Quantifying key uncertainties in the costs of nuclear power

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1Abstract

Nuclear and renewables both offer the potential for low greenhouse emissions electricity production, but their potential contributions to economic future electricity generation portfolios remains unclear. Renewable generation is variable and non-synchronous, bringing grid integration challenges. Nuclear power is more conventional in grid interaction, but has been associated with significant cost risk. This analysis aims to directly quantify that cost risk, so that it can be included appropriately in studies projecting economic future electricity generation portfolios, and considered more explicitly in climate and energy policy development processes. The most significant factors contributing to uncertainty in the costs of nuclear power generation have been identified, characterised via probability distributions, and combined using a Monte Carlo approach. The resulting probability distributions for the overnight capital cost (OCC) and levelised cost of energy (LCOE) of nuclear power plants directly quantify the uncertainty over the costs of new nuclear power plants. The most important contributors to cost uncertainty are identified to be OCC estimates, the degree of cost escalation over the construction and pre-construction periods, and the duration of those periods. In the absence of cost escalation, the mean LCOE of nuclear power is found to be AU$145/MWh in jurisdictions excluding Asia (or AU$130/MWh if Asian plant costs are included in the distributions), with a standard deviation of AU$62/MWh. Without cost escalation, there is a 50% probability that the LCOE will exceed AU$132/MWh, and a 15% probability that it will exceed AU$183/MWh. However, when cost escalation over construction and pre-construction periods is included at rates observed during nuclear build programs in France and the USA, the mean LCOE increases to AU$515/MWh, with a very large standard deviation of AU$2,646/MWh. These results indicate that nuclear power costs have an 80% probability of exceeding AU$170/MWh, a 50% probability of exceeding AU$278/MWh, and a 15% probability of exceeding AU$650/MWh. This analysis suggests that for jurisdictions such as Australia that have abundant renewable resources, nuclear power is likely to be considerably more expensive than other low emissions alternatives, such as wind (available at AU$80-$120/MWh) and photovoltaics (available at AU$200-$300/MWh), and may be comparable in cost or more expensive than “dispatchable” renewable options such as concentrating solar thermal (AU$300-$400/MWh). Even where the mean costs appear comparable with other low emissions alternatives, the considerable cost risk associated with nuclear power is a significant disadvantage. Probability distributions are provided for overnight capital costs and levelised costs of nuclear power, facilitating direct assessment of the cost risk associated with this technology.

2Introduction

There is strong scientific consensus on the urgent need to mitigate greenhouse gas emissions [1]. The energy supply sector is the largest contributor of greenhouse gas emissions, being responsible for approximately 35% of total anthropogenic emissions globally [2], and will therefore be key to climate mitigation.
Nuclear and renewable generation both offer the potential for electricity generation with low greenhouse emissions, but face different barriers, challenges, costs and cost risks. The majority of new renewable capacity is wind generation and photovoltaics [3]. However, wind and photovoltaics are technically different to conventional power generation technologies, having variable availability, and being non-synchronous [4]. Integrating large quantities of these technologies will therefore necessitate changes to power system operation and planning [5, 6]. This has prompted consideration of conventional nuclear generation as an important low emissions technology [7], even in jurisdictions where wind and photovoltaics are abundantly available, such as South Africa [8] and Australia [9].

Debate over the use of nuclear power generation in Australia is ongoing [10, 9, 11]. Most recently, the Nuclear Fuel Cycle Royal Commission was established by the South Australian Government in 2015 to investigate the potential for nuclear electricity generation, as well as potential participation in other parts of the nuclear fuel cycle such as the mining and processing of nuclear fuels, and the storage and disposal of radioactive and nuclear waste [12]. Australia has no nuclear power at present, instead sourcing the majority (70-80%) of electricity from coal-fired generation [13]. This makes it especially challenging to estimate the cost of establishing a nuclear power industry in Australia [9, 10]. Australia is used as a case study for this analysis, but these results will also be relevant to any jurisdiction considering installation of new nuclear power, particularly where there is no established nuclear industry, or where there are no recent nuclear power station builds such that first-of-a-kind costs are likely to be incurred.

Rather than attempting to estimate a single value for the cost of establishing nuclear power in Australia [14], or applying a scenario-based approach [7], this analysis aims to recognise and directly quantify the uncertainty around nuclear costs. A Monte Carlo simulation approach is applied, allowing explicit analysis of a wide range of potentially interacting uncertainties [15, 16, 17, 18]. The resulting probability distributions for nuclear costs enable more sophisticated modelling of uncertainty in electricity portfolio studies [19, 20]. This analysis also provides a useful input for policy making, allowing cost risk associated with the technology to be assessed with a rigorous approach and taken into account explicitly.

Most nuclear reactors in operation around the world are generation II designs. However, the majority of reactors under construction are large scale (1,000 – 1,600 MW) generation III reactors, such as the AREVA EPR and Westinghouse AP1000 reactors [21]. Generation IV nuclear reactors, which seek to offer advances in safety, reliability and sustainability, are being developed but aren’t expected to be ready for commercial deployment until at least 2030-2040 [22]. In the coming decades, nuclear research and development could focus on improving the constructability and modularity of generation III nuclear reactors in order to reduce capital costs and shorten construction times [23]. As such, if Australia were to invest in nuclear reactors in the next two decades, it would likely invest in generation III reactors. This analysis, therefore, focuses on cost estimates for generation III nuclear reactors. It is acknowledged that this analysis would not apply to emerging nuclear technologies (such as molten salt technologies), which might be considered fundamentally different to nuclear technologies in operation and under construction globally today.

3 Methodology

3.1.1 Quantifying key uncertainties

The various components of costs of installing and operating nuclear electricity generation were surveyed from a wide range of sources, with costs from the most reliable sources collated. The influence of each cost input on the levelised cost was determined. Probability distributions were then established for each of the most significant cost inputs. Correlations between these probability distributions were also investigated and quantified where sufficient data was available.

All costs throughout this paper are quoted in real, 2015, Australian dollars. Costs from each source used were converted to 2015 Australian dollars using consumer price index and exchange rate data.
from the Australian Bureau of Statistics [24] and Reserve Bank of Australia [25] respectively. As of September 2015, 1 AUD = 0.64 Euros = 0.72 USD.

3.1.2 Combination of key uncertainties
Monte Carlo sampling was used to combine the key uncertainties. 10,000 simulations were conducted, using correlated lognormal distributions for the overnight capital cost (OCC) and construction duration, calculated using the multivariate random generators in the statistical toolbox in MATLAB software. Uncorrelated lognormal distributions were applied for the pre-construction duration, and the cost escalation rates during construction and pre-construction periods.

3.1.3 Applying cost escalation
Cost escalation was applied to each Monte Carlo iteration as follows:

\[ \text{OCC}_{\text{Final}} = \text{OCC}_0 \times (1 + r_{PC})^{t_{PC}} \times (1 + r_{C})^{t_{C}} \]

Where:
- \( \text{OCC}_{\text{Final}} \) is the escalated OCC at the time construction is completed
- \( \text{OCC}_0 \) is the original OCC estimate (in 2015)
- \( r_{PC} \) is the cost escalation rate during the pre-construction period
- \( r_{C} \) is the cost escalation rate during the construction period
- \( t_{PC} \) is the duration of the pre-construction period (in years)
- \( t_{C} \) is the duration of the construction period (in years)

3.1.4 Calculating the levelised cost
For each Monte Carlo iteration, the levelised cost of energy (LCOE) was calculated as follows:

\[
\text{LCOE} = \frac{\sum_{t=-c}^{n+d} I_t + FOM_t + VOM_t + F_t + W_t + D_t}{\sum_{t=-c}^{n+d} (1 + r)^t} - \frac{\sum_{t=-c}^{n+d} E_t}{(1 + r)^t}
\]

Where:
- \( t \) is the number of years since plant commissioning (\( t = 0 \))
- \( I_t \) is the total investment expenditures in year \( t \), given by the (escalated) overnight capital cost (\$/kW) multiplied by the plant capacity, spread over the construction period. For this analysis, a normal distribution was applied to spread capital investment over the construction period.
- \( FOM_t \) is the total fixed operations and maintenance (O&M) expenditures in year \( t \)
- \( VOM_t \) is the total variable operations and maintenance (O&M) expenditures in year \( t \), given by the variable operations and maintenance cost (\$/MWh), multiplied by the electricity generation in the year \( t \).
- \( F_t \) is the total fuel expenditures in year \( t \)
- \( W_t \) is the waste disposal expenditures in year \( t \)
- \( D_t \) is the decommissioning expenditures in year \( t \)
- \( E_t \) is the electricity generation in the year \( t \)
- \( r \) is the discount rate (10% per annum was used for this analysis)
- \( n \) is the expected lifetime of the power station (years)
- \( c \) is the construction duration for the power station (years)
\( d \) is the decommissioning time for the power station (years)

The LCOE calculated is a generalised cost estimate and does not account for site specific factors, such as grid connection costs.

4 Quantifying key uncertainties

4.1 Overnight Capital Cost (OCC)

The capital cost of nuclear power is quantified here via the overnight capital cost (OCC), defined as the hypothetical capital cost of a nuclear reactor if it could be built “overnight”, excluding the cost of financing over the construction period. It also excludes the cost of transmission (which has not been assessed in this analysis) and decommissioning (which is quantified separately, as discussed in section 4.7.6).

Recent OCC estimates for generation III nuclear power stations were collated from a range of sources. The highest quality recent and most relevant estimates are compared in Figure 1. These include quoted costs for specific reactors recently or soon to be commissioned [26, 8], supplemented with jurisdictional average estimates from the International Energy Agency Nuclear Energy Agency (IEA-NEA) based on historical data supplied by the operators of 20 light water reactors (LWRs) [27]. Values for the USA are are overlaid by an OCC estimate from the US EIA [28], tailored specifically to that region. Other estimates that were originally based upon these sources were excluded from the dataset to avoid “over-weighting” of these values in the analysis.

OCC estimates are found to vary significantly, being as low as $1,833/kW for Taishan 1&2 [8], a plant under construction in China, to as high as $6,812/kW, a generic cost estimate for the EU [27]. It is apparent that the cost of nuclear reactors in Asia is generally lower than in other jurisdictions.

Values estimated for the establishment of nuclear power in Australia by the Australian Government Bureau of Resources and Energy Economics (BREE) [14] are also overlaid on Figure 1. These are based on the average of the four OCCs reported by Hezir & Davis [26], adjusted using cost multipliers for the cost of labour and availability of equipment and expertise in Australia. First of a kind (FOAK) and Nth of a kind (NOAK) estimates from BREE are illustrated\(^1\).

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\(^1\) FOAK cost estimates include costs incurred when a commercial nuclear reactor is built for the first time, such as design and certification costs. NOAK estimates include only repetitive engineering, equipment, construction, testing and project management costs.
These twenty estimates of OCCs (both reactor-specific, and jurisdictional averages) were compiled in Figure 2. Although only a relatively small data set is available, this can be used as a basis for estimating the probability density function for nuclear plant OCCs. Figure 2a) includes all the high quality OCC estimates fitted with a lognormal probability, which has a mean of $4,596/kW and a standard deviation of $1,339/kW. The mean of this distribution is significantly lower than the BREE estimates of FOAK and NOAK costs for establishing nuclear power in Australia [14] ($6,392 and $5,437 respectively), partly due to the cost multipliers used by BREE to adjust the original estimates for Australian conditions.

Reactors constructed in Asia were separated from the main dataset to create two distinct distributions, as illustrated in Figure 2b) and c). The Asian lognormal probability density function is found to have a mean of $2,781/kW and standard deviation of $1,131/kW, while the ‘rest of world’ lognormal probability density function has a mean of $5,080/kW and slightly smaller standard deviation of $916/kW. These values are summarised in Table 2. The difference between OCC estimates in Asia and the rest of the world has been attributed to Asia’s cheap cost of labour, less stringent safety regimes, and sustained nuclear build program over the past decade [23]. Unlike the rest of the world, where effectively no new nuclear capacity has been added in the past 15-20 years [7], nuclear capacity in East and South Asia has experienced unprecedented growth in recent years. For instance, over the period 2002-2014, China commissioned 20 new nuclear reactors and has another 30 reactors either under construction or in the pre-construction phase [29]. Thus, the Asian plant costs could be argued to be more representative of NOAK nuclear plant costs. In contrast, due to the infrequency of new builds in the ‘rest of world’ it could be argued that the ‘rest of world’ costs are more representative of FOAK nuclear plant builds.
4.2 Cost escalation during construction

Cost escalation has been described as intrinsic to nuclear power [30, 31]. Lovins proposed that with increasing deployment, and with advances in nuclear technology, the complexity of nuclear reactors inevitably increases (to incorporate fuel cycle management, improved safety standards, etc.), leading to construction delays and cost escalation [32]. Harris et al. (2013) emphasised the significant influence that cost escalation can have over levelised costs [7]. Cost escalation can be examined in two ways: escalation in costs over the course of a large nuclear build program, and escalation in costs over the construction period of a single plant. Both are examined below.

To illustrate cost escalation over nuclear build programs, experiences during the French and U.S. programs of the 1970-2000’s, the largest nuclear build programs in history, are illustrated in Figure 3.

4.2.1 Experience in the USA

Between 1970 and the mid-1990s, 99 nuclear reactors (a mix of pressurised water reactors (PWRs) and boiling water reactors (BWRs)) were built in the US. The observed average annual cost escalation over this period was 8.1% [7]. Regulatory changes and construction delays were the primary drivers of cost escalation, although the lack of centralized decision making and the involvement of many entities also contributed [33]. Additionally, US reactors designs weren’t standardised; US electric
utilities contracted reactor design and construction to engineering firms to tailor each reactor to local sites, which delayed construction and led to cost escalation [34].

Figure 3 - Historical OCC escalation. Author’s own analysis, with data from sources: [35, 36]

4.2.2 Experience in France
The French nuclear build program has been labelled the most successful scale-up of complex and capital-intensive energy technology in recent history [30]. Between 1971 and 2000, France built 58 PWRs. As is clear from Figure 3, the French build program experienced much lower cost escalation than the U.S. build program. Grubler calculated the cost escalation rate to be 5.6% (real, compounded) per annum [30, 7]. Escobar Rangel & Leveque recently revised this downwards to 4.7% per annum, utilising more accurate cost data released by the French Court of Auditors [37].

Cost escalation over the French nuclear build program is attributed to slight changes to the size and design of nuclear reactor being installed [37]. The size of reactor installed increased from 900MW to 1450MW over the course of the French PWR program. Cantor and Hewlett found that larger reactors increase project complexity, subjecting them to managerial problems and stricter regulatory scrutiny that increase costs [38]. Cost escalation is also attributed to increasing labour costs over the course of the PWR build program [37]. Furthermore, ÉDF (Électricité de France, the nationalized French electric utility company) made changes to the intermediary reactor cooling system, fuel rod containment structure, circuitry, steam generators, primary pumps and command room over the course of the program, such that ÉDF couldn’t apply previous experience or learnings to the program’s last four reactors [31]. These last four reactors were new N4 reactors, which differed significantly from the standard PWR reactors installed earlier in the program. These cost approximately twice as much to build, per kilowatt, as the other 54 reactors [34], since they reintroduced learning and first of a kind costs [31]. Komanoff therefore revised the cost escalation rate over the French nuclear build program downwards to 3.6% (real, compounded) per annum by minimising the impacts of these last four reactors [34].

Grubler attributes the relative success of the French PWR build program (compared with the much higher cost escalation rates experienced in the USA) to [30]:

- A unique institutional setting that facilitated centralized decision-making between a limited number of entities;
- Regulatory stability;
A powerful nationalized electric utility (ÉDF), whose substantial in-house engineering resources enabled it to act as principal and agent of nuclear reactor construction simultaneously; and

Dedicated efforts to standardize reactor designs.

This suggests that replicating the very low cost escalation rate of 3.6% per annum as experienced during the French nuclear build program could be contingent upon these conditions being present.

Also included in Figure 3 are eight cost estimates pertaining to reactors currently under construction or reactors that recently began commercial operation. The reactors currently under construction in Finland (Olkiluoto-3) and France (Flammanville-3), have experienced severe cost escalation. Olkiluoto-3’s OCC is reportedly twice the original estimate of $2,800/kW, while Flammanville-3 is 50% over its $2,900/kW cost estimate [39]. The Olkiluoto-3 and Flammanville-3 average annual cost escalation rates are 9.9% and 12.2% respectively [7].

Table 1 summarises the described nuclear power cost escalation rates. These are illustrated in Figure 4, weighted by the number of reactors experiencing each observed rate. For this analysis, the lognormal probability distribution illustrated in Figure 4 has been applied, with a mean of 6.5% and a standard deviation of 2.2%. A maximum possible construction cost escalation rate of 15% per annum was applied for the Monte Carlo simulation. It is acknowledged that this probability distribution is informed by a limited amount of data; future work would benefit from a detailed analysis of the diversity of cost escalation rates experienced by individual reactors throughout the USA and French build programs, as well as nuclear plant constructed in other jurisdictions. However, this probability distribution is informed by the best available data on real historical experiences, and therefore is considered a reasonable input to this analysis.

<table>
<thead>
<tr>
<th>Jurisdiction</th>
<th>Cost escalation (real, compounded p.a.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>French PWR build program (58 reactors, 1970-2000)</td>
<td>3.6%</td>
</tr>
<tr>
<td>US nuclear build program (99 reactors, 1970-1990)</td>
<td>8.1%</td>
</tr>
<tr>
<td>Flammanville-3 (France) (1 reactor)</td>
<td>9.9%</td>
</tr>
<tr>
<td>Olkiluoto-3 (Finland) (1 reactor)</td>
<td>12.2%</td>
</tr>
</tbody>
</table>

Figure 4 - Nuclear power cost escalation rates during the construction period. Author’s own analysis, with data from source: [7]

4.2.3 FOAK to NOAK transition

Cost escalation operates in opposition to a FOAK-to-NOAK (First of a Kind to Nth of a Kind) OCC transition. Escobar Rangel & Leveque [37] found some evidence of learning during France’s PWR build program that prevented cost escalation from being as severe as was experienced over the US build program. As the number of reactors built of the same type and size increased, construction costs...
decreased (i.e. construction costs transitioned from FOAK to NOAK costs). Similarly, The University of Chicago [40], using evidence from the US nuclear build program, found that unpredictable regulation and construction stoppages reduced the potential for learning during the program.

One measure of the success of a chemical plant build program is its rapidity [41]. The FOAK-to-NOAK transition occurred in France because the time between reactor construction starts was short enough (in France, on average, a new reactor construction start occurred every 6 months) that experience and learnings accumulated by nuclear engineers and other professionals could be ‘spilled over’ between projects. Significant learning spill-overs were confined to reactors that were constructed by the same team of engineers and other professionals [42]. If new reactor construction starts are spaced too far apart in time, or if engineers and other professions have limited prior construction experience, experience and learning cannot be transferred from project to project [43]. In Australia, there might be some scope for recruiting workers who have worked on recent nuclear projects internationally, with proximity to Asia potentially providing an advantage. However, due to the overall low level of global nuclear construction activity over the past 20 years, the pool of talent from which to recruit is limited [43], and differences in jurisdictional regulatory requirements may limit the potential for benefiting from international experience.

This analysis suggests that Australia could achieve lower cost escalation by enabling the FOAK-to-NOAK transition, through standardising reactors, constructing multiple reactors at single sites and ensuring sustained competition among nuclear engineering and construction firms [40].

4.3 Construction Duration

The construction phase involves the engineering, procurement and construction (EPC) of reactors, associated infrastructure development, grid connection and first fuelling [7]. Historical construction durations for nuclear power plants are illustrated in Figure 5. US construction durations were sourced from Koomey & Hultman (2007) [35], while historical French construction durations were sourced from the IAEA (2015) [36]. Five-yearly average construction durations for Asian reactors that began commercial operation between 1980 and 2010 were sourced from the IAEA (2013) [44]. Also included are estimates pertaining to reactors currently under construction or that recently began commercial operation [26, 8].

As illustrated in Figure 5, the French PWR program experienced notably short construction times. Despite the fact that construction times increased over the course of the program, the mean
construction time was 76 months (6.3 years), while around half of the French reactors had construction times of less than 72 months (6 years) [36].

Construction times within the US nuclear program were observed to escalate more significantly over time. Nuclear reactors ordered in the US in the 1950’s took an average of 5 years to build, whereas reactors ordered during the 1970’s took an average of 14 years [43]. Most attribute increasing construction times to the evolving US nuclear regulatory process, including revised safety codes and inspection requirements.

One lesson learned from the construction time increases of the French and US build programs is that plant design should be completed before the start of construction. In the US and UK, design certification is now generally a two-stage process [45]. In the first stage (1-2 years), regulators review reactor designs in principle to ensure that they are not “fatally” flawed, and in the second stage (3-7 years) regulators review detailed reactor designs [45]. However, this two stage process has not been adopted everywhere. France and Finland carried out only the first design stage before construction on the Olkiluoto-3 and Flamanville-3 reactors commenced. Safety inspectors were not satisfied with the detailed reactor designs that were proposed mid-construction, leading to extensive construction delays [45]. For instance, construction on Olkiluoto-3 began in 2005 and was expected to be completed in 2009, while construction on Flamanville-3 began in 2007 and was expected to be completed by 2011 [43]. Revised estimates reveal that and Flamanville-3 and Olkiluoto-3 will not be completed until at least 2017 and 2018 respectively [46, 47].

Recent experience in Asia suggests that construction duration can be shortened by using large cranes, concrete plants and maintaining an open containment during construction [23]. The average construction duration of Asian reactors has decreased from 7.4 years in 1980-1985 to 5.3 years in 2005-2010 [44]. Additionally, the Taishan 1 & 2 reactors, on which construction began in 2009 and 2010, are expected to be completed by late 2015 and 2016 (construction durations of 6 years) [48]. Between 1990 and 2005, two Japanese reactors and one Korean reactor took less than four years to fully construct [44]. AREVA notes that, “thanks to the operating experience gained by AREVA’s teams on the two (FOAK) EPR reactors at Olkiluoto and Flamanville, the (Taishan 1 & 2) project has been shortened by 40 months” [49].

Despite the very short construction durations experienced in Asia, roughly 8% of US reactors, and 9% of all reactors that began commercial operation between 1980 and 2000 experienced construction durations greater than or equal to 15 years [35, 44]. This suggests that very long construction durations are possible.

Figure 6 illustrates histograms of construction durations for 77 nuclear reactors that began commercial operation between 1980 and 2012, sourced from the IAEA [44]. Construction durations were cited as five-yearly, country-wide averages. The average construction time was 8.7 years, with a standard deviation of 4.3 years (used to compute the lognormal probability density function). The average construction time in Asia was 6.5 years, while the average ‘rest of the world’ construction time (excluding Asian plant) was 9.9 years.
4.4 Correlation between OCC and construction duration

Evidence from the US and French nuclear build programs reveal a strong correlation between construction delays and OCC, as illustrated in Figure 7. This can be understood by the fact that long construction times generate additional costs owing to immobilized equipment and labour forces [42]. This is in addition to the fact that the cost of financing is higher with a longer construction period.
(which is explicitly included in the levelised cost calculation). This analysis indicates an $R^2$ correlation coefficient of 0.53 for the USA, and 0.62 for France. The average value of 0.58 was applied for this analysis in the calculation of correlated Monte Carlo probability distributions for OCC and construction duration.

![Figure 7 – Correlation between OCC and construction duration during the French and US nuclear build programs. Author’s own analysis, with data from sources: [35, 36]](image)

### 4.5 Pre-construction period

The pre-construction phase involves securing operating licenses and financing, reviewing technical designs, conducting public enquiries and acquiring and/or preparing the reactor site [7]. The World Nuclear Association [50] estimates a global average pre-construction duration of between three and seven years, while MacDonald [51] estimates that pre-construction in the UK will take four years. Harris et al. indicate that the shortest pre-construction phase for applications currently before the US Nuclear Regulatory Commission (NRC) is four to five years [7], and suggest a pre-construction period of five to six years is a “reasonable estimate”.

The pre-construction duration could decrease over the course of an Australian nuclear build program, especially if reactor designs are standardised. When the diversity of nuclear reactor designs is high, nuclear safety authorities must assess the potential risks of different models of reactors, which prevents rapid monitoring and approval processes [42]. With standardization, approval processes for reactor construction and operating licenses can become more streamlined. For example, the US NRC has recently adopted several new procedures intended to streamline the US nuclear regulatory process. These procedures include pre-approving standard reactor designs, early site permitting processes, and combining construction and operating licenses which previously were applied for separately [52].

On the basis of these estimates, the probability distribution illustrated in Figure 8 was developed and applied for this analysis, with a mean of 4.8 years, and a standard deviation of 1.5 years. A maximum possible pre-construction period duration of seven years was applied.
Cost escalation is often experienced over the pre-construction period, likely caused by a combination of delays due to the time taken to secure federal level and state level subsidies, delays to reactor design approvals, and the challenges inherent in securing project partners [7]. Harris et al. suggest that OCC estimates for nuclear plant increased at an average of 14.2% per annum on a real compounded basis between 2005 and 2011 in the USA [7]. Similarly, the average cost escalation rate of all 19 nuclear reactors currently in the pre-construction phase in the US is 15.7% p.a. (over the 2005-2011 period) [7].

Indicative estimates of pre-construction cost escalation were provided in [7] for fourteen nuclear power units in the USA, illustrated in Figure 9 in a histogram with a lognormal distribution, with a mean of 15% and a standard deviation of 13%. Notably, the range of uncertainty in pre-construction escalation is very large; some units experienced almost no cost escalation over this period, while other units experienced cost escalation of 40% per annum over the pre-construction period. This probability distribution was applied for the Monte Carlo simulation, with the pre-construction escalation rate limited to a maximum of 45% per annum.

4.6 Summary of key uncertainties
The key variables characterised via probability distributions in the Monte Carlo analysis are summarised in Table 2.

<table>
<thead>
<tr>
<th>Distribution Type</th>
<th>Mean</th>
<th>Standard Deviation</th>
<th>Maximum applied</th>
</tr>
</thead>
</table>
### 4.7 Static inputs to levelised cost calculation

The variables described in this section were characterised as static inputs to the levelised cost calculation.

#### 4.7.1 Operations and maintenance

Operation and Maintenance (O&M) costs can be divided into fixed and variable components. Fixed O&M costs cover expenses that must be incurred in order for the plant to be available in a particular year, and typically include costs such as labour, administration, and routine preventative and predictive maintenance. In contrast, variable O&M costs are only incurred as each additional megawatt hour is generated, and typically cover expenses such as process water and chemicals, and unplanned maintenance [14, 28].

A range of O&M cost estimates were collated from a range of sources, including the Australian Government Bureau of Resources and Energy Economics (BREE) [14], the EIA [28], the South African Department of Energy [53], MIT [54] and the IEA-NEA [27]. These estimates are collated in Figure 10. The fixed/variable cost split varied between sources. The majority of the EIA, South African DOE and MIT’s O&M cost estimates are comprised of fixed costs, with variable costs ranging from $0.46/MWh to $3.97/MWh, and averaging $2.21/MWh. In contrast, BREE’s estimate includes scheduled maintenance as a variable cost, and therefore has a much higher variable cost estimate of $15.21/MWh.

The average total O&M cost (fixed plus variable, assuming a capacity factor of 90%) was found to be $15.50/MWh with standard deviation $4.70/MWh. This is very close to the EIA’s O&M estimate, which has been adopted for this analysis (including the EIA’s assumed split between fixed and variable O&M).

![Figure 10 - O&M cost estimates comparison. Author’s own analysis, with data from sources: [14, 28, 53, 54, 27]](image-url)
O&M costs have been observed to remain relatively constant over time [41]. Over the US nuclear program, O&M costs exhibited a slight increasing trend [35].

4.7.2 Fuel costs

Uranium fuel costs include the costs of uranium mining and milling, conversion, enrichment and fabrication [55]. Certain characteristics of the nuclear fuel cycle depend on nuclear reactor type. This analysis only considers the pressurised water reactor (PWR) nuclear fuel cycle, as both generation III AP1000 and EPR reactors are PWRs.

4.7.2.1 Mining and Milling

The principal product from nuclear fuel mining and milling is U₃O₈. The selling price of U₃O₈ has fluctuated markedly over time, ranging from as low as $18/kg in 1992 to as high as $219/kg in 2007 [56]. Over the historical period from 1975 to 2014, U₃O₈ selling prices have averaged $58/kg, with a standard deviation of $43.30/kg. In 2014, the selling price averaged $71/kg.

The U₃O₈ selling price has been in decline since March 2011, due to the U₃O₈ supply overhang induced by the Fukushima nuclear disaster. BREE forecasts that U₃O₈ prices will increase in response to tighter market supply conditions to around US $137 per kilogram in 2019 [56]. The rate at which Japan’s nuclear power industry restarts, as well as the rate at which China’s nuclear power industry expands, are key factors affecting this projection and delays to either may slow the rate of price growth over the medium term [56].

For this analysis, a central U₃O₈ selling price of $100/kg has been assumed, slightly less than the average annual U₃O₈ selling price over the 2005-2014 period ($112/kg) [56]. This is consistent with a recent study by Rothwell & Ganda [57].

4.7.2.2 Conversion, enrichment and fabrication

During conversion, U₃O₈ is converted to UF₆. Rothwell & Ganda estimate that this processing costs $10/kg U₃O₈ [57]. Following conversion, the concentration of ²³⁵U in UF₆ is enriched [58]. The work required to enrich UF₆ is measured in Separative Work Units (SWU) [59]. A product assay of 4.5% was assumed, in line with Rothwell & Ganda [57]. The average price per SWU over the period 1975-2014 was $142/kg U₃O₈ [60]. The current price per SWU is less than $100/kg U₃O₈ and Rothwell & Ganda propose that it is unlikely to ever again exceed $142/kg U₃O₈ [57]. For this analysis, a set price per SWU of $100/kg U₃O₈ is assumed. Following enrichment, UO₂ fuel rods are fabricated from enriched UF₆ [55]. In line with Rothwell & Ganda [57], the UO₂ fabrication price is assumed to be $300/kgUF₆.

4.7.2.3 Fuel costs summary

Combining the various stages of fuel processing, the total front-end fuel cost is calculated to be $2,064/kg UO₂, or $5.20/MWh and $1.40/GJ. This is consistent with Rothwell & Ganda [57] and MIT estimates [58] of $5.40/MWh. The World Nuclear Association [55] and the IEA-NEA [27] both quote slightly higher front-end fuel costs of $6.51/MWh and $7/MWh respectively. BREE [14], quotes a significantly lower front-end fuel price of only $2.66/MWh. It appears that BREE has only considered the selling price of U₃O₈ in its calculations, and has neglected to include the costs of the conversion, enrichment and fabrications processes.

The front-end fuel cost breakdown reveals that the most expensive processes are the mining and milling, and enrichment processes, which together account for 81% of the total cost.

4.7.3 Waste disposal

The majority of the world’s nuclear power production is based on the “open” fuel cycle, in which spent fuel and associated high-level nuclear waste is sent directly to storage (instead of reprocessed to recover uranium and plutonium). The IEA-NEA estimates that spent fuel storage costs $3/MWh [27], while Rothwell & Ganda [57], Koomey & Hultman [35] and BREE [14] refer to the fact that nuclear power plants in the USA are required to contribute a fee of US $1/MWh for spent fuel storage. Since 1983 the US Department of Energy has collected this fee from US nuclear reactors, intended
eventually to finance a centralized storage facility for spent nuclear fuel [43]. This cost was assumed for this study (AUD$1.30/MWh).

4.7.4 Operating lifetime
Although the intended lifetime of both the generation III EPR and AP1000 nuclear reactors is 60 years, only a limited number of nuclear reactors have operating lifetimes in exceedance of 30 years [7]. 130 nuclear reactors have been decommissioned worldwide, with an average operating lifetime of only 22 years [45]. Recent UK experience indicates that reactor lifetimes of 60 years are possible, but not without additional costs for refitting of ageing reactor components, additional O&M and declining load factors [61]. These additional costs have not been factored into the LCOE model. Instead, a forty year operating lifetime has been applied, as in analyses by the Worldwatch Institute [45] and the MIT [54].

4.7.5 Capacity Factor
The capacity factor is the ratio of the actual output of a power plant over a period of time to its potential output if it operates at nameplate capacity throughout its operating life. The average annual US nuclear reactor capacity factor has increased from below 60% during most of the 1980’s to an average of approximately 90% in the post-2000 period [62]. Some of the increase is attributed to reduced equipment related reactor trips and shutdowns, and refuelling outages [63]. For this analysis a 90% capacity factor is assumed, based upon the average annual US nuclear reactor capacity factor over the 2000-2015 period [62]. This assumes that a nuclear power station would only be constructed in a market where it could operate with a high capacity factor, which may prove difficult to guarantee in practice.

4.7.6 Decommissioning
Only a limited amount of data is available on the cost to decommission nuclear reactors. A typical assumption is that the cost to decommission a nuclear reactor is between 9% and 15% of the reactor’s total investment cost [64, 65]. For this analysis, a decommissioning cost of 9% of the reactor’s total investment cost (OCC) is assumed. It is further assumed that the reactor is decommissioned over a period of ten years, following cessation of generation over the plant operating life. Decommissioning costs are assumed to be distributed equally per year over this period.

4.7.7 Construction profile
During the construction period, small amounts of the construction cost will be spent early on preparing the site, large amounts will be spent during the middle on equipment (including on reaction vessels and turbines), and small amounts will be spent late in construction on instrumentation, training and fuel loading [57]. Hence, a normally distributed nuclear reactor construction profile is assumed, with a mean equal to the middle year of construction and standard deviation equal to 1 year. Other distributions (such as a flat profile) were also applied to determine the sensitivity to this assumption; it was found to have relatively little influence on the levelised cost calculation.

4.7.8 Summary
These LCOE input assumptions are summarised in Table 3, with the relevant sources and justification for each.

<table>
<thead>
<tr>
<th>Input Parameter</th>
<th>Value Assumed</th>
<th>Source/justification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor net capacity (MW)</td>
<td>1,215</td>
<td>[14]</td>
</tr>
<tr>
<td>Construction profile</td>
<td>Normal distribution</td>
<td>[57]</td>
</tr>
<tr>
<td>Fixed O&amp;M ($/MW/y)</td>
<td>96,278</td>
<td>[28]</td>
</tr>
<tr>
<td>Variable O&amp;M ($/MWh)</td>
<td>2.21</td>
<td>[28]</td>
</tr>
<tr>
<td>Fuel (Front-end) ($/GJ)</td>
<td>1.4</td>
<td>Calculated value</td>
</tr>
<tr>
<td>Waste processing and disposal ($/MWh)</td>
<td>1.3</td>
<td>[14, 35, 57]</td>
</tr>
<tr>
<td>Capacity Factor</td>
<td>90%</td>
<td>Average annual US nuclear reactor capacity factor over the 2000-2015 period</td>
</tr>
<tr>
<td>Input Parameter</td>
<td>Value Assumed</td>
<td>Source/Justification</td>
</tr>
<tr>
<td>---------------------------------</td>
<td>---------------</td>
<td>----------------------</td>
</tr>
<tr>
<td>Thermal Efficiency</td>
<td>34%</td>
<td>[14]</td>
</tr>
<tr>
<td>Operating lifetime (years)</td>
<td>40</td>
<td>[54, 45]</td>
</tr>
<tr>
<td>Decommissioning (% of OCC)</td>
<td>9%</td>
<td>[64, 65]</td>
</tr>
<tr>
<td>Time to decommission (years)</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Discount Rate</td>
<td>10%</td>
<td>[14]</td>
</tr>
</tbody>
</table>

5 Central estimates

The mean estimates for OCC, construction duration, pre-construction duration, construction cost escalation and pre-construction cost escalation for each of the “Rest of World (excluding Asia)” and “Global” distributions, listed in Table 2, were combined as described in section 3.1.3. The resulting central estimates of OCC are illustrated in Figure 11. The historical cost escalation experienced over the US and French build programs are included so that these values can be considered in historical context. It is clear that cost escalation during the construction and pre-construction periods has a significant influence on the OCC, and there is considerable uncertainty over these values. This is likely to be the source of significant uncertainty in nuclear plant costs.

![Figure 11 - Historical OCC escalation, compared with projections of potential future cost escalation (central estimates). Projected values in 2015 are central estimates without escalation, values in 2020 are with pre-construction escalation only, and values in 2029 and 2030 are with pre-construction and construction escalation, or with construction escalation only as indicated. Author’s own analysis, with data from sources: [35, 36]](image)

The mean estimates for each variable listed in Table 2 for each distribution were combined with the estimates of other cost components listed in Table 3 to calculate central estimates of levelised costs, illustrated in Figure 12. Without escalation, the levelised cost of nuclear power is projected to be $138/MWh, or $122/MWh if Asian plant estimates are included. During pre-construction this is projected to escalate to $244/MWh, or $212/MWh including Asian plant. By the completion of construction, costs are projected to have escalated to a central value of $428/MWh, or $345/MWh including Asian plant. If pre-construction escalation is excluded, the final total levelised cost is projected to be $230/MWh, or $188/MWh including Asian plant. Even in the exceptional case that all pre-construction escalation could be avoided, and construction escalation limited to the low value observed during the optimal part of the French build program (3.6%), levelised costs are calculated to be $182/MWh, or $155/MWh including Asia.
Figure 12 - Levelised cost projections for central (mean) estimates. Percentages illustrate the proportion of the levelised cost related to capital expenditure. Labels above columns indicate the total LCOE. Source: author’s own analysis.

6 Contributions to cost uncertainty

Table 4 provides an indication of the sensitivity of the levelised cost calculation for nuclear power to the various input variables. The mean values for the “rest of the world (excluding Asia)” distributions have been applied to calculate a “central” levelised cost of $138/MWh (without escalation), or $428 (with escalation). Each variable was then individually adjusted to a “high” and “low” value, where these were selected to provide an indication of the potential range in each input variable (selecting outermost estimates from the literature surveyed). The impact on the levelised cost was calculated, and summarised for each variable in Table 4. This analysis indicates a strong division between variables that are important contributors to nuclear plant cost uncertainty, and variables that are significantly less important. The most important variables are those that affect capital and financing costs, such as the OCC, the construction duration, escalation rates and the discount rate. The capacity factor at which the plant operates is also found to be important.

Conversely, variables related to the operation of the plant, such as operations and maintenance, fuel, waste disposal and thermal efficiency were found to be relatively insignificant contributors to cost uncertainty. The plant operating life was also relatively unimportant, as was the decommissioning cost and time to decommission the plant (since these occur far in the future, and are therefore strongly discounted).

Table 4 – Sensitivity to assumptions in LCOE calculation, applied to “rest of world (excluding Asia)” estimates. The central LCOE is $138/MWh without cost escalation, and $428 with cost escalation.

<table>
<thead>
<tr>
<th>Important contributors to cost uncertainty</th>
<th>Central Estimate</th>
<th>High Estimate</th>
<th>Low Estimate</th>
<th>Impact on LCOE (Δ$/MWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overnight Capital Cost ($/kW)</td>
<td>5080</td>
<td>6812</td>
<td>1833</td>
<td>High</td>
</tr>
<tr>
<td></td>
<td>Low</td>
<td></td>
<td></td>
<td>36</td>
</tr>
<tr>
<td></td>
<td>136</td>
<td>-68</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>-254</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Construction Duration (years)</td>
<td>9.9</td>
<td>20</td>
<td>4</td>
<td>High</td>
</tr>
<tr>
<td></td>
<td>Low</td>
<td></td>
<td></td>
<td>76</td>
</tr>
<tr>
<td></td>
<td>886</td>
<td>-27</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>-192</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cost escalation rate during construction (% pa)</td>
<td>6.5%</td>
<td>12.2%</td>
<td>3.6%</td>
<td>High</td>
</tr>
<tr>
<td></td>
<td>Low</td>
<td></td>
<td></td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>269</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>-95</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
This analysis suggests that if the aim is to minimise plant costs and cost uncertainty, the focus should be on minimising capital cost escalation. This may be achieved by utilising standard plant designs, repeatedly constructed over a short period of time without design changes. Design changes that may incrementally increase plant efficiency or reduce operating costs are unlikely to be cost effective. However, design changes may also be driven by increasing safety measures, which may be cost effective or otherwise justified if they contribute to avoiding rare but extremely expensive catastrophic events [37].

This analysis also indicates that in order to better project the possible future costs of nuclear power, the focus should be on better quantifying the “important” variables, while the “unimportant” variables can be adequately quantified based upon existing analysis. For example, the cost of decommissioning a nuclear power plant remains highly uncertain, but since it is not an important contributor to total plant costs (due to discounting), this uncertainty is relatively unimportant. Of course, there may be non-cost related implications related to factors such as waste disposal and decommissioning which may be important factors in the decision to invest in or support the development of nuclear power, but these are considered beyond the scope of this analysis.

Note that although the capacity factor and discount rate are identified as important variables that contribute to cost uncertainty, these have not been included as probability distributions in the Monte Carlo analysis. The appropriate discount rate may vary significantly depending upon the financing arrangements applied, but in any specific case is likely to be relatively well understood prior to the commitment to construct the plant. Similarly, the capacity factor at which a plant operates may vary significantly depending upon the intended operational mode of the plant, but is likely to be relatively well understood for a specific project to be constructed for operation in a particular market. Therefore, these variables have been included as static variables (not contributing to uncertainty) in this analysis. If there were additional uncertainty around these variables in any particular case, it would be important to capture this uncertainty in that analysis.
7 Monte Carlo Simulation Results

This section presents the results of the Monte Carlo simulation, combining the probability distributions for the variables listed in Table 2 to create probability distributions for OCC, levelised cost, and the year of commissioning.

7.1 OCC

The resulting distributions for OCC are illustrated in Figure 13. Even without escalation, there is considerable uncertainty over OCC, as illustrated in blue in Figure 13. Pre-construction escalation exacerbates this uncertainty (illustrated in orange), and construction cost escalation spreads it further to a broad distribution (illustrated in black). The distribution with pre-construction and construction escalation has a mean of $19,043/kW (or $15,796 including Asian plant), and a very large standard deviation of $104,385/kW. This illustrates the considerable degree of uncertainty over nuclear plant costs.
Figure 13 – Probability distributions for OCC estimates in 2015 (blue), when construction commences (orange), and when the plant commissions (black), comparing simulation results for a global average (dotted), and excluding Asian plant (solid).

Figure 13b) provides the cumulative probability distribution. This illustrates that even without escalation, there is a 50% probability that a nuclear plant OCC will exceed $4,500/kW, and a 15% probability of exceeding $5,500/kW. With escalation, there is a 50% probability that nuclear plant OCC will exceed $11,500, and a 15% probability that it will exceed $24,500/kW.

7.2 Levelised costs
The probability distributions for levelised costs are illustrated in Figure 14. As with OCC values, uncertainty is present even without escalation, and is strongly exacerbated by the application of cost escalation. Without escalation, the mean levelised cost is $145/MWh (or $130/MWh including Asian plant), with a significant standard deviation of $62/MWh. With cost escalation included, the mean levelised cost increases to $515/MWh (or $412/MWh including Asian plant), with a very large standard deviation of $2,646/MWh. Figure 14b) illustrates that even without cost escalation, there is a 50% probability that levelised costs will exceed $132/MWh, and a 15% probability that costs will exceed $183/MWh. With cost escalation, this increases to a 50% probability of costs exceeding $278/MWh, and a 15% probability of costs exceeding $650/MWh. There is an 80% probability of costs exceeding $170/MWh.
Figure 14 – Probability distributions for levelised cost estimates in 2015 (blue), when construction commences (orange), and when the plant commissions (black), comparing simulation results for a global average (dotted), and excluding Asian plant (solid).

The mean, median and standard deviation of each distribution are summarised in Table 5.

<table>
<thead>
<tr>
<th></th>
<th>OCC ($/kW)</th>
<th></th>
<th>LCOE ($/MWh)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>Median</td>
<td>Standard</td>
<td>Mean</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Deviation</td>
<td></td>
</tr>
<tr>
<td>Without escalation</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>4,593</td>
<td>4,417</td>
<td>1,341</td>
<td>130</td>
</tr>
<tr>
<td>Rest of world (excluding Asia)</td>
<td>5,075</td>
<td>4,988</td>
<td>918</td>
<td>145</td>
</tr>
<tr>
<td>With pre-construction escalation</td>
<td>8,035</td>
<td>5,820</td>
<td>38,045</td>
<td>203</td>
</tr>
<tr>
<td>Global (including Asia)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rest of world (excluding Asia)</td>
<td>9,001</td>
<td>6,391</td>
<td>52,753</td>
<td>235</td>
</tr>
<tr>
<td>With pre-construction and construction escalation</td>
<td>15,796</td>
<td>9,895</td>
<td>63,967</td>
<td>412</td>
</tr>
<tr>
<td>Global (including Asia)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rest of world (excluding Asia)</td>
<td>19,043</td>
<td>11,909</td>
<td>104,385</td>
<td>515</td>
</tr>
</tbody>
</table>

7.3 First year available for commissioning

Figure 15 illustrates the uncertainty around the date of first nuclear plant commissioning, with the mean, median and standard deviation of each distribution listed in Table 6. This analysis assumes that the pre-construction period commences immediately (in 2015). Given the lack of political consensus and lack of public support for nuclear power in Australia, this is unlikely to occur, but it is used to provide an indication of the first possible date of commissioning, if there were an immediate national consensus that nuclear generation should be established in Australia.

Due to uncertainty around pre-construction durations, plant construction may be able to commence as early as 2017, but may be as late as 2023. The mean time for starting construction, for pre-construction commencing in 2015, is 2020. Construction durations enhance the uncertainty, with the first possible year for commissioning having a mean of 2028 to 2030, with a standard deviation of four years. There is a 15% probability that commissioning of the first plant will occur after 2035.
7.4 Best case sensitivity
To project the absolute best case possibility, an additional sensitivity was calculated setting the pre-construction escalation rate to zero, and the construction escalation rate to 3.6%, the value observed during the French build program. Note that iterations of this nature were included in the original Monte Carlo simulations, by virtue of the probability distributions applied for those variables. This sensitivity removes all uncertainty related to cost escalation (making these values static), and therefore underrepresents the degree of uncertainty. It is used only for comparison purposes.

In this sensitivity, the OCC distribution was found to have a mean of $7,476/kW (or $6,554/kW if Asian plant are included), and a standard deviation of $2,651/kW. The OCC had a 50% probability of exceeding $6,919/kW, and a 15% probability of exceeding $9,500/kW.
The LCOE distribution was found to have a mean of $209/MWh (or $181/MWh if Asian plant are included), and a standard deviation of $151/MWh. The LCOE had a 50% probability of exceeding $171/MWh, and a 15% probability of exceeding $270/MWh.

8 Discussion

The probability distributions applying to ‘rest of world’ (excluding Asia) could be considered a reasonable first order estimate of the FOAK cost of establishing nuclear in Australia and in other OECD jurisdictions that haven’t yet implemented nuclear power. This assumes that Australia’s economic and regulatory environments are more akin to the USA and EU than Asia. This probability distribution has not been adjusted for the cost of labour and the availability of equipment and expertise in Australia (as was done by BREE [14]), due to the significant uncertainty over the appropriate escalation factors. Therefore, this distribution may represent an underestimate of the FOAK cost of nuclear power in Australia.

Similarly, the probability distribution of costs applying globally (including Asia) could be argued to be a reasonable first order estimate of the NOAK cost of establishing nuclear in Australia. This allows for a substantial degree of learning to bring down costs as the transition from FOAK to NOAK occurs, represented by the inclusion of the lower cost Asian plant in the distribution. However, it also recognises that Australia is likely to have a regulatory and economic environment more similar to Europe and the USA, and is likely to experience higher labour costs, both of which may prevent NOAK costs being as low as observed for the Asian plant. The inclusion of all plant in the probability distribution represents the higher uncertainty over the transition from FOAK to NOAK, and the eventual cost of nuclear in Australia if a sustained build program were established.

Even without any cost escalation, a mean LCOE of $130-$145/MWh, with a 50% probability of costs exceeding $132/MWh, and a 15% probability of exceeding $183/MWh, nuclear power is likely to struggle to compete on an economic basis with renewable options in Australia when seeking to achieve major emission reductions. Wind generation is widely available for commercial deployment in Australia at present at a well-established cost of $80-$120/MWh, and solar photovoltaics at a cost of $200-$300/MWh [14]. Furthermore, wind and photovoltaics generation have low cost risk by comparison with nuclear generation. If there is any cost escalation, as is typical with nuclear power, costs for nuclear will be higher. Central estimates of cost escalation indicate a mean LCOE of $412-$515/MWh, with a 50% probability of costs exceeding $278/MWh, and a 15% probability of costs exceeding $650/MWh. This puts nuclear generation at a far higher cost than readily available wind and photovoltaics generation. It is emphasised that these are central estimates for cost escalation; higher levels of cost escalation were observed during the USA nuclear build program, and for plant currently or recently under construction in the USA, Finland and France. Even in the very best case, with no pre-construction cost escalation, and the very lowest possible cost escalation during construction (3.6%), the levelised cost of nuclear exceeds $200/MWh, making this technology substantially more expensive than wind generation in Australia.

Given the variable availability of wind and photovoltaic technologies, nuclear and wind generation are not directly comparable on an LCOE basis alone. A full power system optimisation is required to appropriately consider the role that nuclear generation might cost-effectively play in a future market; this is proposed as future work. It is possible that nuclear generation may be a cost effective alternative to “dispatchable” and synchronous renewable technologies such as solar thermal and geothermal generation, with concentrating solar thermal estimated to be available at a cost of around $300-$400/MWh in Australia [14]. However, hourly power system modelling indicates that these technologies may only be included in small proportions in a least-cost optimal generation mix, with the majority of energy being instead sourced from wind generation [66]. The flexibility of nuclear generation would be an essential consideration for inclusion in such a system, and the detrimental impacts upon plant capacity factor are likely to reduce nuclear cost competitiveness. It is worth noting that previous work indicates wind primarily displaces “base-load” generation in a least-cost
generation portfolio [67], suggesting that high wind portfolios require partnership with intermediate and peaking plant, rather than additional baseload generation such as nuclear.

9 Policy Implications and Conclusions

Although nuclear and renewables both offer the potential for low greenhouse emissions electricity production, this analysis suggests that when the substantial cost risk of generation III nuclear power is taken into account, it is unlikely to be economically competitive in nations like Australia. Emerging nuclear technologies, such as molten salt reactors, may have economic potential, but are at a very early stage of commercial development at present, and have not been considered here.

This analysis indicates that although wind and photovoltaics are variable and bring other integration challenges, these technologies may be more suitable for achieving cost effective low emissions electricity systems, when compared with generation III nuclear. This suggests that policies and mechanisms aiming to achieve low emissions electricity may be better targeted at overcoming the integration challenges associated with renewable technologies such as wind and photovoltaics, rather than supporting the development of nuclear power. Future modelling studies that compare role of nuclear and renewables in economic future electricity generation portfolios should take care to appropriately include this cost risk, as well as the integration costs associated with renewable technologies, in order to make an accurate comparison between the technologies. This is facilitated by the quantification of the cost risk provided in this study.

The considerable cost risk associated with nuclear power indicates the necessity of explicitly considering risk in any assessment of policy mechanisms to support nuclear development. The party that will ultimately bear cost risk is a consideration of central importance; will delays and cost overruns be borne by industry, the government (and therefore ultimately the public), or some other entity?

10 Acknowledgements

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11 References


