Cost estimates for nuclear power in the UK

ICEPT Working Paper

August 2012
Ref: ICEPT/WP/2012/014

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Executive Summary

The primary conclusion of this paper is that the capital cost estimates for nuclear power that are being used to inform current UK Government policy rely on costs escalating over the pre-construction and construction phase of the new build programme at a level below those that have been experienced by past US and European nuclear build programmes. This suggests that nuclear power may be more expensive than recent Government commissioned reports have indicated, and may therefore require greater levels of financial support (reflected, for example, in the strike price for the Contracts for Difference envisaged in the UK's Energy Bill) than policymakers might have originally envisaged.

Current UK Government policy documents rely upon a central estimate of 'overnight cost' (i.e. construction costs excluding financing costs) of £3,742/kW for the new build programme and an associated levelised cost of £95/MWh. This estimate is based upon the following major assumptions:

- Construction costs escalating over the construction phase of the new build programme at an implied rate of ~1.5% (real, compounded).
- A construction phase of 6 years.
- The technical specifications of nuclear reactors to inform assumptions on reactor operating lifetimes and plant load factors.

The capital cost of nuclear plants represents around 80% of the overall cost of nuclear power generation, and the scope and complexity of nuclear reactor plants drive pre-construction and construction phases to span upwards of 14 years, in turn exposing the nuclear build process to a significant amount of exogenous pressures that impact final 'out-turn' capital costs.

This paper has analysed the cost escalation rates of 179 reactors from US and European nuclear build programmes. The implied ~1.5% cost escalation rate that current estimates for the UK market rely upon is significantly below the escalation rates that have been experienced by previous French (3.6%) and US (8.1%) nuclear build programmes and current European (11.1%) and US (14.2%) new build programmes. For the purposes of the analysis, this paper uses an escalation rate of 5.4% which represents the weighted average escalation rate of the 58 reactors in the French build programme between the 1970s and 1990s, the 99 reactors in the US new build programme between the 1970s and 1990s and the IHS/Cambridge Energy Research Associates (CERA) European Power Capital Cost index. Applying this cost escalation rate to the 'more than £9 billion' cost estimate provided by EDF Energy to construct two new reactors at the Hinkley C site, results in the overnight cost estimate for the UK market increasing from the current estimate of £3,742/kW to c£4,885/kW.

The 6 year construction phase estimate that is being used to inform cost projections for the UK new build programme is 2 years shorter than the current global average. With construction phase times in the US and France increasing due to new reactor technologies and regulatory requirements, the paper uses the global average construction time of 8 years as a baseline.

Following a similar approach, this paper relies upon global averages and historical performance as the primary indicators of future plant operating performance rather than relying on the technical specifications of reactors that are yet to begin operation anywhere in the world.

Finally, based on industry estimates for the nuclear new build programme in the UK market we base our calculations on a Weighted Average Cost of Capital (WACC) of 11% versus the current estimate of 10%.

Figure 1 below demonstrates how sensitive existing levelised cost estimates are to these revised assumptions, with levelised costs increasing from £95/MWh to £164/MWh.

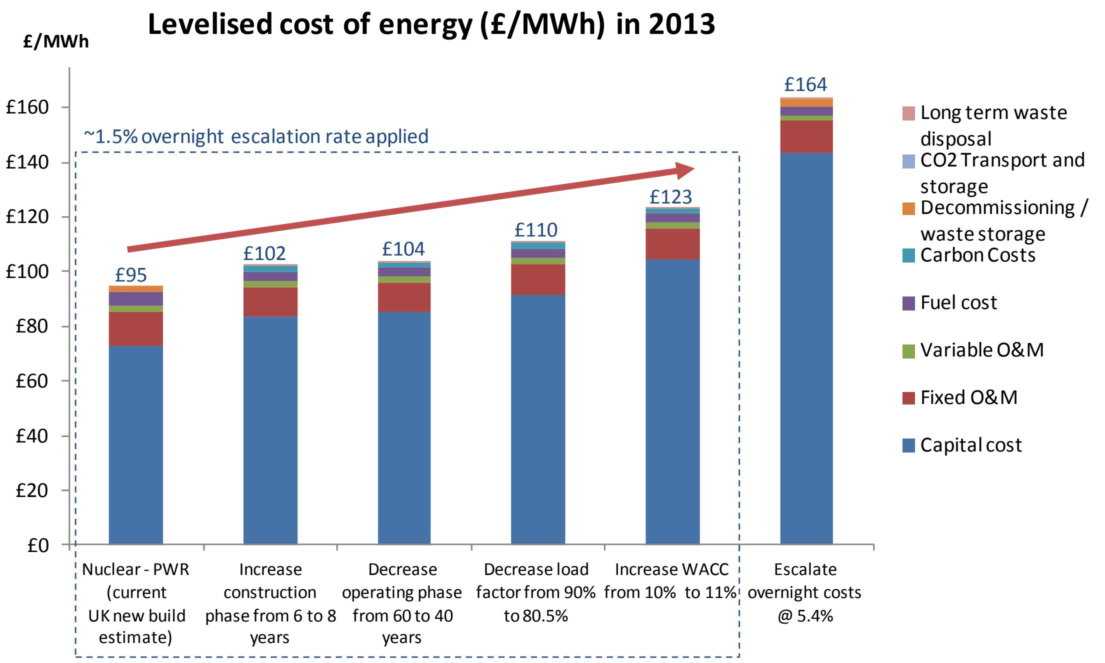


Figure 1 Sensitivity of UK Government levelised cost estimates to changes in key assumptions, Sources: (Mott MacDonald, 2010) and the analysis presented in this paper.

Due to the significant uncertainties that surround cost estimates for nuclear power in general it is very difficult to give a high level of confidence to any single levelised cost estimate. This paper does however show that there is sufficient empirical evidence to support the notion that costs may be substantially higher than recently envisaged.

It is of course possible that nuclear project developers will take a more optimistic view on the potential for cost escalation during the pre-construction and construction phase, and chose to take projects forward with a level of policy support that is consistent with this more optimistic perspective. In doing so, they would be bearing the risk of cost escalations unless they believe that there may be a possibility in future to seek additional support if costs do rise. A further possible outcome is that it proves impossible for Government and project developers to agree on the support level required, leaving the UK with the challenge of how to achieve its energy policy objectives without any additional contribution from nuclear power.

1. Introduction

As recently as 2002, the view of the UK Government was that the focus for its energy policy should be energy efficiency and a substantial increase in electricity generation from renewables, with the option of new nuclear power 'kept open' but with no direct support (PIU, 2002). By the mid-2000's however, the UK Government's disposition towards new nuclear power was much more positive. The 2006 Energy Review concluded that the economics of the technology had improved and that, 'new nuclear power stations would make a significant contribution to meeting our energy policy goals', albeit with the clear proviso that, 'it will be for the private sector to initiate, fund, construct and operate new nuclear plants', with the role of Government limited to, 'addressing potential barriers'(DTI, 2006). This position was informed, at least in part, by an assessment of the relative costs of the range of large-scale low-carbon electricity generating technologies available to the UK (DTI, 2006, Kennedy, 2007), and was followed by the 2008 White Paper on Nuclear Power (BERR, 2008) which confirmed the UK Government's view that, 'nuclear power has a key role to play as part of the UK's energy mix'.

The current UK Government was formed in 2010 from a coalition of the Conservative and Liberal Democrat parties and its initial position with regards to support for new nuclear power reflected the divergent positions of the coalition members, with the Conservative party supportive and the Liberal Democrats opposed (Cabinet Office, 2010). The resolution to this conflict involved an agreement that Government would support new nuclear power projects, 'provided that they receive no public subsidy' (ibid). Whilst the position of no public subsidy is still government policy, the on-going Electricity Market Reform (EMR) process appears likely to offer support for new nuclear power stations (and other low carbon generation options) through a package of measures including a Feed-in Tariff (FiT) via a Contract for Difference (CfD) and an underpinning of the price of CO_2 emissions (DECC, 2011a, HM Government, 2012).

Since the change of heart towards nuclear from the mid-2000s onwards, projected costs for new nuclear plants have risen considerably, as have costs for many other electricity generation technologies (Greenacre et al., 2010, Heptonstall et al., 2012). That notwithstanding, as Figure 2 shows, recent cost projections for electricity from nuclear power in a UK context are up to around £100/MWh, which if realised, puts this technology towards the lower end of costs for low-carbon generation. These cost estimates helps to underpin the current UK Government's commitment to nuclear power described above.

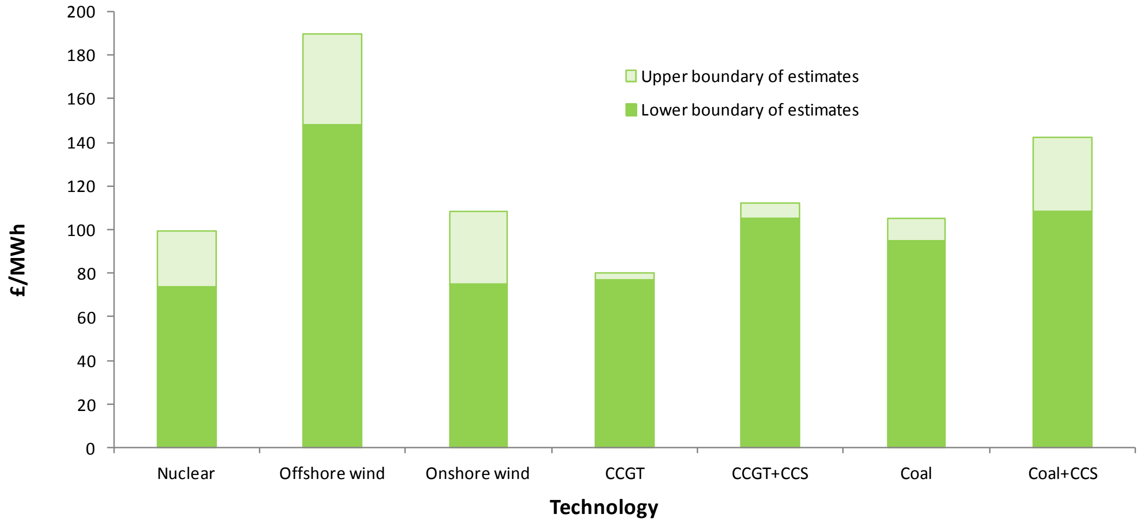


Figure 2: Range of recent estimates for large-scale electricity generation in the UK. Note that these estimates are for projects starting around the time the sources were published (i.e. they are not forecasts for projects starting some years into the future). Carbon costs are included where applicable. Sources: (Mott MacDonald, 2010, Mott MacDonald, 2011, Arup, 2011, Parsons Brinckerhoff, 2011)

More recent analysis suggests even lower costs for 'nth of a kind' (NOAK) plants built after the first wave of new generation plants, with the latest projections commissioned by DECC suggesting a levelised cost for electricity from nuclear plants of around £65/MWh for a notional NOAK plant with a 2017 project start date (Parsons Brinckerhoff, 2011).

Of course, cost projections for any of the technologies outlined in Figure 2 can turn out be wrong for a range of reasons including unanticipated changes in commodity prices, currency movements, supply chain constraints, lack of technological maturity, appraisal optimism, and changes to the regulatory environment (Greenacre et al., 2010). The central contention of this paper is that recently published levelised cost estimates for nuclear new build in the UK may not be fully adjusted to reflect the following market realities that surround new build nuclear economics:

- In the US, European and the UK markets nuclear new build programmes have been effectively dormant for the past 15 – 20 years.
- The pre-construction and construction phases of nuclear plants last around 14 years. This time frame exposes the nuclear build process to a significant amount of exogenous pressures that impact final 'out-turn' capital costs.
- There are no reactors of any generation type that have been built in liberalised energy markets under commercial terms that the UK new build programme will operate under.

These factors all increase the uncertainty surrounding new build nuclear capital cost estimates and, in turn, there has been a wide range of levelised cost estimates for nuclear power.

This paper therefore examines the potential impact on nuclear cost projections of adopting different assumptions for key time and cost variables, based on historic and current observed values. Section 2 explains the approach and methodology for the analysis, Section 3 summarises the findings from an examination of the history of nuclear power projects, Section 4 explains the results of applying these historical lessons to current estimates for nuclear power in the UK and Section 5 concludes with observations on the implications for policymakers.

2. Approach and Methodology

In their series of ‘Projected Costs of Generating Electricity’ reports the International Energy Agency (IEA) define levelised cost per unit of electricity output (LCOE) as, ‘the average price that would have to be paid by consumers to repay exactly the investor/operator for the capital, operation and maintenance and fuel expenses, with a rate of return equal to the discount rate’ (IEA, 2005). The calculation results in a cost per unit of output (£/MWh) that has been used by policymakers to understand the relative costs of different electricity generation technologies.

The results from such cost projections, whatever the technology, depend on the set of assumptions around variables such as capital cost, construction times, the expected plant life, operational and maintenance costs, fuel costs, plant availability, load factor and discount rates (Gross et al., 2010). This paper focuses in particular on the length of the pre-construction and construction phases and how capital costs can change over these phases, drawing on evidence from US and European nuclear programmes. It then compares this experience with assumptions that feed into current UK nuclear cost estimates and goes on to substitute values based on the observed experience into a levelised cost model to examine the effect that using these alternative values may have on the projected costs of nuclear power. Finally it looks at the possible implications for UK energy policy.

The analysis that underpins this paper uses a LCOE model that calculates cash flows for each of the phases of the nuclear life-cycle on a real, pre-tax basis, based on a flexible set of inputs. The model then discounts these cash flows and divides the resultant value by the discounted energy generated by the plant throughout its lifetime in order to calculate the levelised cost of generation on a £/MWh basis. In order to maintain comparability with most other studies, our assumptions and calculations focus on ‘busbar’ costs (i.e. up to where the power station connects to the transmission grid) and ignores any items such as losses in transmission and distribution or additional system balancing costs (Gross et al., 2006, Strbac et al., 2012).

3. Findings from analysis of US and European nuclear programmes

Pre-construction period

The pre-construction phase involves securing operating licenses, reviewing technical designs, conducting public enquiries, performing site acquisition/preparation and completing financing negotiations.

Length of the pre-construction period

The World Nuclear Association estimated a global average pre-construction phase of approximately 3-7 years for nuclear power (World Nuclear Association, 2011a). Based on an analysis of the applications that are currently before the US Nuclear Regulatory Commission (NRC), the shortest pre-construction phase is estimated to be around 4-5 years. This figure is for the Vogtle 3 & 4 plants which applied to the NRC in March 2008 and received their construction and operating license in February 2012. Twelve further plants that applied at a similar time have all experienced significant delays and have yet to begin construction due to the time taken to secure Federal level (e.g. loan guarantees) and state level (e.g. Construction Work in Progress) subsidies, delays to reactor design approvals and the challenges inherent in securing project partners (due primarily to the Fukushima incident in Japan which has increased the uncertainty surrounding the capital and regulatory environments supporting nuclear new build programmes).

In the UK the pre-construction phase is estimated to take 4 years (Mott MacDonald, 2011). Currently Hinkley C is the most advanced site which has made positive progress since 2010; however due to a range of on-going uncertainties in the UK market (e.g. what companies and what reactor technologies might replace the capacity proposed by the defunct Horizon Nuclear Power consortium, what will be the final implications of the Fukushima incident on the approval/licensing process and the regulatory uncertainty surrounding the UK Government's Electricity Market Reforms) we suggest that a pre-construction period of 5-6 years is a reasonable estimate for the first reactor builds. This figure is consistent with other recent estimates (Deloitte, 2010).

We consider that it is too early to revise current estimates of the associated costs of the pre-construction phase as the uncertainties identified above could either serve to increase or decrease the costs associated with this phase in the future.

Cost changes during the pre-construction period

The most recent and relevant case studies relating to how overnight cost estimates can change during the pre-construction period come from the US due to this market having similar labour costs, licensing procedures and reactor technologies to the UK. Analysis of publicly available information on US projects indicates that, on average, overnight construction cost estimates in the pre-construction phase increased at 14.2% per annum on a real compounded basis between 2005 and 2011, see Figure 3.

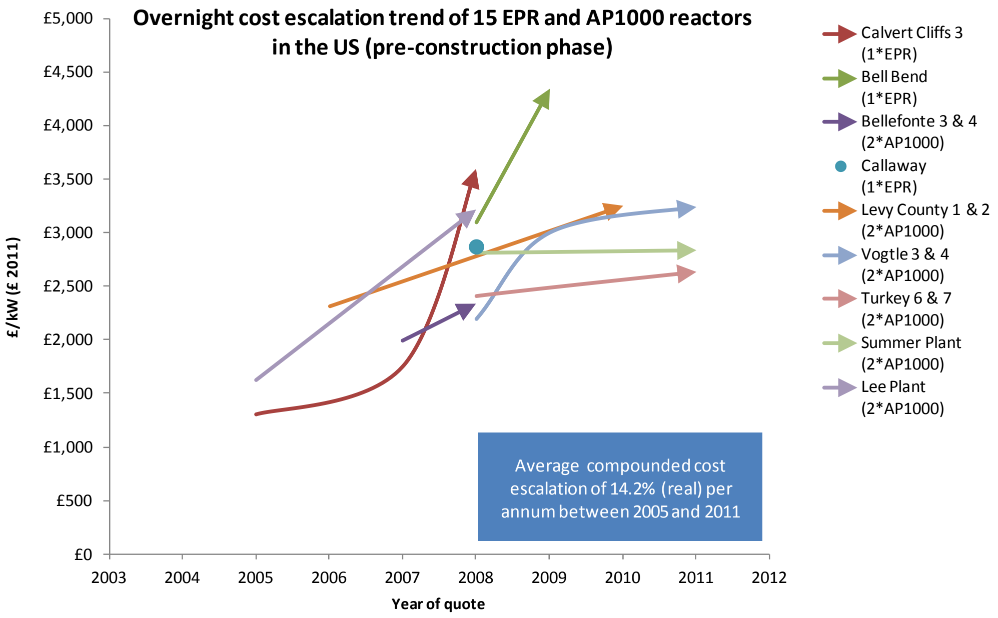


Figure 3: Overnight cost escalations in the pre-construction phase of US reactors between 2005 and 2011 (EPR and AP1000 reactor types only). All costs are expressed in 2011 values using the US CPI to index historic costs. For the Bell Bend and Callaway plants, where pure overnight cost estimates were not available, we have reduced quoted construction cost estimates by 23% (the average reduction that was experienced from other US plants in this analysis). Data sources are diverse and of varying credibility and content, so emphases should be placed on overall trends in the data, rather than on individual project-level estimates. Source: Authors own analysis from a range of sources outlined in Appendix 1.

The reasons behind these cost escalations are wide-ranging however, in general, they stem from the same reasons that lie behind why the majority of plants have experienced delays in progressing through the pre-construction phase.

Construction period

The construction phase includes the engineering, procurement and construction (EPC) of reactors, associated infrastructure development, grid connection and first fuelling.

Length of the construction period

Estimated construction times for new reactors have varied primarily due to the type of reactors being built (for example, between Generation III/Generation III+ and Generation II designs), how the technical approval process is structured (for example, whether the design approval is required before construction commences) and who is making the estimates (utilities, vendors, independent sources or the media). As with many major infrastructure projects, actual completion times can vary substantially from initial estimates. The reason why this uncertainty is so crucial to the nuclear industry is that, due to high levels of capital at risk, for every year a project is delayed the LCOE increases by approximately 10%.

Figure 4 shows that, since the 1970s, the median global construction time including reactors constructed in Asia is 7.7 years whilst the median figure excluding Asia is 8.3 years.

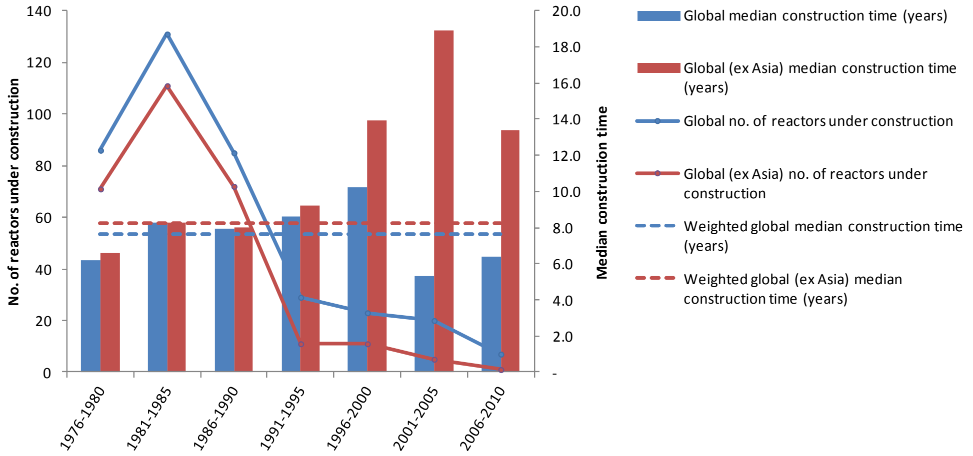


Figure 4: Construction time of global reactors (construction start to first grid connection). Source: Authors own analysis using IAEA-PRIS database (IAEA, 2012).

In 2007, the UK Department of Trade and Industry estimated that the construction phase was likely to last between 5 to 10 years (DTI, 2007a). The two Generation III+ reactors currently being built in France and Finland reflect the higher end estimate with a currently forecasted construction time of 9 years for Flamanville-3 (originally estimated to be completed in 6 years) and an unknown construction time for Olkiluoto-3 which was originally estimated to be completed by 2009 (within 4 years). The reason why the Olkiluoto-3 plant still has an undetermined construction timeline is that, in July 2012, the utility responsible for Olkiluoto-3 confirmed that due to slower than expected progress on key installations, the plant would not be constructed by their revised estimate of 2014 (representing a 9 year construction phase) and is unable to confirm any new timeline. (Johnstone, 2011, NCE, 2009, Kinnunen, 2012, BBC, 2012).

Of key relevance to the UK new build programme is understanding the impacts that new reactor technologies and larger reactor sizes have had on construction times. Using US Department of Energy data, Davis (2011), estimated that due primarily to increase regulatory requirements in the US, ‘reactors ordered during the 1950s took an average of about 5 years to build, whereas reactors ordered during the 1970s took on average 14 years’.

Supporting this upward trend, Figure 5 shows the results of analysis by (Grubler, 2009) of the French reactor history.

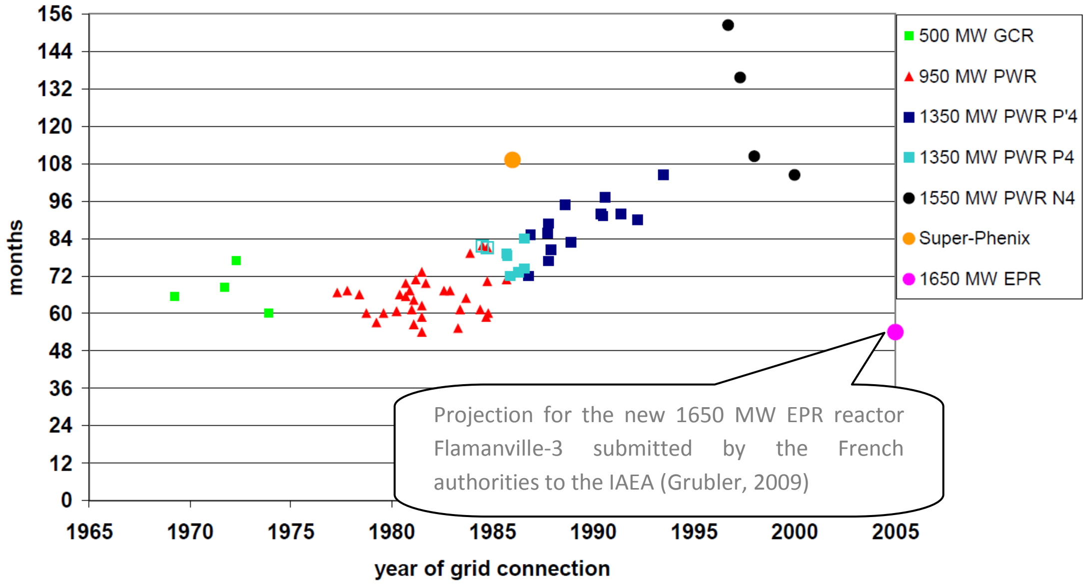


Figure 5: Construction time of French reactors (construction start to first grid connection). Source: (Grubler, 2009).

Whilst EDF has recently estimated a 5.5 to 6 year construction period for the Hinkley point plant (EDF, 2011b), for the analysis in Section 4 we have used an estimate of 7 to 8 years, based on the global median construction time of 7.7 years. We consider this estimate (which is based on data from 381 reactors over the period 1976-2010) to be relatively conservative taking into account that the average construction times for reactors built outside of Asian markets has increased from an median of 9.3 years for the 1991-1995 period to 15.3 years for the 1996-2010 period, and that the last five completed French reactors have taken more than 8 years to be constructed.

Cost changes during the construction period

US history

Based on data from Koomey and Hultmann (2007), Figure 6 shows the post-construction overnight costs of 99 reactors that were built in the United States between the 1970s and the mid-1990s.

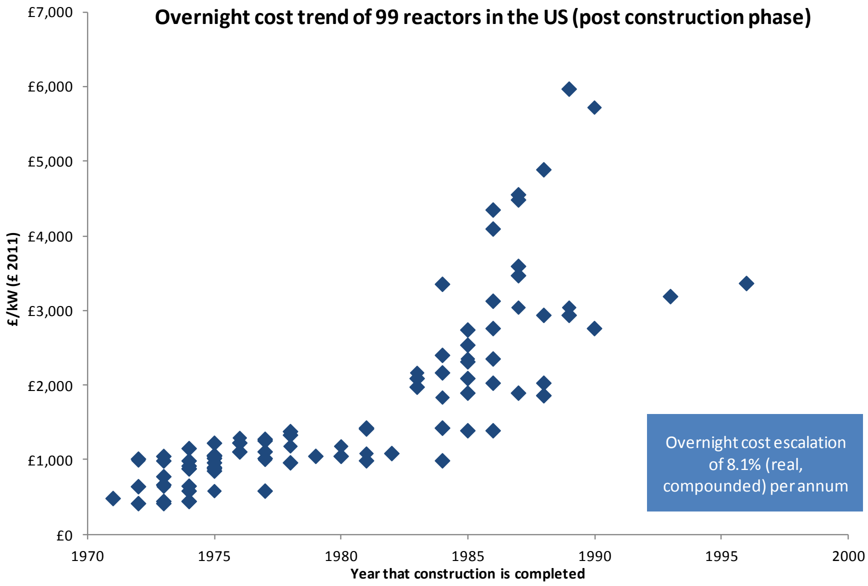


Figure 6: Overnight costs of 99 reactors built between the 1970s and the mid-1990s, in 2011 values. Costs were originally provided in 2004 values. We have inflated to 2011 GBP values by relying on the US CPI and a GBP/USD exchange rate of 0.616. Source: Authors own analysis using data from (Koomey and Hultman, 2007).

According to Cooper (2009) construction delays and regulatory changes were the primary drivers behind this cost trend although reactors were also adversely affected by design flaws that were time consuming and costly to fix. This situation was compounded by the non-uniformity of reactor designs that reduced the ability of the industry to benefit from learning rates that were sufficient to offset cost escalations. Using the Koomey and Hultmann data, we calculate the average cost escalation during this programme to be 8.1% per annum (real, compounded).

French history

According to Komonaff (2010), 'unlike the American electric utility companies, which for the most part contracted plant design and construction to architect-engineering firms that in turn tailored each project to local site and grid conditions....the French utility EDF and reactor supplier Framatome had largely standardised their reactor designs'. Grubler conducted a comprehensive review of the overnight cost trend of the French build programme and reached the conclusion that overnight costs had increased by, 'more than a factor of three between the first and last reactor generations built' (Grubler, 2009), as Figure 7 shows. We calculate that this represents a cost escalation of c5.6% (real, compounded) per annum.

Grubler attributes the worst of the cost escalation to extensive modifications to reactor designs late on in the build programme. This involved replacing the standard PWR of 900 – 1300MW capacity reactor designs that had been relied upon for the majority of the programme (54 of the 58 reactors) with 4 new N4 reactors, each of 1,500MW capacity. This resulted in a 'negative learning process', reducing any potential gains from standardisation and 'reintroduced learning and first of a kind costs' (Cooper, 2010). In recognition of the limitations of using point estimates to estimate escalation rates over a new build programme, Komanoff performed a regression analysis on the French data. He concluded that, 'taken as a whole, the last 4 N4 reactors cost approximately twice as much to build, per kilowatt, as the other 54 reactors' (Komanoff, 2010). By minimising the impacts of the last 4 reactors, Komanoff calculated a lower cost escalation rate of 3.6% (real, compounded) per annum for the French build programme.

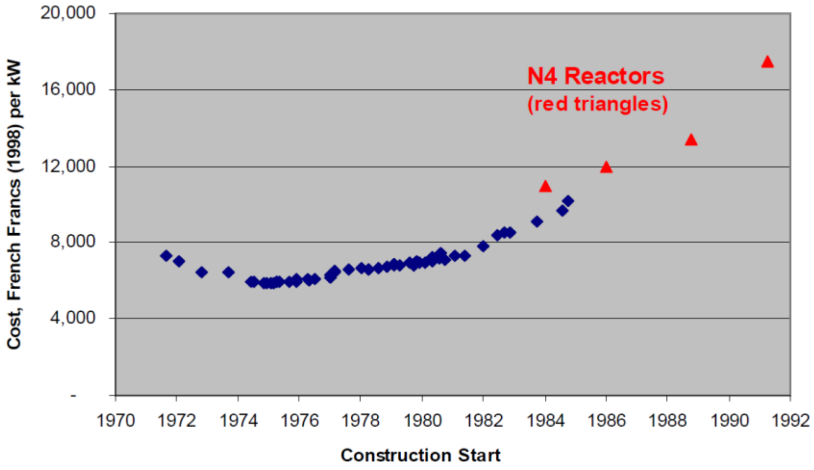


Figure 7: Overnight costs of PWR reactors in France. Source:(Komanoff, 2010).

Adjusting US and European cost estimates to reflect observed costs escalations

Table 1 summarises the most recent overnight costs estimates of EPR and AP1000 reactors in the US and European markets.

Site	Reactor type	Phase	Overnight cost £/kW (£ 2011)
Turkey 6 & 7	2*AP1000	Pre-construction	£2,635
Bellefonte 3 & 4	2* AP1000	Pre-construction	£2,347
Callaway	1*EPR	Pre-construction	£2,874
Summer Plant	2*AP1000	Pre-construction	£2,843
Lee Plant	2*AP1000	Pre-construction	£3,226
Vogtle 3 & 4	2*AP1000	Pre-construction	£3,249
Calvert Cliffs 3	1*EPR	Pre-construction	£3,606
Levy County 1 & 2	2*AP1000	Pre-construction	£3,257
Bell Bend	1*EPR	Pre-construction	£4,351
Flamanville-3	1*EPR	Construction	£3,527
Olkiluoto-3	1*EPR	Construction	£3,131

Table 1: Most recent overnight cost estimates for EPR & AP1000 reactors. All costs are expressed in 2011 values using the US CPI to index historic costs and using a GBP/ USD exchange rate of 0.616. Flamanville-3 quoted overnight costs do not include fuel so we have added fuel costs based on a 24 month fuel cycle as per EPR technical specifications. Olkiluoto 3 construction cost include financing costs so we have reduced this estimate by 9% (due to the low interest rate of 2.6% obtained for 60% of the debt portion, interest during construcion is significantly lower than US plants). The Flamanville quote was provided in 2011. The Olkiluoto quote was provided in 2009 so we have expressed this quote in 2011 values using Finnish CPI data. We have used a GBP/ EUR exchange rate of 0.882. Source: Authors own analysis using various sources outlined in Appendix 1 and (BankTrack, 2011, IEER, 2011, World Nuclear Association, 2011b, Thomas, 2010, Hollinger, 2010).

In order to place these recent estimates in their historical context, Figure 8 combines data from Table 1 and the Koomey and Hultman data set (Figure 6).

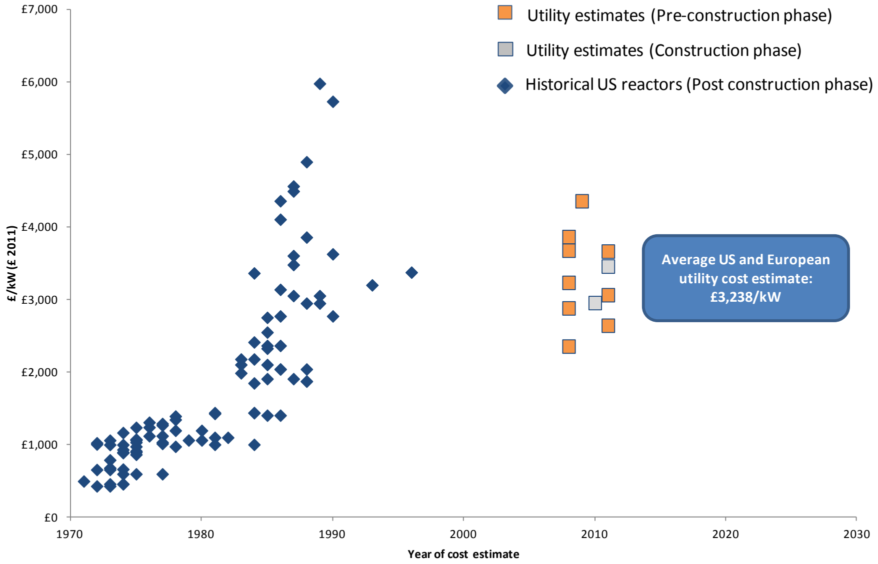


Figure 8: Most recent overnight cost estimates for EPR and AP1000 reactors. Source: (Koomey and Hultman, 2007), and authors analysis using various sources outlined in Appendix 1, and (BankTrack, 2011, IEER, 2011, World Nuclear Association, 2011b, Thomas, 2010, Hollinger, 2010).

It is important to note that the recent utility estimates are not directly comparable with the historical data set as the recent estimates are for reactors that are yet to be constructed and it will be several years before the final costs of these rectors will be known.

To aid in the estimation of this final cost, cost escalation rates have historically been applied by utilities and market analysts to initial capital cost estimates provided at the bidding stage. As Table 2 shows, there is a wide range of cost escalation rates that could plausibly be used for this process and so a decision must be taken as to which rate to use in the face of considerable uncertainty. For example, the drawback from simply relying upon the IHS/CERA power capital cost indices for an appropriate escalation rate is that these indices rely only on the price trends of the key components of nuclear reactors and ignore some of the major reasons behind nuclear cost escalations (for example, regulatory delays, technical design requirements, safety requirements, incorrect materials being used and human errors). This is the reason why the range of the indices (between 4.4% and 5.2%) is so much narrower than the range of actual reactor cost escalations during the same period (9.9% to 16.4%, taken from Table 2).

Source of cost escalation	Cost escalation: Real (compounded per annum)
Escalation rate of IHS CERA European Power Capital Costs Index (EPCCI), including nuclear (2000 - 1HY 2011)	4.4%
Escalation rate of IHS CERA US Power Capital Costs Index (PCCI), including nuclear (2000 - 1HY 2011)	5.2%
Escalation rate of total French build programme (58 reactors, 1970s - 1990s)	3.6%
Escalation rate of total US build programme (99 reactors, 1970s - 1990s)	8.1%
Escalation rate of Flamanville-3 (1 reactor, 2006 - 2011)	9.9%
Escalation rate of Olkiluoto-3 (1 reactor, 2004 - 2009)	12.2%
Escalation rate US build programme (50 reactors, 1980 - 1990)	13.7%
Escalation rate of European reactors currently in the pre-construction (Belene) and construction (Olkiluoto and Flamanville) phases (3 reactors, 2004 - 2011)	16.4%
Escalation rate of 15 reactors currently in the pre-construction phase in the US (EPR & AP1000 reactors only) (2005 - 2011)	14.2%
Escalation rate of 19 reactors currently in the pre-construction phase in the US (all reactor types) (2005 - 2011)	15.7%

Table 2: Examples of approaches that could be used to model potential cost escalations during the pre-construction and construction phases of a new nuclear build programme. Inflation rates for EPCCI rely on the Eurozone CPI data. The PCCI, US, France, Finland and Bulgaria build programme uses respective national CPI data. Source: Authors own analysis, (Koomey and Hultman, 2007, IHS, 2011)

Given this uncertainty we have taken a conservative approach and use an annual escalation rate of 5.4% for the analysis presented in Section 4. This 5.4% represents the weighted average real escalation rate of the 58 reactors in the French build programme between the 1970s and 1990s, the 99 reactors in the US new build programme between the 1970s and 1990s and the IHS/Cambridge Energy Research Associates (CERA) European Power Capital Cost index. Note that for this analysis, the IHS/CERA index was assigned a weight equal to the combined weight of the French and US escalation rates.

Due to the costs escalations being more recent, involving only EPR and AP1000 reactor designs and, in the case of the US reactors, drawn from projects that are at the same stage as the UK new build programme, there is an argument that the escalation rate associated with the plants in the pre-construction phase in the US (14.2%) and the European reactors currently in the construction phase (11.1%) are more relevant to the UK new build programme. The reason why we have not included these recent estimates in our analysis is that we would prefer to use 'out-turn' escalation rates from reactors that have completed the construction phase to inform our estimate.

Without having access to the commercial terms of the majority of the quoted overnight costs it is impossible to estimate what escalation rates have been included in quoted numbers or, if they have been included, to analyse their appropriateness. Based on the information available from the sources in Appendix 1, the Bell Bend, Summer, Turkey, Levy and Vogtle plant quotes have indicated that escalation rates have been included in their overall construction cost estimates. The Levy and Vogtle plants have specified that a 2% and 2.5% (respectively) escalation rate has been included in their overall construction cost estimates. Although the Levy plant specifies that this is a real escalation rate, there is little information as to whether the Vogtle plant is applying this on a real or nominal rate basis and what proportion of the total construction cost is subject to this escalation rate. To remain conservative we have assumed that this is provided on a real basis and applied to 100% of the overnight costs. We have therefore applied a 3.2% cost escalation rate to the overnight costs estimates of these 9 reactors.

Figure 9 builds on Figure 8 to show the impact of applying the 5.4% real escalation rate (or the 3.2% rate where applicable) to the current EPR and AP1000 reactor estimates in the US and Europe through to the end of the construction phase. Applying the escalation rate increases the average cost estimate from £3,238/kW to £4,613/kW.

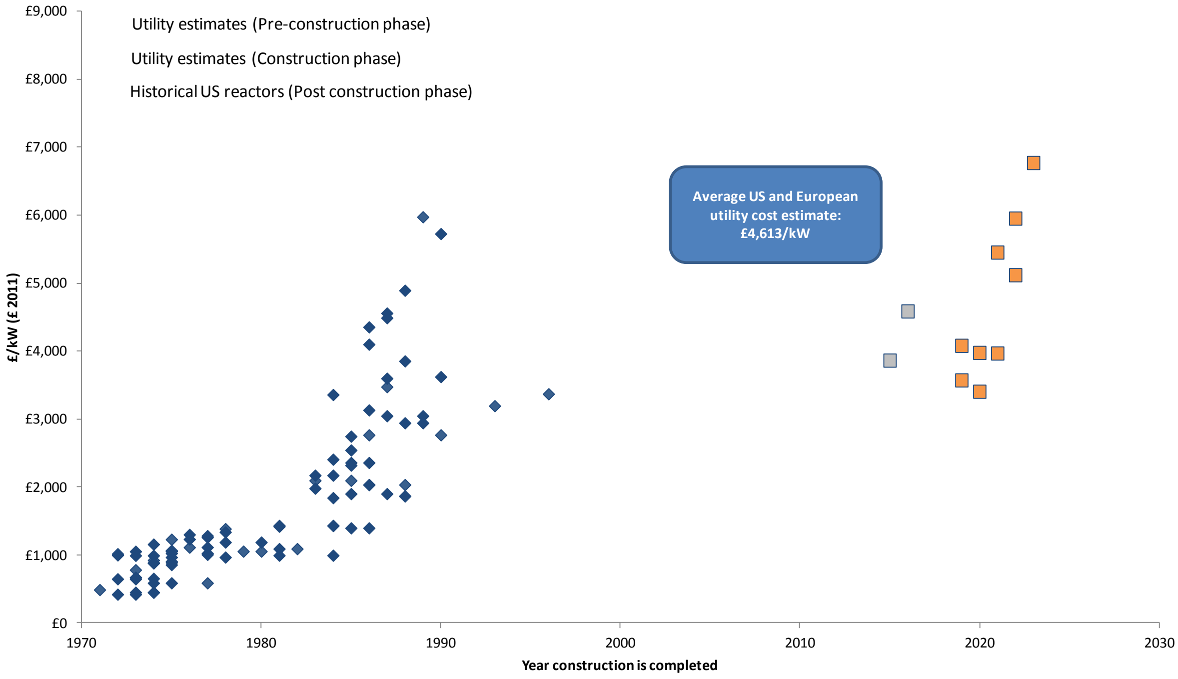


Figure 9: Impact of applying a real 5.4% escalation rate to current US, Canadian and European reactors. The escalated overnight costs are plotted against a notional completion year for each project shown in Table 1. For the US plants, we have estimated potential construction dates based on the current status of the reactors. We have assumed the Flamanville 3 reactor will be operational by 2016 and the Olkiluoto 3 plant will become operational in 2015. Source: Authors own analysis.

Adjusting UK cost estimates to reflect observed costs escalations

In December 2010, the EDF-led consortium was reported to have estimated costs of 'more than' £9bn ($13.9bn) for building two 1600MW EPR reactors in the UK (Hollinger, 2010). It has recently been reported that this cost has subsequently escalated to £14bn (The Times, 2012). Since this latter estimate has not been confirmed our analysis uses the December 2010 estimate. Since it is not clear what this cost includes (for example, whether this is the full capital cost of the plants including financing charges and interest during construction or if escalation rates are included) we have modelled four sets of assumptions to determine which sets give the best fit with the post-escalation estimates shown in Figure 9. Each set of assumptions and the resultant overnight cost is described in Table 3 below.

Item	Option A	Option B	Option C	Option D
Total capex cost	£9,000,000,000	£10,252,334,427	£17,805,565,692	£20,283,179,349
Estimated IDC	£1,099,120,226	£1,252,334,427	£2,174,495,266	£2,477,613,657
Total overnight cost (2011)	£7,900,879,774	£9,000,000,000	£15,631,070,426	£17,805,565,692
Overnight escalation rate	0.0%	0.0%	5.4%	5.4%
Pre-construction period (years)	5.5	5.5	5.5	5.5
Construction period (years)	7.5	7.5	7.5	7.5
Capacity	2*1600MW	2*1600MW	2*1600MW	2*1600MW
Overnight (£/kW)	£2,469	£2,813	£4,885	£5,564

Overnight cost per reactor	£3,950,439,887	£4,500,000,000	£7,815,535,213	£8,902,782,846

Table 3: Assumptions made in estimating the overnight costs of a new UK nuclear plant. Option A assumes that the £9bn is the final 'all in' capital cost so interest during construction is deducted from this figure to reach the overnight cost. We have assumed that this figure includes any potential cost escalations. Option B assumes that the £9bn is in fact the overnight cost estimate so no further amendments need to be made. We have assumed that this figure includes any potential cost escalations. Option C follows Option A but with an assumed 5.4% cost escalation during a 5.5 year pre-construction and a 7.5 year construction phase. Option D follows Option B but with an assumed 5.4% cost escalation during a 5.5 year pre-construction and a 7.5 year construction phase. Source: Authors own analysis.

Comparing the overnight costs of options A – D from Table 3 to the range of escalation-adjusted estimates shown in Figure 9 suggest that the results from options C and D are consistent with the adjusted estimates (which have an average value of £4,613/kW). For the analysis used in Section 4 we have therefore used UK overnight cost estimates of £4,885/kW (the option C result) and £5,564/kW (the option D result).

Other key cost input assumptions

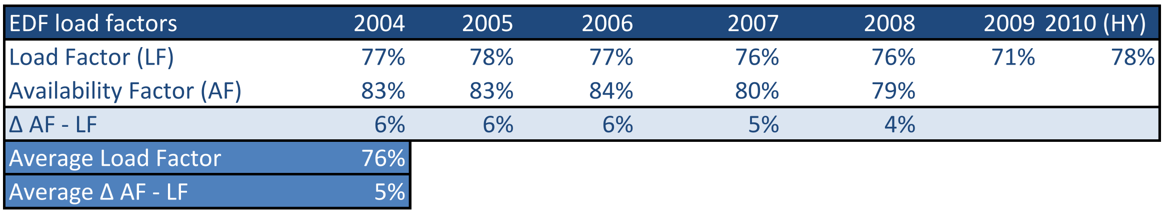
Plant operating life

Although the intended technical lifetime of both the AP1000 and EPR reactors is 60 years, operating experience for nuclear power stations beyond 30 years is limited. According to (Schneider et al., 2011) the average age of the 130 nuclear units that have already shut down is around 22 years. Recent UK experience suggests life extensions are possible (Nuclear Engineering International, 2012) and it is reasonable to expect that newer reactors will indeed have longer lives than early designs from the 1960s, but 60 year plant lives are for now unproven. It is also important that cost estimates allow for refitting key components, declining load factors and/or additional O&M costs as plants age. Therefore, for the analysis presented in Section 4 we have followed the same approach as DECC for a 'generic PWR' in (DECC, 2011b), the Worldwatch Institute (Schneider et al., 2011), and the Massachusetts Institute of Technology (2009) by assuming operating lifetimes of 40 years for new plants.

Plant load factor

Globally, US reactors achieve some of the best load factor performance, achieving an average of around 90%. According to Harding, some of this is, 'attributable to changes in technical specifications that [allows] equipment to operate within a wider range and to higher fuel enrichments. The first [factor] reduces the number of equipment related trips and shutdowns. The second [factor] reduces the number of regular outages' (Harding, 2007). Further drivers behind this performance are that the US regulated electricity market supports the ability of nuclear operators to co-operate on key challenges (for example through shared employee schemes which allow skilled employees to be 'loaned' from one plant to another) and that the US nuclear industry is able to benefit from around 900 reactor years of experience.

According to the EPRs Generic Design Assessment (GDA) submission the EPR reactor has a target availability of 90% (EDF, 2009). As reactors of this design have not been constructed yet it is impossible to empirically test this figure against actual operational performance, and it is our view that it would be optimistic to take this technical potential as certain. Based on Citibank and HSBC estimates there is approximately a 5% difference between availability and load factors that EDF have reported for their operated plants with an average load factor of 76%. The last 7 years of load factor performance for EDF is summarised in Table 4.



EDF load factors	2004	2005	2006	2007	2008	2009	2010 (HY)
Load Factor (LF)	77%	78%	77%	76%	76%	71%	78%
Availability Factor (AF)	83%	83%	84%	80%	79%		
Δ AF - LF	6%	6%	6%	5%	4%		
Average Load Factor	76%						
Average Δ AF - LF	5%						

Table 4: Overview of EDF average load factor performance versus plant availability. Sources: (HSBC, 2010, Citigroup, 2009)

We recognise that French nuclear load factors can be affected by the partial load following role that nuclear performs in the French energy market, however it appears reasonable to rely upon EDF's actual operating experience. Therefore, our assumption for the analysis in Section 4 is that reactors will have an average load factor of between 76% and 85%, with the higher figure calculated by subtracting the difference between load factors and availability factors found in Table 4 (5%) from the target load factor for the UK new build programme (90%). This range is backed up by a study (Thomas et al., 2007) which found that only the top 100 out of the 414 plants which had been operating for at least one year had a lifetime load factor of more than 80% (compared to the mid-point of 80.5% in our range). Interestingly, that study also suggested, after analysing the characteristics of the top 13 plants, that performance was not due to what reactor technology was being used but rather determined by the skills of the operators and management experience.

Plant operation and maintenance costs

For the analysis in Section 4 we will rely upon the figures from the Mott Macdonald 2010 work commissioned by DECC, shown in Table 5, with two revisions. The first is to remove the £2.1/MWh that Mott Macdonald use for on-site waste and decommissioning costs, and use the cost confirmed by the UK Government in early 2011 (DECC, 2010a). This has a very marginal impact of increasing the costs to £2.4/MWh. The second amendment is to add the costs associated with the price cap on long term disposal of waste, estimated to be c£0.45/MWh (ibid) because we believe that owners of nuclear plant will have a preference for incurring a fixed cost per unit of output to limit their exposure to the uncertainty surrounding potential future waste disposal costs.

Operating costs	unit	FOAK	NOAK
O&M fixed	£/MW/yr	50,000	37,500
	£m/yr	80	60
O&M variable	£/MWh	2	1.8
	£m/yr	21.8	20.1
Total O&M costs	£m/yr	101.8	80.1

Insurance	£/MW/yr	22,000	18,000
	£m/yr	35.2	28.8
Connection and UoS charges	£/MW/yr	6,000	6,000
	£m/yr	9.6	9.6
Total variable + fixed operating costs	£m/yr	146.6	118.5

Table 5: Mott Macdonald estimates for total variable and fixed operating costs. Source:(Mott MacDonald, 2010). These costs are provided in real terms and yield a total O&M cost of around £8.5/MWh which is close to the estimates by the (World Energy Council, 2007) of around £10.1/MWh, broken down as £6.6/MWh for O&M and £3.5/MWh for fuel costs. (Severance, 2009) also has a similar overall O&M cost of £9.2MWh.

Financing costs and structures

The high capital cost of nuclear plants means that their overall economics, and the feasibility of their financing, depend greatly on the cost of that capital, and more accurately the Weighted Average Cost of Capital (WACC), which is essentially the weighted sum of the interest rate on loans and the rate of return on equity investment (Gross et al., 2010, NEA, 2010).

One of the biggest challenges in estimating what WACC will be appropriate for the new build programme is that there is more than one consortium bidding for the work and each consortium is made up of companies that will follow different routes in order to access the UK market. For example, there is uncertainty surrounding what role Export Credit Agreements (ECAs) will play. Based on past experience, it seems likely that non-UK governments, through ECAs, will expand the pool of capital available to UK nuclear projects, and with favourable terms (Koplow, 2011). In 2001 for example, of the 25 reactors that were under construction throughout the world 14 were part funded by an ECA from a G8 country. This support can take the form of direct credits or financing, refinancing, interest-rate support (where the government supports a fixed interest-rate for the life of the credit), aid financing (credits and grants), export credit insurance and guarantees. Examples include the Compagnie Française d'Assurance pour le Commerce Extérieur (Coface) €0.6 billion export credit guarantee to the Olkiluoto project, repayable over 17 years, allowing the project to re-finance approximately 30% of the project debt portion (€2.4 billion). Coface has also been involved with the recent EPR reactors being built in Taishan, China, providing a €1.5 billion guarantee to Areva NP (BNP Paribas, 2004, OECD, 2011, EC, 2011).

The detailed terms associated with these agreements are not publicly available so the associated impact on the WACC is difficult to confirm. However, to provide an indication of the possible impact, if 30% of the debt for a project is able to be financed via an ECA, at around 3.6% (BNP Paribas, 2004) this would be sufficient to reduce an estimated cost of debt from 5.0% to 4.6%. Due to this lower cost of debt, developers could potentially increase project gearing to 55:45 or 60:40 if we assume a 50:50 debt to equity ratio is the baseline (Du and Parson, 2009, Lekander et al., 2011, MIT, 2009). This would in turn reduce the WACC from approximately 13% to approximately 12% (or approximately 11% if 60:40 debt to equity ratio is used). As we discuss in Section 4, due to high levels of capital at risk and lengthy construction times, relatively small percentage changes in WACC result in significant changes to the levelised costs of nuclear power.

In February 2011, Citigroup stated that EDF Energy had confirmed that it would build new nuclear plants in the UK based on a 10% post-tax, nominal cost of capital (E&CCC, 2011). Supporting this view, in September 2010 HSBC estimated EDF's overall post tax, nominal WACC to be approximately 6.4% (HSBC, 2010), a view supported by Morgan Stanley in January 2011 (Turpin and Lee, 2011), and financial statements ending 30 July 2011 stated that EDF will, 'invest in projects that create value at 300 basis points (i.e. 3%) above the weighted average cost of capital' (EDF, 2011a).

It is of course possible that this WACC estimate for EDF is not representative of the wider market, so we have also assessed more general estimates for the nuclear programme in the UK. Taking the measures outlined in the UK Government's December 2010 White Paper consultation on Electricity Market Reform (DECC, 2010b) into account, in April 2011 Oxera Consulting prepared a report (Oxera, 2011) for the UK Committee on Climate Change that looked specifically at the cost of capital required for the UK's new nuclear build programme by conducting a survey of market participants to ascertain expected rates of return. This survey produced a range of between 9% and 13% (pre-tax, real). Providing support for figures towards the mid-point of this range is the estimate provided by Areva, whose view in March 2010 was that liberalised markets would require a 11% (pre-tax, real) WACC (Gautrot, 2010). By way of comparison, Citigroup's July 2011 view was that some companies would be, 'looking at a project cost of capital of at least 15 per cent' (Chestney, 2011).

Taking these findings into account, it appears that 11% is a reasonable starting point for the analysis presented in Section 4.

4. Implications for the UK nuclear cost estimates

The assumptions used for key variables in the levelised cost model, drawn from the observed experience discussed in Section 3, are summarised in Table 6 below together with the resultant LCOE. It is important to note that, due the high level of uncertainty surrounding new nuclear economics, that there is a wide range of estimates for LCOE even amongst relatively recent figures, ranging from around £40/MWh (DTI, 2007b, World Energy Council, 2007), gradually increasing to £56/MWh (Du and Parson, 2009), to £81/MWh (Lazard, 2008) and £95/MWh (Mott MacDonald, 2010).

Drawing upon the observed historical cost trends, recent overnight cost estimates, likely financing costs for UK new build reactors, and the other assumptions that we identify in Section 3, our calculations suggest that the levelised cost of nuclear generation in the UK could potentially be between £164/MWh (in our Scenario 1) and £175/MWh (in our Scenario 2), well above even the higher figures in recent market estimates.

Major Assumptions	Scenario 1 (2011)	Scenario 2 (2011)
Market	UK	UK
Technical Assumptions		
Pre construction (years)	6	5
Construction time (years)	8	7
Operating period (years)	40	40
Power output (MW)	1600	1600
Plant efficiency (%)	35%	35%
Load factor (%)	80.5%	80.5%
Aux load (%)	5.00%	5.00%
Financing Assumptions		
Debt : Equity	50:50	60:40
WACC	11.00%	11.00%
Inflation rate	2.2%	2.2%
Tax rate	30%	30%
Cost assumptions		
Pre-construction cost (£/kW)	£197	£203
Overnight cost (£/kW)	£4,885	£5,564

Levelised cost breakdown	Scenario 1 (2011)		Scenario 2 (2011)	
	Levelised cost (£/MWh)	% of total	Levelised cost (£/MWh)	% of total
Capital cost	£144	87.8%	£155	88.6%
Fixed O&M	£12	7.1%	£12	6.6%
Variable O&M	£2	1.2%	£2	1.1%
Fuel cost	£3	2.1%	£3	1.9%
Decommissioning / waste storage	£2	1.5%	£2	1.4%
Long term storage	£0	0.3%	£0	0.3%
Total	**£164**		**£175**	

Table 6: Levelised cost of electricity results. Source: Authors own analysis.

The right hand bar of Figure 10 shows that the main driver for this is the application of the 5.4% escalation rate to current utility overnight cost estimates. The remaining five bars of Figure 10 show the impact of each of the other assumptions of our Scenario 1 before the application of a 5.4% escalation rate, with the decrease in plant operating life having the least impact and the increase in the cost of capital having the second greatest impact after the overnight cost escalation rate.

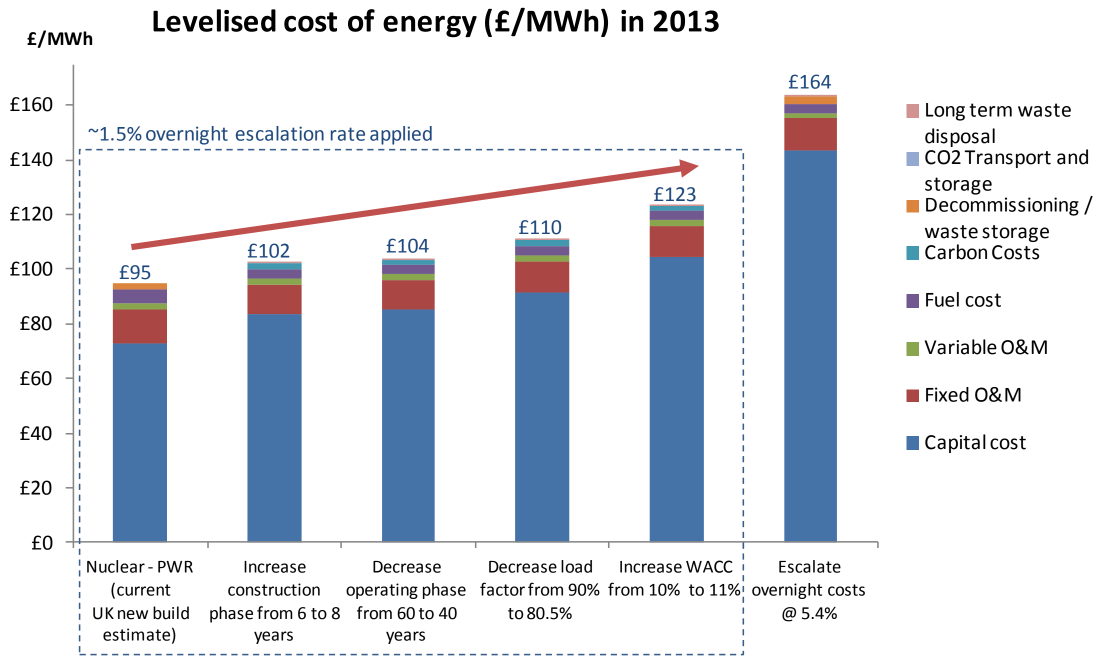


Figure 10: Levelised cost estimates for nuclear power, assuming 2013 project start. Source: (Mott MacDonald, 2010), authors own analysis.

Levelised costs are extremely sensitive to input assumptions (Heptonstall, 2007) so, using our Scenario 1 as a baseline, Figure 11 shows the sensitivity of our results to variations of the key input assumptions of overnight cost, length of construction period, operating life of the plant and WACC.

Because the levelised cost calculation attributes proportionally greater value to costs and output that occur closer to the calculation start year, reducing plant operating lifetime has a greater (negative) impact on levelised costs then increasing plant operating lifetime by the same quantum. Somewhat counter-intuitively, any increase in the construction phase timeline results in lower total (discounted) costs because the impact of discounting the cost stream by a further year offsets the increase in interest costs and commitment fees that result from an extended construction timeline. However, because the generating phase is also delayed, the impact of discounting the power output by a further year more than offsets this cost reduction, resulting in an increase in the overall levelised cost.

							Scenario 1					
Overnight cost	Δ in overnight cost	-25% (£3,727)	-20% (£3,975)	-15% (£4,224)	-10% (£4,472)	-5% (£4,720)	0% (£4,969)	5% (£5,217)	10% (£5,466)	15% (£5,714)	20% (£5,963)	25% (£6,211)
	Levelised Cost	£132	£139	£146	£153	£159	£164	£173	£180	£187	£193	£200
	Δ in Levelised Cost	-20%	-15%	-11%	-7%	-3%	0%	5%	10%	14%	18%	22%
Construction timeline	Δ in construction time		-4 (4)	-3 (5)	-2 (6)	-1 (7)	8	+1 (9)	+2 (10)	+3 (11)	+4 (12)	
	Levelised Cost		£130	£137	£147	£159	£164	£181	£193	£211	£231	
	Δ in Levelised Cost		-21%	-16%	-10%	-3%	0%	10%	18%	29%	41%	
Operating timeline	Δ in operating time		-20 (20)	-15 (25)	-10 (30)	-5 (35)	40	+5 (45)	+10 (50)	+15 (55)	+20 (60)	
	Levelised Cost		£188	£177	£172	£168	£164	£165	£164	£163	£163	
	Δ in Levelised Cost		15%	8%	5%	2%	0%	1%	0%	-1%	-1%	
WACC / Hurdle rate	Δ in WACC	6%	7%	8%	9%	10%	11%	12%	13%	14%	15%	16%
	Levelised Cost	£90	£102	£116	£131	£148	£164	£186	£208	£231	£256	£284
	Δ in Levelised Cost	-45%	-38%	-29%	-20%	-10%	0%	13%	27%	41%	56%	73%

Figure 11: Levelised cost sensitivities using our Scenario 1 as the baseline. Source: Authors own analysis.

5. Conclusions and implications for policy

The UK Government believes that nuclear power can play a key role in reducing CO_2 emissions and maintaining security of supplies (DECC, 2011a). Government policy has been informed by cost estimates that suggest that electricity from new nuclear power stations will be competitive with alternative low carbon generation options. Indeed, recent estimates suggest that the levelised cost of nuclear power are towards the lower end of the range of low carbon generation alternatives, with some analyses projecting even lower costs for so-called 'nth of a kind' (NOAK) plants built after the first wave of new generation plants.

However the evidence and analysis presented in this paper suggests that the capital cost estimates for nuclear power that are being used to inform these projections rely on costs escalating over the pre-construction and construction phase of the new build programme at a level significantly below those that have been experienced by past US and European programmes. Importantly, the evidence suggests that construction costs in real terms have often increased relative to expectations, and there is no evidence of a consistent declining cost trend during any period over the last past 40 years in the US, France and Europe. The notion (based on technology learning rates) that costs could decline for reactors being constructed as early as 2017 would therefore appear to be inconsistent with the historical evidence reviewed above.

Indeed, the empirical evidence reviewed in this paper suggests that the capital costs of nuclear power may be substantially higher, and construction periods longer, than anticipated, and that the resultant effect on levelised cost estimates could be dramatic, with our analysis suggesting that it is possible that costs may turn out to be over £160 MWh. Recent academic estimates (Mitchell, 2012), and indications from industry (Gosden, 2012, Clark, 2012) suggest that costs may indeed approach this level.

The UK Government is currently considering the level of support that will be available through the proposed CfD FiT. Whilst at the time of writing the level of support has yet to be agreed, it will be interesting to compare the results of our analysis with the outcome of this process and the government's negotiations with nuclear developers. Clearly it is possible to take a different view on the potential for cost escalations but the analysis presented above has sought to be conservative with regards to cost escalation during the pre-construction and construction phases. There is evidence to suggest that some nuclear build programmes have experienced escalation rate well above the 5.4% used in this paper. What is clear is that levelised costs for nuclear power will be extremely high if UK projects experience the higher end of the cost escalation rates recently encountered elsewhere.

It is possible that nuclear project developers will take a more optimistic view on the potential for cost escalation and chose to take projects forward with a lower level of support. In doing so, they would be bearing the risk of cost escalations unless they believe that there may be a possibility in future to seek additional support if costs do rise. Another possible outcome is that it proves impossible for Government and project developers to agree on the support level required, and so new nuclear projects will not go ahead, leaving the UK with the challenge of how to achieve its energy policy objectives without any additional contribution from nuclear power.

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