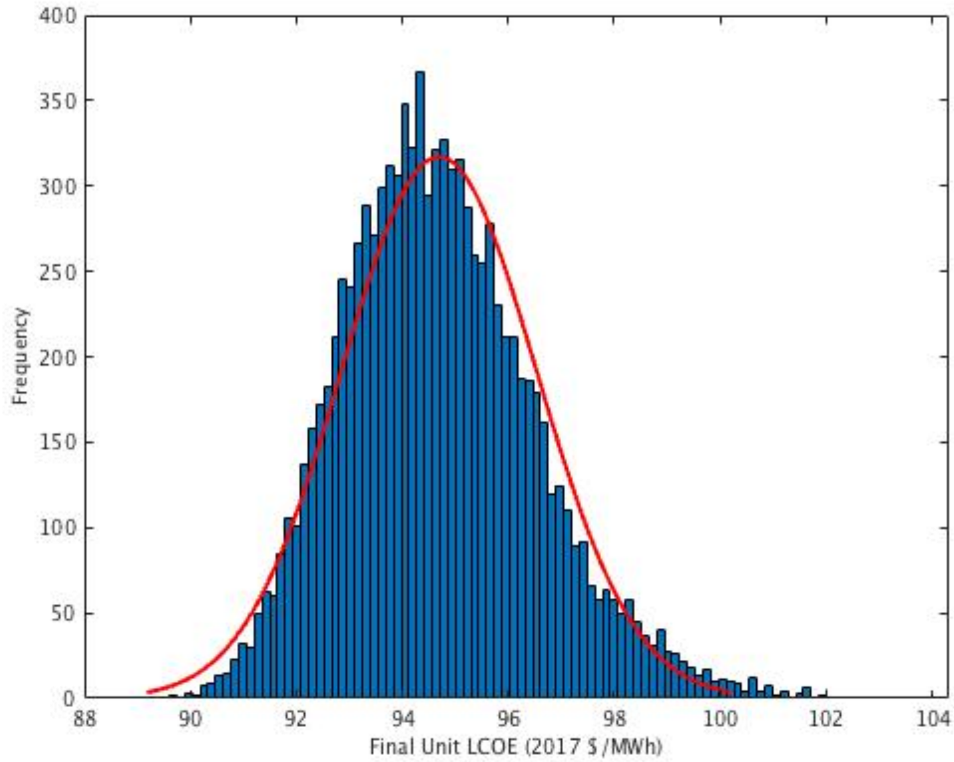

Figure 58: Final unit LCOE distribution due to learning uncertainty

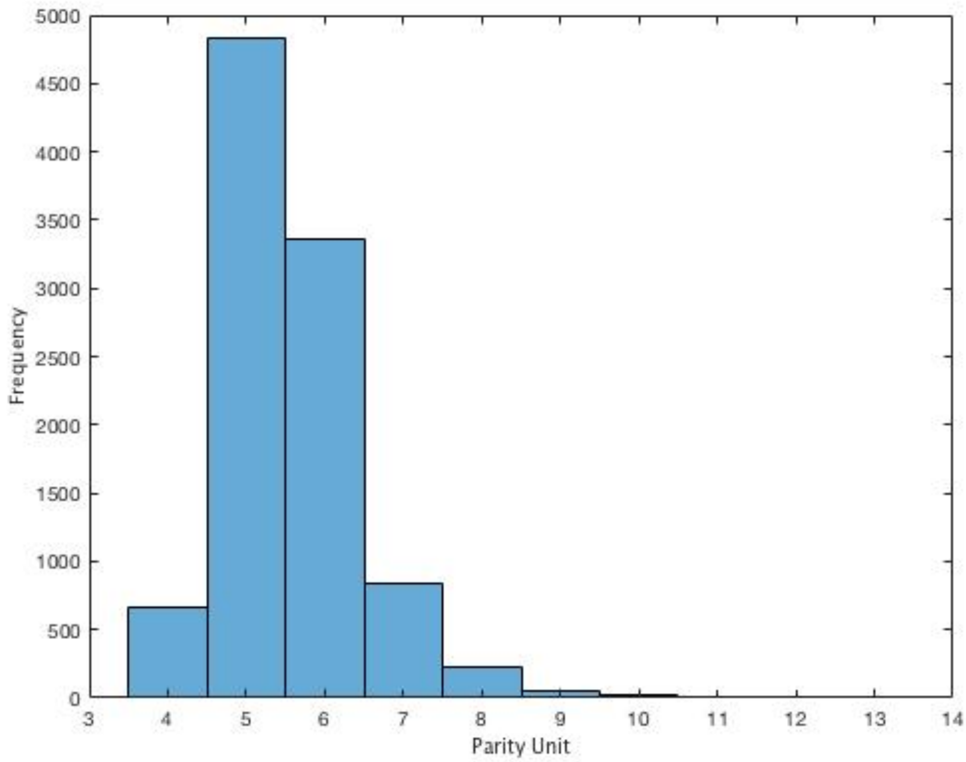

Figure 59: Parity unit distribution due to learning uncertainty

Table 37 shows the statistics for the normal distributions fitted to the uncertainty results, while for comparison Table 38 contains the deterministic results for the measured output costs under the fixed parameter conditions. As expected from the sensitivity results presented in Section 2.8, the uncertainty in the build time creates the greatest uncertainty for the cost reduction achieved in SMR production: the standard deviation in the first unit LCOE is approximately double that of the variation arising from standardisation and modularisation uncertainty. However, the uncertainty in learning has the greatest bearing on the long term economic competitiveness of an SMR programme. The coefficient of variation in TCC for the final unit due to learning uncertainty is approximately 3.12%, while that for the first unit due to standardisation is approximately 1.44%, and approximately 1.27% due to modularisation.

	$\mu_{final\ unit\ TCC}$	$\sigma_{final\ unit\ TCC}$	$\mu_{final\ unit\ LCOE}$	$\sigma_{final\ unit\ LCOE}$
Scaling	5,181	455	95	5
Standardisation	5,046	115	94	1
Modularisation	5,046	44	94	1
Build Time	-	-	94	2
Learning	5,121	160	95	2

Table 37: Final unit cost uncertainty statistics

Final unit TCC ($/kW)	5,046
Final unit LCOE ($/MWh)	94
Parity unit	5

Table 38: Deterministic results for fixed parameters

While the uncertainties in the individual cost reduction measures are considered separately in this analysis, it is crucial to recognise that the performance of these measures is coupled. The extent of standardisation will limit the extent of modularisation, as it is not economical to design a modularisation scheme for the custom, site-specific elements of a plant. Moreover, the reduction in the construction critical path length, and hence build time, is driven by the extent of modularisation.

Finally, the learning cost reduction achievable is limited by the cost distribution between high and low learning environments, which is determined again by modularisation. For this reason, it is not appropriate to aggregate the uncertainties of these four measures; however detailed consideration of the combined effect of such correlated uncertainties in nuclear plant construction costs is provided by Maronati (2018). Given the relatively small resultant uncertainties from the individual input variations, the combined uncertainty would also be expected to be small.

8. Discussion & Conclusions

In seeking to determine how supply chain configuration will affect the economics of small modular reactors, this research has taken the following approach:

1. Develop a cost model employing defendable cost data and methods, that incorporates supply chain configuration parameters;
2. Establish credible supply chain configurations for a SMR programme by combining supply chain design theory and real-world nuclear sector constraints;
3. Evaluate the economic performance of the configurations using the model, to identify the crucial supply chain design decisions;
4. Investigate the influence of supply chain constraints, such as market access, localisation, and programme set up costs.

The cost model presented and demonstrated in Section 2 relies on the capital cost data provided by the US DOE's EEDB, which provides a detailed breakdown by component and cost category. This structure enables the key cost estimating methods employed in the model: power scaling, standardisation, modularisation, schedule reduction, and production learning. It is in this final element where supply chain configuration has a significant bearing: this model uses both supplier relationship types and individual component production rate and volumes to calculate overall learning cost reduction, as detailed in Section 3. In this way, the model charts a middle course between the common top-down, industry level application of the experience curve (International Energy Agency, 2000), and a bottom-up aggregation of direct labour learning (Chen, et al., 2013). The demonstration results from the model show that the combination of standardisation and modularisation across the whole plant can offset the cost increases from economies of scale for smaller plants, such that a first-of-a-series SMR can be competitive with a conventional large reactor on specific total capital costs. Furthermore production learning can further reduce SMR costs.

The findings from the single programme analysis in Section 4 make a compelling case for changing the nuclear construction paradigm. Production volume and production rate are both important for creating the opportunity for the underlying innovation that enables learning cost reduction. An SMR size of 250 MW is best placed to balance economies of scale with the learning benefits that come from volume production.

The savings from learning could be at risk of getting captured in the supply chain. Traditional transactional relationships, based on single project models, will not deliver the necessary cost improvements on factory components to SMR vendors. Instead, commitment and collaboration are essential to sharing the risk and rewards of an ambitious, long-term programme. SMR vendors should seek to establish strategic partnerships with their key suppliers, in the same manner as Boeing has in the aerospace sector (Tang & Zimmerman, 2009). Without such partnerships market-based reactor vendors, even those with some in-house manufacturing capability, will struggle to compete against other fully-integrated organisations.

The global analysis in Section 5 indicates that the demand exists for several large SMR programmes, if costs can be brought down to compete with conventional large reactors. Moreover this demand is not in one single global market. With the strength of their indigenous nuclear industries, the US, China and Russia will be closed markets to each other and other foreign vendors. Each of these countries has sufficient demand to support a domestic SMR programme. If segmented by individual country, demand in the rest of the world could not support further SMR programmes. However if grouped into export markets for the 3 aforementioned programmes, this demand would add substantial production volume. This would be dependent upon significant harmonisation of global technical standards and regulation, such that the necessary design standardisation can be realised and market access enabled. If this can be achieved, SMRs could be produced in enough volume to bring costs down to a globally competitive LCOE of $90/MWh, equating to a TCC of $6,280/kW for a 250 MW SMR.

With lower labour costs, an integrated vendor, and access to cheap government financing, a Chinese programme would likely be much more competitive than their US counterpart. However, the realisation of export opportunities will not be driven solely by cost: localisation is often a business-winning tactic, both for nuclear and other sectors such as aerospace. Some countries may require a degree of local manufacturing as part of their plant orders, in order to realise direct economic benefit from their investment. While the analysis suggests that labour rate variations can make up for the loss of learning in module production, it must be reiterated that factory component supply must continue to be consolidated in order to maintain learning benefits. Indeed, this presents a motivation for establishing international supply partners even at the outset of a purely domestic programme, enabling future market access; this can arguably be observed in the partnerships being established by the likes of NuScale (Bailey, 2019). Alternatively, countries with little or no nuclear experience may prefer the opposite: delivery of the complete power plant package with no local content as often done for other high technology products such as civil aircraft. In such cases, countries would prefer the greater project certainty, shorter build periods and lower costs associated with standardisation, rather than opting for higher local content covering the simpler construction scope of work.

Finally, the analysis is Section 6 further emphasises the need for a large volume programme of at least 10 GWe. With development costs likely to reach close to $4bn, vendors must be assured of sufficient sales over which to amortise these costs and recover their upfront investment. Moreover, these costs highlight the importance of early government involvement. While in certain markets governments are wary of financial involvement in specific nuclear plant projects, their support of the early development efforts could make the difference in reducing the risk of embarking on an SMR production programme. With the case having been made that a sufficient programme size can deliver cost competitive SMRs without state subsidy, governments may be more willing to take a stake in development projects in order to reap the economic benefits of such a programme.

In summary the following conclusions can be drawn from the analysis presented in this study:

1. While standardisation and modularisation can deliver first-of-a-series unit SMRs with lower capital costs than the equivalent large reactors, production learning is required to achieve further progressive reduction in LCOE, and thus make SMRs economically competitive.
2. Learning is dependent on both production volume and rate, necessitating a significant multi-plant programme of at least 10 GWe committed upfront. The optimum reactor unit size appears to be in the region of 250 MW, though the specific value is to an extent dependant on the cost of finance.
3. Long-term relationships with strategic suppliers will be critical, as factory made components have the dominant potential for learning cost reduction; collaborative partnerships must be pursued rather than conventional transactional relationships.
4. While conservative estimates of aggregate global demand could support multiple vendors to deliver cost competitive SMRs, geopolitics and variations

in national markets will segment demand; nearly half of global demand will be closed to foreign competition.

5. Progress is required in harmonising international technical standards and safety regulation to make the standard design and product-like concept proposed here economically effective.
6. While modularisation moves significant amounts of on-site labour into more productive off-site labour, variations in global labour costs still have a discernible effect on SMR costs.
7. Localisation of module manufacturing, to secure market access or overcome logistical constraints, can be justified for a sufficiently large market if design standardisation and build performance is maintained; volume for learning is much less important than the cost and time productivity benefits.
8. Localisation of component supply is much harder to justify, as both concentrated production volumes and long term supplier relationships are required for learning.
9. While the approximate $3.8bn up-front costs to establish an SMR programme will not significantly alter the economic competitiveness of individual SMR units, they reinforce the need for government support and a large committed market. Moreover, the risk involved in such an investment will likely deter private actors without some form of initial government financial support.

9. Appendix A: Modularisation Percentages

Table 39 presents the modularisation percentages applied to the EEDB direct cost accounts for different reactor sizes. They were adopted as outputs from detailed work done by (Lloyd, 2019).

		100 MW	250 MW	500 MW	1,144MW
		Cost-Weighted Average			
Account Number	**Account Name**	**80.37%**	**76.03%**	**56.82%**	**30.30%**
211	Yardwork	0.00	0.00	0.00	0.00
212	Reactor Containment Bldg	0.81	0.72	0.54	0.19
213	Turbine Room + Heater Bay	0.90	0.90	0.90	0.22
214	Security Building	0.81	0.72	0.54	0.19
215	Prim Aux Bldg + Tunnels	0.89	0.78	0.50	0.19
216	Waste Process Building	0.89	0.78	0.50	0.19
217	Fuel Storage Bldg	0.81	0.72	0.54	0.19
218a	Control Rm/D-G Building	0.90	0.90	0.90	0.32
218b	Adminstration + Service Bldg	0.81	0.72	0.54	0.19
218d	Fire Pump House inc Fndtns	0.79	0.71	0.53	0.19
218e	Emergency Feed Pump Bldg	0.79	0.71	0.53	0.19
218f	Manway Tunnels	0.79	0.71	0.53	0.19
218g	Elec. Tunnels	0.79	0.71	0.53	0.19
218h	Non-Essen. Swgr Bldg	0.79	0.71	0.53	0.19
218j	Mn Steam + FW Pipe Enc.	0.79	0.71	0.53	0.19
218k	Pipe Tunnels	0.81	0.72	0.54	0.19
218l	Technical Support Centre	0.79	0.71	0.53	0.19
218p	Contain EQ Hatch Msle Shld	0.79	0.71	0.53	0.19
218s	Waste Water Treatment	0.79	0.71	0.53	0.19

		100 MW	250 MW	500 MW	1,144MW
		Cost-Weighted Average			
Account Number	**Account Name**	**80.37%**	**76.03%**	**56.82%**	**30.30%**
218t	Ultimate Heat Sink Struct	0.79	0.71	0.53	0.19
218v	Contr Rm Emg Air Intk Str	0.79	0.71	0.53	0.19
220a	Nuclear Steam Supply (NSSS)	0.00	0.00	0.00	0.00
220b	NSSS Options	0.00	0.00	0.00	0.00
221	Reactor Equipment	0.90	0.90	0.42	0.42
222	Main Heat Xfer Xport Sys	0.90	0.90	0.42	0.42
223	Safeguards System	0.90	0.90	0.42	0.42
224	Radwaste Processing	0.90	0.90	0.42	0.42
225	Fuel Handling + Storage	0.90	0.66	0.66	0.67
226	Other Reactor Plant Equip	0.90	0.90	0.42	0.42
227	Rx Instrumentation + Control	0.90	0.90	0.42	0.42
228	Reactor Plant Misc Items	0.90	0.90	0.42	0.42
231	Turbine Generator	0.82	0.80	0.77	0.52
233	Condensing Systems	0.74	0.71	0.65	0.14
234	Feed Heating System	0.74	0.71	0.65	0.14
235	Other Turbine Plant Equip	0.74	0.71	0.65	0.14
236	Instrumentation + Control	0.82	0.80	0.77	0.52
237	Turbine Plant Misc Items	0.87	0.86	0.84	0.20
241	Switchgear	0.85	0.80	0.72	0.54
242	Station Service Equipment	0.85	0.80	0.72	0.54
243	Switchboards	0.85	0.80	0.72	0.54
244	Protective Equipment	0.85	0.80	0.72	0.54
245	Elec. Struc + Wiring Contnr	0.85	0.80	0.72	0.54
246	Power & Control Wiring	0.85	0.80	0.72	0.54
251	Transportation & Lift Eqpt	0.79	0.71	0.53	0.19

		100 MW	250 MW	500 MW	1,144MW
		Cost-Weighted Average			
Account Number	**Account Name**	**80.37%**	**76.03%**	**56.82%**	**30.30%**
252	Air, Water + Steam Service Sy	0.79	0.71	0.53	0.19
253	Communications Equipment	0.79	0.71	0.53	0.19
254	Furnishings + Fixtures	0.79	0.71	0.53	0.19
255	Wastewater Treatment Equip	0.79	0.71	0.53	0.19
261	Structures	0.60	0.57	0.54	0.14
262	Mechanical Equipment	0.90	0.90	0.90	0.59

Table 39: Modularisation percentages applied to each direct cost account

10. Appendix B: EEDB Accounts Four Box Scores

Table 40 contains the individual scores for each EEDB four digit direct cost account. The scores were determined by the method described in Section 4.1.3. Yellow shaded scores are based on information from the Nuclear Energy Agency (2015); orange shaded scores are based on related accounts from the ANS Buyers Guide (American Nuclear Society, 2016); grey shaded accounts follow the assumed trend discussed in Section 4.1.3.

Account	Account Name	Account	Account Name	Quality Requirements & Risk	Number of Suppliers	Based on related account
211	Yardwork	211.1	General Yardwork	Low	High	-
		211.4	Railroads	Low	High	-
		211.7	Structure Associated Yardwork	High	Low	-
212	Reactor Containment Bldg	212.1	Building Structure	High	Low	-
		212.2	Building Services	High	Low	-
213	Turbine Room + Heater Bay	213.1	Building Structure	Low	High	-
		213.2	Building Services	Low	High	-
214	Security Building	214.1	Building Structure	Medium	Medium	-
		214.2	Building Services	Medium	Medium	-
215	Prim Aux Bldg + Tunnels	215.1	Building Structure	Low	High	-
		215.2	Building Services	Low	High	-
216	Waste Process Building	216.1	Building Structure	Low	High	-
		216.2	Building Services	Low	High	-
217	Fuel Storage Bldg	217.1	Building Structure	Medium	Medium	-
		217.2	Building Services	Medium	Medium	-
218a	Control Rm/D-G Building	218A.1	Building Structure	Medium	Medium	-
		218A.2	Building Services	Medium	Medium	-
218b	Adminstration + Service Bldg	218B.1	Building Structure	Low	High	-
		218B.2	Building Services	Low	High	-

Account	Account Name	Account	Account Name	Quality Requirements & Risk	Number of Suppliers	Based on related account
218d	Fire Pump House inc Fndtns	218D.1	Building Structure	Medium	Medium	-
		218D.2	Building Services	Medium	Medium	-
218e	Emergency Feed Pump Bldg	218E.1	Building Structure	Medium	Medium	-
		218E.2	Building Services	Medium	Medium	-
218f	Manway Tunnels	218F.1	Building Structure	Low	High	-
		218F.2	Building Services	Low	High	-
218g	Elec. Tunnels	218G.1	Building Structure	Low	High	-
		218G.2	Building Services	Low	High	-
218h	Non-Essen. Swgr Bldg	218H.1	Building Structure	Low	High	-
		218H.2	Building Services	Low	High	-
218j	Mn Steam + FW Pipe Enc.	218J.1	Building Structure	Medium	Medium	-
		218J.2	Building Services	Medium	Medium	-
218k	Pipe Tunnels	218K.1	Building Structure	Low	High	-
		218K.2	Building Services	Low	High	-
218l	Technical Support Centre	218L.1	Building Structure	Medium	Medium	-
		218L.2	Building Services	Medium	Medium	-
218p	Contain EQ Hatch Msle Shld	218P.1	Shield Structure	High	Low	-
218s	Waste Water Treatment	218S.11	Building Structure	Low	High	-
		218S.12	Building Services	Low	High	-
		218S.2	Waste Water Holding Basins	Low	High	-
218t	Ultimate Heat Sink Struct	218T.1	Building Structure	Low	High	-
		218T.2	Building Services	Low	High	-
218v	Contr Rm Emg Air Intk Str	218V.1	Building Structure	Medium	Medium	-
		218V.2	Building Services	Medium	Medium	-
220a	Nuclear Steam Supply (NSSS)	220A.1	Quoted NSSS Price	High	Low	-

Account	Account Name	Account	Account Name	Quality Requirements & Risk	Number of Suppliers	Based on related account
		220A.2	Distributed NSSS Cost	High	Low	-
220b	NSSS Options			High	Low	-
221	Reactor Equipment	221.1	Reactor Vessel + Accessory	High	Low	-
		221.2	Reactor Control Devices	High	Low	-
222	Main Heat Xfer Xport Sys	222.11	Fluid Circulation Drive System	High	Low	-
		222.12	Reactor Coolant Piping System	High	Low	-
		222.13	Steam Generator Equipment	High	Low	-
		222.14	Pressurizing System	High	Medium	-
223	Safeguards System	223.1	Residual Heat Removal System	High	Low	-
		223.3	Safety Injection System	High	Low	-
		223.4	Containment Spray System	High	Low	-
		223.5	Combustible Gas Control System	High	Low	-
224	Radwaste Processing	224.1	Liquid Waste System	Low	Medium	-
		224.2	Radioactive Gas Waste Processing	High	Medium	-
		224.3	Solid Waste System	Low	Medium	-
225	Fuel Handling + Storage	225.1	Fuel Handling Tools + Equipment	High	Low	-
		225.3	Service Platforms	High	Low	-
		225.4	Fuel Storage, Cleaning, +	Low	High	-

Account	**Account Name**	**Account**	**Account Name**	**Quality Requirements & Risk**	**Number of Suppliers**	**Based on related account**
			Inspection Equipment			
226	Other Reactor Plant Equip	226.1	Inert Gas System	Low	High	-
		226.3	Reactor Makeup Water System	Low	High	-
		226.4	Coolant Treatment & Recycle	Low	High	-
		226.6	Fluid Leak Detection System	High	Medium	-
		226.7	Auxillary Cooling System	High	Low	-
		226.8	Maintenance Equipment	Low	High	-
		226.9	Sampling Equipment	Low	High	-
227	Rx Instrumentation + Control	227.1	Benchboard, Panels + Racks	High	High	-
		227.2	Process Computer	High	Medium	-
		227.3	Monitoring Systems	High	High	-
		227.4	Plant Control Systems	High	High	-
		227.5	Reactor Plant I+C Tubing + Fitting	High	High	-
		227.9	TMI Instrumentation	High	Low	-
228	Reactor Plant Misc Items	228.1	Field Painting	Low	High	-
		228.2	Qualification of Welders	High	Low	-
		228.4	Reactor Plant Insulation	High	Low	Insulation, radiation resistant
231	Turbine Generator	231.1	Turbine Generator + Accessory	Medium	Medium	-
		231.2	Foundations	Low	Medium	-

Account	Account Name	Account	Account Name	Quality Requirements & Risk	Number of Suppliers	Based on related account
		231.4	Lubricating Oil System	Low	High	-
		231.5	Gas System	Low	High	-
		231.6	Moisture Separator/Reheater Drain System	Low	Low	-
233	Condensing Systems	233.1	Condenser Equipment	Low	Medium	-
		233.2	Condensate System	Low	Low	-
		233.3	Gas Removal System	Low	High	-
		233.4	Turbine Bypass System	Low	Low	-
		233.5	Condensate Polishing	Low	Medium	-
234	Feed Heating System	234.1	Feedwater Heaters	Low	Medium	-
		234.2	Feedwater System	Low	Low	Feedwater regulators
		234.3	Extraction Steam System	Low	High	-
		234.4	FWH Vent + Drain System	Low	Medium	Feedwater heaters
235	Other Turbine Plant Equip	235.1	Main Vapor Piping System	High	High	Pipe categories
		235.2	Turbine Auxiliaries	Low	High	-
		235.3	Turbine Closed CLG Water System	Low	High	-
		235.4	Demineralised Water Makeup System	Low	Medium	DM Water Treatment Equipment & supplies
		235.5	Chemical Treatment System	Low	High	-

Account	Account Name	Account	Account Name	Quality Requirements & Risk	Number of Suppliers	Based on related account
		235.6	Neutralization System	Low	High	-
236	Instrumentation + Control	236.1	Process IC Equipment	Low	High	Electronic Instrumentation & supplies
		236.2	Process Computer	Low	High	Electronic Instrumentation & supplies
		236.3	Turbine Plant I+C Tubing	Low	High	Tubing
237	Turbine Plant Misc Items	237.1	Field Painting	Low	High	-
		237.2	Qualification of Welders	High	Low	-
		237.3	Turbine Plant Insulation	Low	Medium	Insulation, thermal
241	Switchgear	241.1	General Equipment Switchgear	Low	Low	-
		241.2	Station Service Switchgear	Low	Low	Electrical Distr. & Control
242	Station Service Equipment	242.1	Station Service & Startup Transformer	Low	Low	-
		242.2	Unit Substations	Low	Low	Electrical Distr. & Control
		242.3	Auxilary Power Sources	Low	High	Power supplies
243	Switchboards	243.1	Control Panels	Low	High	Control equipment, power plant (non-reactor)
		243.2	Auxilary Power & Signal Boards	Low	High	Control equipment, power plant (non-reactor)
244	Protective Equipment	244.1	General Station Ground System	Low	Low	Electrical Distr. & Control
		244.2	Fire Detection + Suppession	Low	Low	Alarm Systems - Fire; Fire Protection

Account	Account Name	Account	Account Name	Quality Requirements & Risk	Number of Suppliers	Based on related account
		244.3	Lightning Protection	Low	High	-
		244.4	Cathodic Protection	Low	High	-
		244.5	Heat Tracing + Freeze Protection	Low	High	-
245	Elec. Struc + Wiring Contnr	245.1	Underground Duct Runs	Low	Low	Ducts
		245.2	Cable Tray	Low	Low	-
		245.3	Conduit	Low	Low	Ducts/Cable tray
246	Power & Control Wiring	246.1	Generator Circuits Wiring	Low	Medium	Wire
		246.2	Station Service Power Wiring	Low	Medium	cable, power
		246.3	Control Cable	Low	Medium	-
		246.4	Instrument Wire	Low	High	cable, instrumentation
		246.5	Containment Penetrations	Low	High	-
251	Transportation & Lift Eqpt	251.1	Cranes & Hoists	Low	Low	mixture of crane & hoists types (limiting)
252	Air, Water + Steam Service Sy	252.1	Air Systems	Low	High	-
		252.2	Water Systems	High	Low	-
		252.3	Auxiliary Steam System	High	Low	Steam generators, standy-by, auxiliary
		252.4	Plant Fuel Oil System	High	Low	-
253	Communications Equipment	253.1	Local Communications System	Medium	Low	Communication system
		253.2	Signal System	Medium	Low	Emergency warning systems (worker)

Account	Account Name	Account	Account Name	Quality Requirements & Risk	Number of Suppliers	Based on related account
254	Furnishings + Fixtures	254.1	Safety Equipment	Medium	Medium	-
		254.2	Chemical Lab Shop	Low	High	-
		254.3	Office Equipment + Furnishings	Low	High	-
		254.4	Change Room Equipment	Low	High	-
		254.5	Environment Monitoring Equipment	Low	High	-
		254.6	Dining Facilities	Low	High	-
255	Wastewater Treatment Equip			Low	Medium	Water treatment equipment & supplies
261	Structures	261.1	Makeup Water Intake	Low	Medium	Water Intake facilities
		261.2	Circulating Water Pump House	Low	Medium	structural supports, component
262	Mechanical Equipment	261.3	Makeup Water Pretreatment Building	Low	Medium	Water Intake facilities
		262.1	Heat Rejection System	High	Low	Heat sinks, ultimate; towers, cooling

Table 40: EEDB accounts four box scores

11. Appendix C: Key Component Suppliers

The component descriptions and supplier information shown in this appendix are taken from both the NEA (2015, pp. 148-153) and Nuclear Energy International (2012, pp. 46-87). Table 41 shows the region key for supplier locations.

Region Key	
(blue)	North America
(green)	Europe
(red)	Asia

Table 41: Supplier Locations

11.1. Reactor Plant Equipment – Reactor Equipment:

- *Reactor pressure vessel (RPV)*
  - ‘a thick-walled, high integrity, pressure vessel’, made up of ‘large and ultra-large forgings, which can only be manufactured in a few places around the world’;

RPV Suppliers	Country
Ansaldo	Italy
AREVA	France
Doosan	Korea
IHI	Japan
Mitsubishi Heavy Industries	Japan
OMZ	Russia
Skoda	Czech Republic

Table 42: List of RPV Suppliers

- *RPV internals*
  - ‘high precision, high quality components’ which support the fuel within the core and provide shielding to reduce the amount of radiation leaving the core; usually produced by the RPV supplier;

11.2. Reactor Plant Equipment – Main Heat Transfer and Transport System:

- *Steam generator*
  - a pressure vessel containing ‘heat exchange tubes welded into a thick tube plate, along with steam dryers and separators’; only a small number of suppliers are capable of their manufacture and assembly;

SG Suppliers	Country
AREVA	France
AtomEnergoMash	Russia
Babcock & Wilcox	USA
Doosan	Korea
ENSA	Spain
Larsen and Toubro	India
Mangiarotti	Italy
Mitsubishi Heavy Industries	Japan
Shanghai Boiler Works	China

Table 43: List of Steam Generator Suppliers

- *Pressuriser*
  - a pressure vessel containing both heating and water spray systems; vessel is smaller than both RPV and steam generator, so there are a greater number of potential suppliers; internals can be produced by many separate suppliers;

- *Valves and pumps*
  - the most safety critical pumps and valves are provided by specialists; lower grade components can come from many suppliers;

Pump Suppliers	**Country**
AtomEnergoMash	Russia
AREVA JSPM	France
Curtiss-Wright Flow Control	USA
EBARA	Japan
Flowserve	USA
Hayward Tyler	USA
HMS Pumps	Russia
KSB AG	Germany
Mitsubishi Heavy Industries	Japan
Shanghai Electric	China
SPX Flow Technology	USA
Teikoku Electric Manufacturing	Japan
Weir Group	UK

Table 44: List of Pump Suppliers

Valve Suppliers	Country
AtomEnergoMash	Russia
AUMA	Germany
Armatury Group	Czech Republic
Dresser	USA
Emerson Process Management	USA
Flowserve Corp.	USA
KSB AG	Germany
Larsen & Toubro	India
Oka Ltd	Japan
Okano Valve Manufacturing	Japan
PK Valve	Korea
Samshin Ltd	Korea
SPX Flow Technology	USA
Toa Valve Engineering	Japan
Toshiba	Japan
TyazhPromArmatura	Russia
Tyco Flow Technology	USA
Weir Group	UK
Westinghouse	USA
Velan Inc.	Canada

Table 45: List of Valve Suppliers

- *Pipework*
  - primary loop pipework, being 'thick-walled pipe made from forgings', can only be manufactured by a few suppliers; usually done by a strategic partner of the reactor vendor; lower grade pipework can be provided by a greater number of suppliers;

11.3. **Turbine Generator Plant Equipment – Turbine/Generator Plants**

- *Turbine and generator*
  - for current reactor designs which have outputs of more than 1,000 MWe these are ‘very large by comparison to other thermal power plants’ and often use wet (or saturated) steam rather than superheated steam, therefore only a limited number of potential suppliers;

TG Suppliers	Country
Alstom	France
Bharat Heavy Electricals	India
China First Heavy Industries	China
China Dongfang Electric Corp.	China
Doosan/Skoda Power	Korea
GE	USA
Hitachi	Japan
Mitsubishi Heavy Industries	Japan
OMZ	Russia
Siemens	Germany
Silmash	Russia
Toshiba	Japan

Table 46: List of Turbine & Generator Suppliers

11.4. Electrical Equipment and I&C Plant Equipment

- *High voltage transformers and switchgear*
  - often provided by the T&G vendor;
- *Back-up power supplies*
  - can be provided by a broad set of suppliers;
- *Control and instrumentation*
  - *Power plant control*
    - based on a standard I&C platform, provided by specialist suppliers;
  - *Ancillary C&I*
    - provided by specialist suppliers;
  - *Reactor sensors*
    - provided by specialist suppliers;
  - *Reactor protection system*
    - these systems are usually provided by the reactor vendor or a strategic partner, due to the need of familiarity with the design:

C&I Suppliers	Country
AREVA	France
AtomEnergoMash	Russia
Doosan	Korea
GE Hitachi	USA/Japan
Invensys	UK
Lockheed Martin	USA
Mitsubishi Electric Corp.	Japan
Rolls-Royce	UK
Skoda JS	Czech Republic
Toshiba	Japan
Westinghouse	USA

Table 47: List of Control & Instrumentation Suppliers

- *Fuel handling equipment*

Fuel Handling Equipment Suppliers	Country
Andritz AG	Austria
NES	UK
Babcock International	UK
Babcock Noell GmbH	Germany
China Advanced Technologies	China
Ederer Nuclear Cranes Division	USA
Newburgh Engineering Co Ltd	UK
PaR Nuclear Inc	USA
Precision Components Corp	USA
Preferred Engineering	USA
Reel SA	France

Table 48: List of Fuel Handling Equipment Suppliers

- *Fuel storage racks*

Fuel Storage Racks Suppliers	Country
Equipos Nucleares SA	Spain
Siempelkamp Nuclear Services, Inc	USA
Siempelkamp Nuclear Technology, Inc	USA
Siempelkamp Nuclear Technology UK Ltd	UK
Siempelkamp Nukleartechnik GmbH	Germany
Skoda JS	Czech Republic
CCI AG	Switzerland
Holtec International	USA
Holtec Manufacturing Division	USA
Northeast Technology Corp	USA
Precision Components Corp	USA
Roberts Engineering Services Inc	USA
Transnuclear, Inc	USA

Table 49: List of Fuel Storage Rack Suppliers

- *Radioactive waste plant*
  - specialist companies required for design of this system, but there are many firms that are capable of manufacturing it;
- *Heating, Ventilation, and Air Conditioning (HVAC)*
  - many suppliers available to provide both the nuclear and conventional HVAC systems.

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