UKERC Technology and Policy Assessment

Cost Methodologies Project: Nuclear Case Study

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This working paper was produced as part of the TPA Cost Methodologies project.

Contents

1. Introduction

This paper examines global cost trends in nuclear energy, both in terms of historical contemporary costs and also historical forecasts of future costs. The rationale for the study is to support and inform the UKERC TPA report 'Presenting the Future: An assessment of future cost estimation methodologies in the electricity generation sector'. Approximately 75 academic articles and grey literature reports have been reviewed for this case study, both for data gathering and analysis purposes, in order to achieve three specific aims:

- Examine the key trends in contemporary cost estimates and future cost projections (Section 2);
- Understand the drivers underlying these key trends and the reasons for disparities between anticipated cost levels and actual outcomes (Section 3);
- Identify implications for cost estimation methodologies (Section 4).

2. Costs trajectories

In this section we analyse how future costs forecasts compare with 'contemporary' cost outcomes i.e. we compare past expectations about the future with the 'reality' of costs at a given time. Largely because of commercial confidentiality reasons and lack of industry transparency, the evidence we draw upon provides figures for contemporary costs which are not confirmed hard data from utility companies or reactor vendors. Instead they are invariably estimates from academic and governmental analysts and other nuclear industry observers. Cost out-comes are therefore not genuinely 'actual' but are estimated and may also be expressed as cost ranges.

Our analysis focuses predominantly on capital rather than levelised costs. In part, this is because there is more data on capex in the evidence reviewed, but also because nuclear capital costs account for the majority (60% – 75%) of the levelised costs of electricity generation (MacKerron et al., 2006); (Grimston, 2012b). By contrast, the costs of the feedstock fuel for example is a very small proportion of the overall costs (typically of the order of 2%) which means that the effects of changes in the uranium price on the cost of nuclear-generated electricity are relatively modest. (Grimston, 2012).

2.1 Expectations of future costs

Forecasts of future capital and levelised costs have been derived mainly from engineering/technical assessment rather than from experience curves. As the following sub-section on actual cost outcomes will show in more detail, this is perhaps unsurprising since much of the track record is characterised by rising and/or highly variable costs rendering learning rates either negative or at least very uncertain.

Figure 2.1 below presents a summary of worldwide capex future forecasts between the late 1980s and the early 2040s as reported in the literature reviewed. It shows the in-year average forecast costs for two groups, one consisting of those forecasts made up to 2005, the other consisting of forecasts made from 2005 onwards. The year 2005 was chosen because the mid-2000s appears to have been a pivotal time when estimates of contemporary costs began to rise significantly from a plateau low.

Figure 2.1 demonstrates how nuclear capital costs have in the past been expected to fall over time, and how they are still expected to do so, albeit from a higher starting point averaging over £3.5m/MW in 2010. In the mid-2000s, cost forecasts for the relatively near future were revised significantly upwards to reflect a new reality of rising contemporary cost estimates. However, costs are still expected to fall in the longer term, though to a level at least £500,000/MW higher than expected by the earlier pre-2005 forecasts.

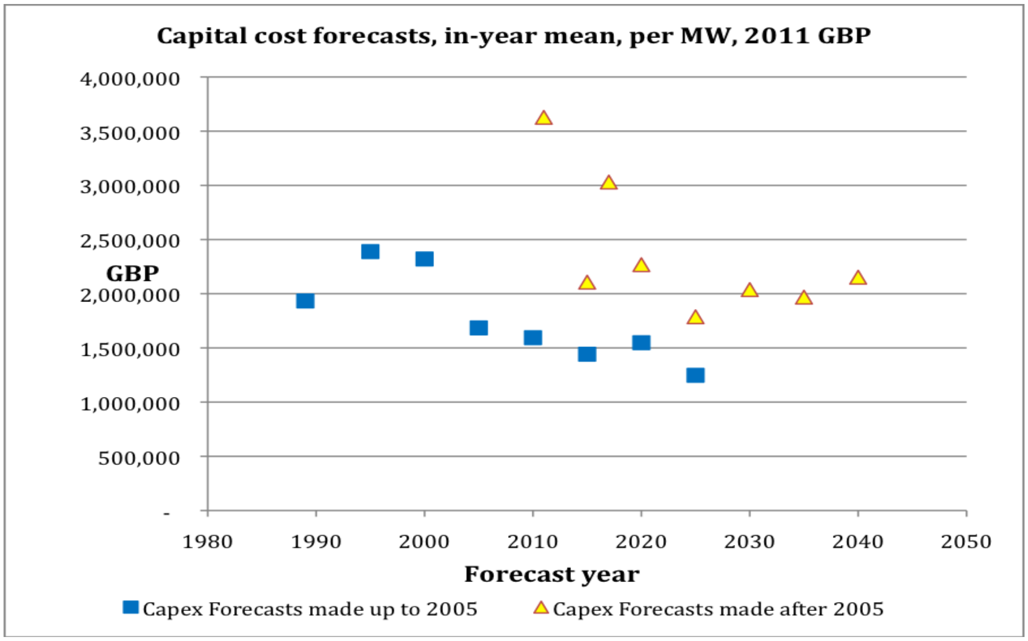

Figure 2.1 Forecast capex worldwide, comparing pre and post 2005 estimates[1]

Turning specifically to the UK, unsurprisingly there are divergent opinions regarding future capital costs with Mott MacDonald, for example, tending towards the more optimistic end and Harris et al., for example, being more pessimistic. According to the latter, the forecasts currently informing the debate on nuclear new build assume significant cost reductions between now and the mid-2020s – for example a 25% reduction in overnight costs[2] from approximately £3.6m/MW to £3m/MW by 2025 (Harris et al., 2012), or even down to £2m to 2.5m/MW by 2020 and to £1.6m to 2.45m/MW in 2040 assuming that a currently assumed £0.7m/MW 'congestion premium' is eliminated (Mott MacDonald, 2011).

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[1] Costs are converted from the original reported currency to GBP using Bank of England historical exchange rates and then inflated to 2011 values using the RPI annual average long run series from the UK Office of National Statistics.

[2] The term 'overnight costs' excludes interest and other financing charges incurred during construction i.e. it assumes that the plant is built 'overnight'.

With regard to levelised costs, the projected future cost of generation that the UK government is currently using to inform policy decisions is approximately £67/MWh in 2023 (Harris et al., 2012). This represents a more than 30% reduction in just over a decade from what (Harris et al., 2012) suggest is the current government estimate of £97/MWh. More substantial reductions are envisaged by Mott MacDonald (2011) which assumes a lower levelised cost of £89/MWh for a plant ordered today reducing to £63/MWh and £50/MWh for plants ordered in 2020 and 2040, respectively (using Mott MacDonald (2011)'s central discount rate projection and assuming the removal of the congestion premium).

(Harris et al., 2012), however, argue that such assumptions and projections are optimistic and suggests that because plant lifetimes and availabilities are unlikely to be significantly improved, there is little scope for further dilution of fixed costs (i.e. for costs to be spread over more megawatt hours). Instead, cost reduction must rely predominantly on capital cost improvements. If a 5.4% cost escalation rate (described by Harris et al as 'conservative') is applied to capex for the period up to 2023, the result is forecasted overnight capital costs of between £9.2m/MW and £11.3m/MW at that time. Regarding levelised costs, the Harris et al. current estimate of between £177 and £186/MWh is already substantially higher than the government's current assumption.

Harris et al. conclude that future nuclear power generation in the UK is likely to be significantly more expensive than currently anticipated by the government. Whilst this conclusion may or may not turn out to be correct, the next sub-section shows that it is at least understandable given the past record of expectations versus estimated reality.

2.2 Contemporary costs outcomes

We now consider cost outcomes over the last four decades and how this data compares with expectations. We emphasise again that such data is estimated rather than actual confirmed outcomes.

Cooper (2009) provides a useful insight into the comparison between expectations and outcomes for the early years of commercialised nuclear power in the U.S.. Figure 2.2 shows the increase in projected and actual costs by date of commencement of construction for completed reactors, expressed as a percentage of the projected cost of the initial reactors i.e. Cooper (2009) uses the projected costs of the 1966-1967 reactors as the base and expresses both future projections and cost outcomes during the ensuing decade as a percentage of that base.

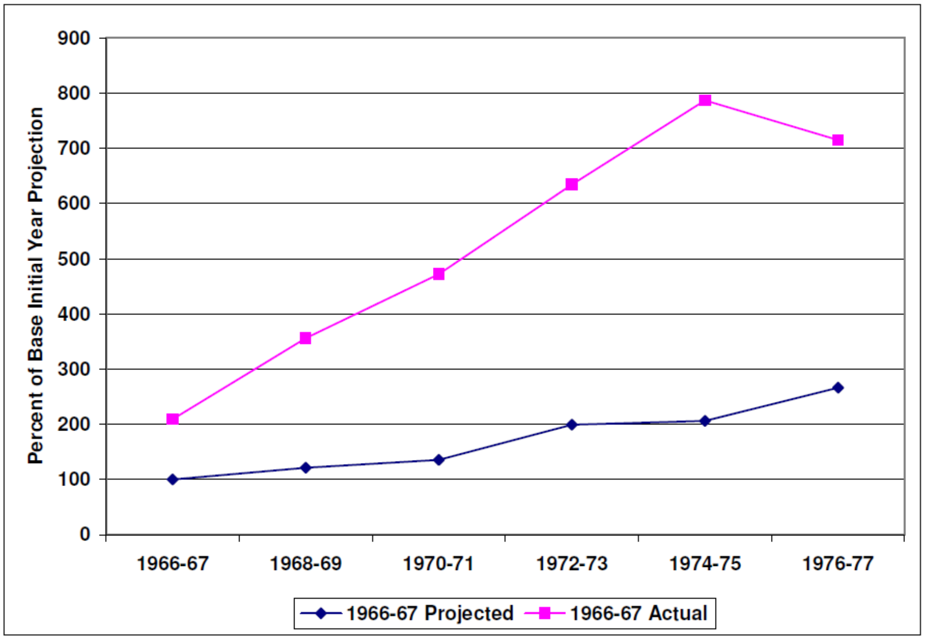

Figure 2.2: Actual and Projected Capital Costs by Date of Commencement of Construction, Completed Reactors (Cooper, 2009). Source: Energy Information Administration, January 1, 1986.

Figure 2.2 reveals not only how both cost projections and actual outcomes were increasing during the decade but also that outcomes were increasing faster than projections. The reactors starting construction in 1966–1967 cost twice as much to build as originally estimated. The reactors commenced in 1968–1969 were projected to cost slightly more than the reactors commenced in 1966–1967, but they actually cost over three times as much as the projected costs of the reactors commenced in 1966–1967. Hence, both capital cost containment and forecast performance deteriorated over the decade. Forecasting accuracy did not improve over subsequent decades as a comparison between Figure 2.1 showing past projections of expected future costs and Figure 2.3 below demonstrates.

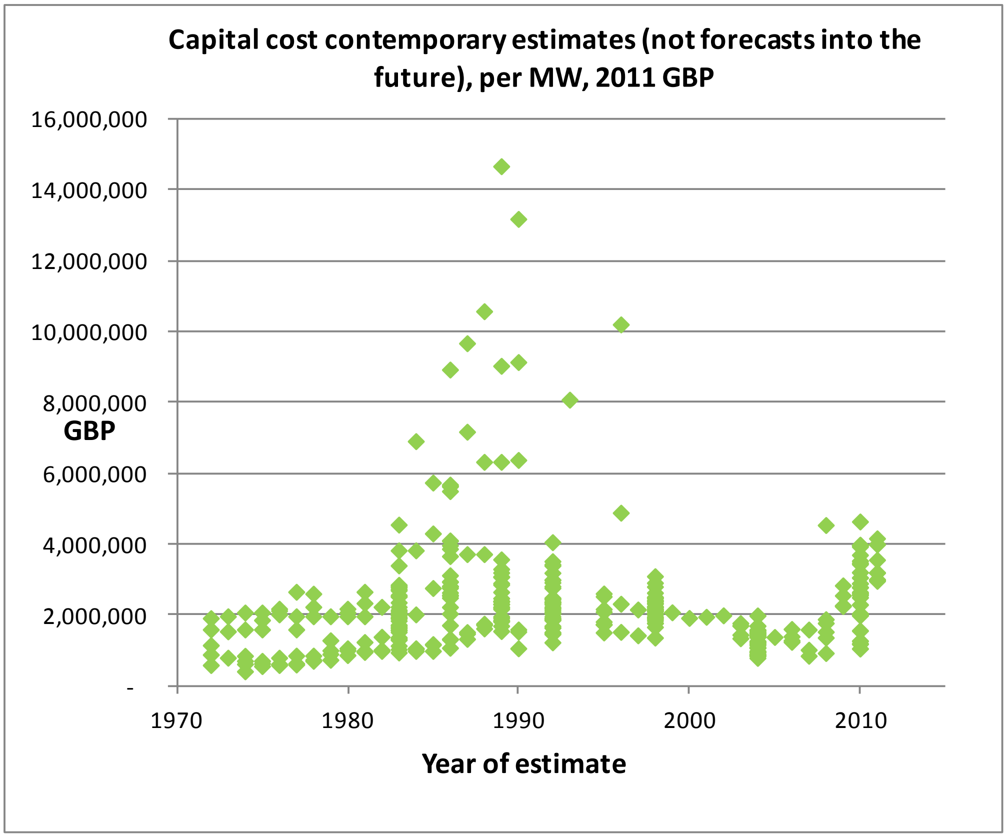

Figure 2.3 Estimated capital costs outcomes worldwide over last four decades

Figure 2.3 presents worldwide estimated capex outcomes between 1972 and 2011. From the early 1970s costs rose gradually before a sharp escalation in the early 1980s which peaked around the late 1980s and early 1990s[3]. In France, for example, real capex rose 40 to 50% between the early 1970s and early 1980s (Thomas, 1988), and between 1970 and 2000 (when the first and last reactor generations were built) overnight costs increased by at least a factor of three (Grubler, 2009). In Germany between 1969 and 1982 pre-construction estimates of overnight cost rose 9% annually i.e. a tripling in 13 years (Thomas, 1988). And in the US, a DOE study showed that predicted construction costs of US$45 billion for 75 reactors had risen to an actual cost of US$145 billion, a cost overrun of more than 220% (Harris et al., 2012). Indeed, Rai et

[3] Note that all the outlier data points above £6m/MW originate from a single source, Grubler (2009) using data from Koomey and Hultman (2007), and apply only to US reactors. It would appear that these cost estimates reflect especially long construction times giving rise to greater overnight and (especially) higher financing costs.

al. (2010) reports that for US plants starting construction between 1967 and 1977, even when 90% complete, costs estimates made at that stage still turned out to be 13% lower than final realised costs.

Comparing Figures 2.1 and 2.3, it is clear that for a period of time between the late 1980s and the mid to late 2000s, forecasts were broadly correct in identifying an upward trend of contemporary costs followed by a downward trend. However, the forecasts significantly part company with estimated outcomes in two ways: i) against expectations, the contemporary cost trend turned sharply back up in the second half of the 2000s; and ii) throughout the period examined, actual cost levels (as opposed to the shape of the trend) have been considerably higher than originally anticipated. Capital costs were expected to peak in the 1990s at an average of around £2.5m/MW and were projected to decline to approximately £1.5m/MW by 2010. In fact, the evidence indicates that actual costs around 1990 were estimated to be anywhere from approximately £1.5m/MW all the way up to more than £14m/MW (see footnote on previous page). Clearly this is a huge range and we will examine cost estimate variability in more detail in sub-section 2.3.

Turning to outcomes during the last decade or so, the evidence shows that the estimated costs for nuclear new build between 2000 and 2010 have for the most part gone up, in some cases by more than 100% to over £4m/MW. Indeed, Cooper (2009) takes an even more negative view, suggesting that costs have quadrupled since the beginning of this century.

Grimston (2012b) reports that in 2004 estimated capital costs for nuclear new build in the US were around $1.4/MW and that subsequent NOAK[4] plants were expected to have capital costs of approximately $1m/MW. However, by the second half of the decade, costs had increased considerably with one 2007 report estimating an overnight cost of $2.95m/MW for a new nuclear plant (or between $3.6m/MW and $4m/MW when interest was included). Also in 2007, Moody's Investor Services estimated a range of between $5m/MW and $6m/MW for the total cost of new nuclear . Meanwhile Florida Power and Light (FPL) estimated the total cost of one of its proposed project as being between $5.5m/MW and $8m/MW (Grimston, 2012b).

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[4] NOAK stands for 'nth of a kind'; FOAK stands for 'first of a kind'. The implication of this distinction is that NOAK plant has benefited from production and operational experience and therefore has lower costs.

In Europe, the still on-going Olkiluoto project in Finland had been expected to cost under €2m/MW and to be completed in May 2009 but by 2010 was running three years behind schedule with projected final costs of nearly €3m/MW. Meanwhile in France, the costs of the Flamanville reactor were restated at €2.3m/MW in 2008, up more than 17% from a year earlier (Grimston, 2012b). According to Parsons Brinckerhoff (2010), between 2008 and 2010 estimates of nuclear generation costs in the UK have risen by 40%.

Mott MacDonald (2010) proposes that realistic current 2010 prices for a new build are around £2.4m/MW to £3.6m/MW in the US or Western Europe and a lower figure of around £2.3m.MW for a non-OECD country. In the UK, the government has been using an overnight cost estimate of £3.6m/MW for a new build programme and a levelised cost of around £95 to £97/MWh (Harris et al., 2012). However, Harris et al. (2012)'s own current estimates for the cost of nuclear generation in the UK range between £177/MWh and £186/MWh, and they suggest that the only way that the government's estimate might prove correct is if, for the first time in over 50 years of UK nuclear history, costs do not escalate over the pre-construction and construction phases.

2.3 Cost estimate variability

Both projections of future costs and estimated contemporary costs are characterised by considerable variation and uncertainty. In part the reasons for this are methodological and/or commercially strategic. As already emphasised, contemporary cost outcome figures are invariably estimates from non-industry sources not actual data from reactor utilities or vendors. Harris et al. (2012) point out that reactor capital costs are very difficult to estimate due to the variety of commercial terms associated with a vendor's quote and because of the lack of transparency behind the majority of published estimates. Indeed, Cooper (2009) argues that utilities may well have an interest in understating costs, especially in the early stages of the regulatory process, as long as the estimates are non-binding (or they don't bear the cost overruns). So-called "low-balling" the costs helps to get a power plant approved.

Mackerron (2006) cautions that the price base for estimates is not always clear and that different estimates may be denominated in prices of different years. In addition, both future projection and contemporary outcome data include figures derived from scenario and sensitivity analysis which produces numerical ranges and thus more variability. Moreover, data may or may not include financing and decommissioning costs on top of overnight costs. Financing costs during construction are particularly significant in that they greatly affect total capital costs. According to Tolley and Jones (2004), by the time a new plant comes on line, total capital cost can be 25 to 80% greater than the overnight costs, depending on interest rates and length of construction period.

There are also other more technical or physical reasons for the variability in capital and levelised cost data. These include the following considerations (Tolley and Jones, 2004); (Harris et al., 2012); (Thomas, 1988); (MacKerron et al., 2006):

- costs vary with reactor technologies and estimates for the same technology can also differ, depending for example on whether FOAK or NOAK is assumed;
- capital costs and costs of generation are country, region and regulatory environment specific – there have been substantial differences of performance in different countries and in different utilities within the same country where regions face different input costs, especially labour;
- actual or assumed construction time is highly significant – delay and prolongment affect costs including labour and, in particular, financing costs (for example, as at 2001, average US construction time was over nine years whereas in France it was less than seven years);
- magnitude of overnight capital cost, including labour costs and productivity variance, is key;
- also important are magnitude of contingencies; single or multiple plant build; project management (in-house utility management tends to yield lower costs than construction firm management); operating experience and other factors affecting load factors (see for example Gross (2007)); plant life assumed; discount rate assumptions (also see Gross (2007)).

Finally, it is worth noting that at least as far as US costs history is concerned, Cooper (2009) sees distinctions in cost estimates and projections depending upon whom they were made by. Early estimates by government and academic bodies tended to be quite low. More recently, utility cost estimates come out higher but tend to be lower than estimates from the financial sector. Independent analysts are typically the highest. Government entities have more recently tended to use an average of other analyses.

3. Cost trend drivers

Section 3 examines the most significant drivers that have influenced nuclear cost trends. In keeping with the main report, this case study distinguishes whether a particular cost trend driver is endogenous, exogenous, or methodological in nature (see main report for further explanation). In addition, the cost driver sub-sections are categorised according to three time periods: in broad terms, costs rose from the early years up to around 1990, seemingly declined until the early to mid-2000s, and then started to escalate again. Notwithstanding these trends, each period will inevitably encompass competing drivers, some up and others down.

The evidence also shows that it can be problematic both to identify and quantify the secondary effects of a driver which lead to a cost impact, as well as to isolate and quantify first causes. For example, longer construction times result in cost escalation but they might do so for several reasons including higher financing charges and greater labour costs. In addition, a prolonged construction time could, for example, be the result of inexperience with a new reactor design or with having to amend, and possibly even back-fit, an older design. In turn, these circumstances might have originated from an autonomous technical decision or from responding to a more stringent regulatory environment, or both.

3.1 The 1960s to 1980s

Environmental & safety concerns

Over several decades, many analysts and commentators have observed that the escalation in costs from the start of commercial reactor construction in the mid-1960s through the 1970s to the late 1980s in very large measure stems from the endogenous effects of an unstable, changing regulatory environment (see, for example, Cantor and Hewlett (1988); Hultman et al. (2007); Neij (2008); (Rai et al., 2010). This is especially so in the US to which much of the evidence and cost data refers.

By the late 1960s nuclear safety and waste disposal was the subject of increasing public focus and had become a predominant theme for the environmental movement (Rai et al., 2010). Public and political opposition to nuclear power continued to grow through the 1970s and became more widespread after the accidents at Three Mile Island in 1979 and Chernobyl in 1986. Direct action, political lobbying and use of legal action introduced major delays into projects and interrupted operations (Grimston, 2012b). In large part this fostered an unstable regulatory climate in which the rules kept changing in apparently arbitrary ways (MacKerron, 1992).

The consequence through much of the 1970s and 1980s was the repeated call for design changes, with regulators demanding more safety features in such areas as fire protection and seismic criteria (NEA, 2000). In many cases these had to be back-fitted after construction had already begun causing additional material, equipment, and labour costs together with significant delays which added to the costs of finance (Tolley and Jones, 2004); (Rai et al., 2010); (Grimston, 2012b).

Between the early and late 70s in the US, tightening Nuclear Regulatory Commission (NRC) regulations led to a 41% increase in the quantity of steel required for a similar rated plant, a 27% increase in concrete, a 50% increase in piping footage, and a 36% increase in electrical cabling (Cohen, 1990). According to Tolley and Jones (2004), regulation was responsible for a 69.2% increase in capital costs from 1967 to 1974 and may have resulted in approximately a 15% per annum increase in plant costs during the 1970s and 1980s (with the caveat that other effects may have been contributing as well).

Whilst there was already an underlying pressure for more stringent regulation, a number of crises during this period increased the uncertainty and upward pressure on nuclear costs (Grubler, 2010); (Grimston, 2012b). In the US, these were the 1975 Browns Ferry incident and the 1979 Three Mile Island (TMI) accident, and in the Ukraine, the 1986 Chernobyl explosion. After the accident at TMI, the industry was subjected to even more intense scrutiny. Construction costs after TMI but before Chernobyl were 95% higher than those completed before TMI with resultant electricity costs increasing by 40%. In addition, the construction costs after Chernobyl were 89% higher than those completed between TMI and Chernobyl (Harris et al., 2012).

A variety of other, but often inter-related, factors also played a part in this period of cost escalations. This, suggests Grubler (2010), was especially so from the early 1980s when the designs perceived as safe had become established and a more stable regulatory climate prevailed. Yet despite this, reactor design and related systems continued to become more complex and costs continued to escalate (Grubler, 2010)

Reactor design and construction time

As mentioned in the previous sub-section, increased construction time – whether due to management and labour force inexperience with new reactor design or because of regulatory-driven changes – has a major impact on costs.

NEA (2000) observes that US plants built before 1979 took an average of five years to build and license whilst the ones post-Three Mile Island averaged almost 12 years. In the latter cases, financing and other time-related cost escalations could represent as much as half the total cost (Spangler, 1983); (NEA, 2000). According to Cohen (1990), the increase in US construction time from 7 years in 1971 to 12 years in 1980 plus the increase in labour and materials costs contributed to a quadrupling of capex.

In Germany, Thomas (1988) notes a clear statistical trend between 1967 and 1977 towards longer construction periods and higher costs. The predominant explanation is the interaction of regulatory and technical factors, especially reactor type. Similarly, regarding the French nuclear programme, Grubler (2010) argues that the move towards a new French reactor design in the 1980s (as well as deviating from the tested Westinghouse license by redesigning reactor components) caused lengthening construction times and consequent cost escalations.

In addition to management inexperience or inadequacy (Ahearne, 2011) and regulatory uncertainty, another reason for prolonged construction was what has been termed 'stretching out'. In the 1980s, utility financial planning was in part derailed by lower trending electricity demand. Utilities therefore sometimes chose to deliberately 'stretch out' the construction time of plants that it appeared would be loss-making once on-line (Thomas, 1988); (Cohen, 1990). The obvious downside to this decision was a consequent increase in interest during construction (IDC).

Design change, lack of standardisation & diseconomies of scale

Despite the unstable regulatory environment, the 1970s saw a rapid growth rate in deployment characterised by competitive reactor pricing coupled with optimistic cost projections (MacKerron, 1992); (Rai et al., 2010). The result was that manufacturers frequently changed reactor designs, not only in response to regulatory pressures but also in order to offer customers increased generating capacities. In the US during this time, over 50 utilities began separate procurement programmes involving at least 6 vendors, 20 architects/engineers, and 26 construction contractors. The result was 110 plants, most having unique design and operating characteristics, and over time, increasing reactor capacities (Rai et al., 2010).

In the mid-1960s, the industry scaled up from a reactor capacity of about 400 to 500 MW to about 800MW. Then, before these were even completed, 1100 MW plants were being constructed. The logic was that economies of scale would bring costs down, but in reality the frequently changing designs precluded the standardization that might otherwise have led to economies of scale and replication (MacKerron, 1992); (Rai et al., 2010). It also led to diseconomies of scale arising from increased complexity, lower morale and productivity (due to lengthening construction horizons), and greater demands on management (Cantor and Hewlett, 1988).

Lack of standardisation and scale economy issues were not confined to the US. In France, Grubler (2010) attributes the worst of the cost escalation to a gradual erosion of standardisation and instead trying to upsize and 'frenchify' the nuclear reactor design late on in the programme. This involved replacing the 900 – 1300MW PWR[5] designs that had been relied upon for the majority of the programme with 1500MW N4 reactors. The result was an endogenously-driven "negative learning process" due to inadequate standardisation and additional learning and FOAK costs.

It is also important to consider that unit size on a scale as large as nuclear may have intrinsic diseconomies since it misses the opportunities of achieving lower costs associated with manufacturing many (smaller scale) units of the same type as in the case of PV (Koomey and Hultman, 2007). That said, the impact of such diseconomies may be lessened in cases where multiple reactors (but usually only two) are built simultaneously on the same site.

Intrinsic problems with learning effects

Experience curve theory argues that savings should accrue from learning by doing. If costs escalate, as they did in the 1970s and '80s, it would seem reasonable to conclude that learning must simply have been overwhelmed by other more powerful negative cost effects. However, the evidence suggests that learning opportunities were in any case endogenously compromised irrespective of other off-setting effects on them.

The rapid rate of deployment of nuclear plants put considerable pressure on the contractors who until then had little experience in the business. More importantly, this rapidity hampered the industry's ability to apply learning from earlier projects to later ones because projects were evolving simultaneously, albeit at different stages (MacKerron, 1992); (Rai et al., 2010).

Moreover, Neij (2008) points out that nuclear plants are individually designed and built according to local conditions which restricts the opportunities for cost reduction related to experience. Experience sharing and spillover have been limited by design diversity and customisation as well as being undermined by long lead times in planning, construction and commissioning periods (Thomas, 1988). This was particularly the case in France when, as mentioned, the industry introduced a new, French design that did not easily allow learning spillovers in design or construction.

Over and above this, the sheer complexities of reactor design and construction in general may also have limited the pace of learning or possibly even reversed it (Grubler,

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[5] Pressurised Water Reactor

2009). Economies of scale, argues MacKerron (1992), have proved elusive because complexity has increased disproportionately as reactor capacity has grown. Indeed, MacKerron argues that the single most important cause of increases in capital costs during this period was the growing complexity of nuclear plants.

Labour

Labour as a cost driver appears to be both endogenous and exogenous. Construction delays and back-fitting increased both skilled and semi-skilled labour costs and also tended to lower morale and productivity. A second endogenous factor is the growth in reactor orders in the 1970s which created a skills shortage in the US (Thomas, 1988). This was arguably within the powers of the vendors and utilities to address through more training (though that itself comes at a cost).

On the other hand, labour is an exogenous driver in that labour costs across the board were rising. In the US, labour costs were less than materials costs in 1976 whereas by 1988 labour was twice as expensive. During this period, nuclear costs increased at an average rate of 13.6% per annum compounded whilst labour costs increased 18.7% and materials costs only 7.7% (Cohen, 1990).

Interest rates

Writing in the early 1980s, Spangler (1983) reports that the economics of nuclear power were impacted by recent high interest rates, especially when construction schedules were also subject to significant delays. To illustrate, in 1976/77 US Federal prime rates ranged between approximately 6% and 8% per annum. By 1980/81 rates had hit a record high of around 21% and in 1983 were still 11% or more (FedPrimeRate.com, 2012). During most of that decade rates remained relatively high such that MacKerron (1992) considered this to be a highly important exogenous factor.

In addition, after the 1979 Three Mile Island accident, financial markets reduced the bond ratings of US utilities. This meant that their borrowing costs rose, thereby increasing the interest during construction (IDC) component of total cost (Thomas, 1988). Thomas assumes that nuclear project financiers elsewhere in the world also took note thus impacting financing costs worldwide.

Methodological factors

The evidence reviewed suggests that methodological reasons have also contributed to the disparity between future cost forecasts and actual outcomes.

In 1970 none of the US reactors ordered during the first wave of commercial orders in the 1960s had yet begun operating. Thus most of the information in the early 1970s when the volume of sales escalated rapidly was based upon expectation and estimates rather than actual experience. Moreover, at the time, cost analysis was the domain of the utility industry, the reactor vendors and government officials. There were few financial markets analysts and independent energy consultancies expressing scepticism and higher cost estimates (Cooper, 2009). Subsequent experience of actual construction meant that costs then had to be revised substantially upwards rather than more realistically starting from a higher initial base.

This problem persisted over at least the next two decades. Thomas (1988) comments that few countries published actual costs containing clear assumption criteria and thus much of the data were hypothetical and substantially underestimated. Furthermore, whilst such estimates might incorporate past cost increases they assumed there would be no future increases and ignored trends to the contrary. Meanwhile, MacKerron (1992) argues that much of the data made public came from official nuclear agencies which unsurprisingly tended to be positive about nuclear power. Certain assumptions, such as discount rates, could be too forgiving, and again the data tended not to be informed by the reality of historical costs but to be forecasts which assumed that "past problems are always solved and new problems will not emerge", i.e. extreme appraisal optimism anticipating large cost savings compared to previous projects.

Alongside natural optimism, deliberate under-estimation ('low-balling') in order to win contracts or to justify investments also played a part. Nuclear critics have repeatedly highlighted concerns about the strategic misuse of cost forecasts Grubler (2010) and it has been suggested that in the 1960s both Westinghouse and GE offered turnkey contracts with artificially low prices in order to penetrate markets. Only a few years later, cost estimates had risen by 80% (Kern, 2011).

3.2 The 1990s to mid-2000s

Figure 2.3 illustrated how, after two decades of increases, costs trended downwards from around 1990 reaching a low in the mid-2000s. From the evidence reviewed the reasons for this are less clear than the reasons for the earlier cost rises. However, the following sub-sections consider the likely main drivers for the downward trend.

Non-OECD country data

Much of the cost estimate data during this period comes from the IEA/OECD and beginning in 1989, data was collected for several non-OECD developing countries – China, India, Indonesia, Korea, and Brazil. From 1992, Hungary and Czechoslovakia were also included, and from 1998 Romania and Russia as well. We analysed the data from 1989 onwards, comparing the average capex for the developed countries of North America, Western Europe, and Japan on the one hand versus the developing countries of South America, Eastern Europe and Asia (minus Japan) on the other.

The difference in 1989 is already noticeable – the developed country group averages capex of approximately £2.6m/MW whilst the developing country group averages £2.3m/MW, a difference of a little over 10%. In 1992, the same comparison results in an average of approximately £2.5m/MW (developed countries) versus £1.8m/MW (developing countries), a difference of nearly 30%. In 1998, the result is an average of around £2.4m/MW (developed countries) versus £2.1m/MW (developing countries), a 12.5% difference. And in 2005, the developing country estimates are one third cheaper at approximately £1m/MW on average versus £1.5m/MW for the developed countries. In 2010 the difference in averages was even greater though by then both averages had risen dramatically (to over £3.1m/MW for developed countries including Eastern Europe and over £1.5m/MW for developing countries).

It is clear that lower estimates in developing countries contributed greatly to the declining trend. However, it is also striking that developed country estimates were also declining even though there was little or no actual construction activity going on (in the US, for example, no reactors have been approved for construction by the NRC since 1978 (Hultman et al., 2007)). We shall return to this point later.

Several reasons are offered as likely drivers behind the cost reductions in developing countries. With the exception of some lower input costs, we categorise the reasons as endogenous. Grimston (2012a) points to a combination of:

- lower input costs, especially labour, in part due to a slowing down of the world economy;
- less cost-forcing regulatory pressures;
- and a greater incidence of command-and-control type economies likely to ensure stable electricity prices which therefore lowered the risk premium on capital financing.

Construction times also played an important role. Tolley and Jones (2004) observes that the nuclear plants in construction since the early 1990s – mostly Asian – were built in shorter construction times than in the US and even in France, and with less cost variability. Up to the late 1970s when the last US plant began construction, the average construction time in the US was nearly ten years. For plants beginning construction between 1993 and 2001, the global average was just over five years.

Possible effects of non-OECD data on OECD country estimates

As noted above, the contemporary estimates of developed countries were also coming down. It is likely that in part the reason for this was methodological and that estimates of cost from the group of countries where little or no construction was occurring were being influenced by the numbers emerging from the lower cost environments where construction was actually taking place (Grimston, 2012a).

Tolley and Jones (2004), for example, points to the experience in Asia as offering a "basis for optimism regarding future construction" in the US, especially with regard to reduced construction times. And in the UK, as late as 2006 when estimates had already started to rise again, Mackerron (2006) reports that recent UK-applicable estimates appear to have derived from studies designed to apply to other countries. Mackerron argues that appraisal optimism is still a significant risk for future UK nuclear projects.

It is probable then that the downward cost trend during the 1990s and early 2000s in great part reflected both the reality of lower costs in developing countries coupled with the appraisal optimism of developed countries where cost estimates were not adjusted sufficiently upwards to take account of differing national conditions.

Additional considerations

Around 1990, several new LWR designs with advanced safety features and reliable operation characteristics became commercially available (Junginger et al., 2008). After the cost escalations of previous decades, in large part due to regulatory requirements, it is possible that a high water mark had been reached with safety-driven costs now fully 'priced in'. In addition, the Nuclear Energy Agency (NEA) was finding cause for optimism in what it saw as the "managerial and operational process transformations" that the US nuclear industry had undergone in the previous decade (NEA, 2000).

Increasing standardisation was also a probable factor, characterised by the growing dominance of the LWR design, and especially the PWR variant. Worldwide (excluding the then Soviet Union), of the more than 100 reactors under construction in 1986 and therefore completed in the 1990s, 80% were LWRs and this pattern has since continued (Kern, 2011). For example, until late in France's programme the roll-out of nuclear power relied on only three standard designs which were reproduced at different locations to enable cost savings. The standardisation of design allegedly led to a reduction in capital costs of 10-15% (Grubler, 2010).

3.3 Mid-2000s to present

During the latter part of the 1990s and into the 2000s, the relative economics of nuclear power once more began to look attractive and the last decade or so has seen a revival in its fortunes (Grimston, 2012b).

Nevertheless, cost data show that contemporary capital costs have been broadly escalating from low estimates of under £1m/MW in the mid-2000s to high estimates in excess of £4m/MW by 2011. According to analysis in (Harris et al., 2012) overnight construction cost estimates between 2005 and 2011 have increased on average by 17.5% per annum above the rate of inflation. Generation costs have been similarly increasing. Parsons Brinckerhoff (2010) reports that estimates of nuclear generation costs rose by 40% between 2008 and 2010. More broadly, our review of the evidence finds that estimated levelised costs have escalated from between £25 and £50/MWh in 2006 to between approximately £50 and £130/MWh in 2011.

The literature reviewed suggests a combination of reasons for these more recent cost escalations. Sub-section 3.3.1 includes both exogenous and endogenous factors whilst sub-sections 3.3.2 to 3.3.4 address primarily endogenous issues. Sub-section 3.3.5 considers some methodological issues.

Commodities and competition

Notwithstanding the global financial crisis in 2008/2009 and ensuing recession, increased estimated costs over the last decade are due, in large part, to worldwide competition for resources and commodities (such as steel and cement) and for manufacturing capacity (Harris et al., 2012). Strong demand for generation plant has resulted in cost increases, supply chain issues and longer delivery times as manufacturers have struggled to meet demand. Nuclear plant operators have also been competing with oil, petrochemical and steel companies for access to resources (Grimston, 2012b).

Specialist components and supply chain bottlenecks

More specifically, nuclear build requires special forgings and other critical components. Harris et al. (2012) suggest that construction times could continue to increase due to supply chain bottlenecks impacting the availability of key parts such as these. For example, there are only two companies that have the heavy forging capacity to create the largest components for nuclear plants (Japan Steel Works and Creusot Forge in France) (Harris et al., 2012); (Grimston, 2012b). Competition with the petrochemical industry and new refineries as well as other electricity generation projects for these forgings is likely to further increase costs and delays if worldwide nuclear activity expands (Grimston, 2012b).

Skills shortages and management ability

Input costs have been exacerbated by a skilled labour shortage causing cost estimates for major construction projects worldwide to rise. In North America, skills shortages in both nuclear design and construction personnel have been expected to delay construction schedules and drive up projected costs (Grimston, 2012b); (Ahearne, 2011).

In the UK, skills shortages have already been highlighted for some time. Harris et al (2012) project that new build programmes worldwide, particularly in Asia, will result in the relatively small UK market facing stiff competition for skills from other countries. At the EU level, it has been estimated that demand for skilled labour will increase by up to 170% by 2018 if all planned new nuclear builds were to be built (Harris et al., 2012). In addition, according to (Ahearne, 2011), the delayed and over-budget Finnish project, which is characterised by inexperienced contractors and poor communication amongst the workforce, suggest that weak management may also be prevalent in the nuclear industry.

Recent experience in Finland and France

The cost and time overruns at Olkiluoto in Finland and Flamanville in France may also be influencing current estimates. Finland lacks both construction experience (two previous plant orders were 25 years ago) and technology experience (in the EPR reactor design). There have been problems with the quality of work and materials, communication and management issues, and delays and changes in design (Harris et al., 2012). In France, there have been delays at Flamanville due to construction accidents, changes in project management, and additional stress tests following the Fukushima crisis in Japan. Flamanville is the first EPR reactor to be built in France and it is also the first reactor to start construction in 15 years (Harris et al., 2012). Grubler (2010) argues that the project's problems exemplify how knowledge obsolescence has resulted from an extended period of no nuclear construction experience. Certainly the nuclear industry worldwide will have taken note of the experiences at Olkiluoto and Flamanville and cost estimates are likely to have been revised accordingly.

Possible methodological drivers

Harris et al. (2012) point to political and commercial reasons for vendors and contractors to 'lowball' cost estimates at the bidding stage – political in order to prove that government R&D policies have been working, and commercial in order to secure business. As with the observations made in sub-section 3.1.7, it is possible that as projects have evolved over time, the true costs have become more apparent thus contributing to the upward cost trend.

A related factor is better price transparency. According to Parsons Brinckerhoff (2010), the reason that nuclear generation cost estimates in the UK rose 40% between 2008 and 2010 was in part because preparing for new nuclear build has resulted in clearer nuclear prices. Tendering for plant internationally has meant that up-to-date cost data are more widely available thus enabling more realistic estimates.

4. Summary and conclusions

This concluding section first summarises the cost trends and significant drivers behind them. It then considers what lessons can be drawn, for costs forecasting in nuclear energy in particular and for electricity generation cost forecasting more broadly.

4.1 Summary

Nuclear cost trends can be broadly divided into three periods: an escalating trend between the 1960s and 1980s; a declining trend in the 1990s and early 2000s; and a further escalating trend from the mid-2000s to the present. The variability in both contemporary costs estimates and future forecasts is considerable due to a variety of reasons, some methodological or strategic, some technical or practical. However, on average, forecasts of future costs that were made in the decades before 2005 predicted that costs would peak in the mid-1990s at around £2.5m/MW, then decline to approximately £1.5m/MW by 2010 and to £1.25m/MW by 2025. In reality, the data collected shows that estimated costs peaked around 1990 at about £4m/MW (excluding the high outliers from Grubler (2010)), declined to a low of approximately £1m to £1.5/MW in the mid-2000s, then escalated again to approximately £4m/MW by 2011. Average global future forecasts made post-2005 take into account the recent cost escalations and start at approximately £3.5m/MW in 2010. They then project a decrease to under £2m/MW by 2025.

Though difficult to quantify, exogenous drivers such as interest rates and commodity prices have played some role in the cost trends. In particular more recently, global competition both within the nuclear industry and amongst large capital projects in general has put upward pressure on commodity and component costs. However, the main drivers, both up and down, appear to have been methodological or endogenous (i.e. stemming from within the industry or its governance).

Endogenous downward pressure in the 1990s and early 2000s included lower labour costs, shorter construction times, and less regulatory burdens in non-OECD countries. This in turn appears to have led to a methodological appraisal optimism in the ‘paper’ estimates of OECD countries which were not actually engaged in nuclear construction at the time.

Endogenous upward cost pressure before the 1990s included:

- cost burdens arising from regulations resulting in design changes, construction delays and overruns, and additional financing costs;
- lack of standardisation due to multiple reactor design variants;
- disappointing economies of scale due both to the absence of mass production benefits and to disproportionately increasing complexity at larger scales;
- less than anticipated learning effects due especially to excessively rapid deployment, excessive design variants, and complexity.

Endogenous or methodological upward pressure within the last decade has included:

- supply chain bottlenecks e.g. for specialist forgings;
- skills shortages and management problems;
- under-estimates later revealed and revised;
- delays and cost overruns on projects in Finland and France due especially to lengthy gaps in nuclear construction experience and specific inexperience with EPR reactor design.

4.2 Conclusions

Use of experience curves versus engineering/project assessment

The global nuclear cost profile over the last five decades makes it extremely difficult to justify the application of the experience curve method of future cost projection. Given the profile's volatility, choosing a limited time frame in which to measure cost change against installed capacity would be arbitrary, but if nuclear energy's entire history were chosen the learning rate would be highly uncertain but most definitely negative. It is not surprising then that projections of future nuclear costs have tended to be based on engineering and project assessment where nuclear advocates have been able to find room for optimism in spite of the uncertain or negative track record.

Appraisal optimism

It is evident from the disparity between future projections and actual outcomes that, notwithstanding some dissent, appraisal optimism has been a fairly consistent feature of nuclear costs analysis. The reasons appears to be a combination of both industrial/ technological enthusiasm and commercial/political pressure to lowball cost estimates.

Either way, estimates have typically not reflected the full range of uncertainties, and accordingly have used inadequate contingencies given nuclear's history of regulatory instability and technical and construction difficulties. In addition, the importance of location and technology specificity has been undervalued with insufficient weight given to reactor types and national conditions.

Potential undermining and/or reversal of learning effects

Nuclear history shows that costs can increase rather than decrease despite (or perhaps even because of) increasing deployment. Learning effects can be overwhelmed by a variety of exogenous or endogenous factors, and it is also possible that learning-by-doing may even be reversed and become ‘negative’.

Some commentators suggest that the latter situation has arisen in nuclear energy in two ways. First, reactor and project scale-up has led to disproportionately cost-increasing complexity and resultant increases in construction times and component and labour costs. This might perhaps be described as ‘unlearning-by-doing at too large and complicated a scale’. Second, long gaps in project experience (as has been the case with Flamanville and Olkiluoto) may result in ‘organisational forgetting’ or ‘knowledge depreciation’ which can compromise project management. As Tolley and Jones (2004) says, “if construction is sporadic, learning effects will suffer”.

Even if not negative, the learning effect can still be compromised or overwhelmed by a variety of cost-increasing factors. **Regulatory instability** can force design changes and even back-fitting leading to higher overnight costs, construction delays, and additional financing charges. It can also exacerbate financier uncertainty and increase possible funding rates. What is particularly clear in the case of nuclear is that **construction duration** is key. It is therefore of concern that, even relatively recently, projected construction periods have been disputed with some analysts projecting five or six years, and others ten years or more (Cooper, 2009).

In large part, the regulatory issues reflect the fact that nuclear power is in **a different safety category** than other generating technologies. The accidents at Three Mile Island, Chernobyl, and now Fukushima demonstrate that nuclear energy is especially vulnerable to cost shocks when there are doubts about its safety. For example, Harris et al. (2012) report that the rating agency Moody’s has estimated the Fukushima accident will likely result in a range of higher costs as a result of increased scrutiny, more stringent safety procedures and longer maintenance outages.

A further intrinsic aspect of nuclear energy is that it tends to be very large-scale, ‘lumpy’ and site-specific and **cannot easily benefit from mass production economies** of scale in the way that, for example, PV or wind turbines can. Economies of unit scale may well be offset by growing complexity, whilst opportunities to benefit somewhat from multiple unit construction at the same site may be infrequent.

Lack of economies of scale have been exacerbated by **too little standardisation**. Despite the relatively small number of basic reactor designs, numerous variants have been tried over the years, undermining learning opportunities and increasing the likelihood of construction and operating problems. Indeed, Tolley and Jones (2004) suggest that perhaps the greatest potential for cost reduction lies in utilising standardised designs and (if possible) constructing plants in series.

The nuclear example also suggests that there can be occasions when **excessively fast roll-out** may compromise the ability to incorporate learning into successive units. In addition, growth in deployment typically leads to increased competition for raw materials, components, and skills, and thus potential commodity squeezes and supply chain bottlenecks. In the case of nuclear, there are sometimes only one or two suppliers for critical parts and nuclear projects also have to compete globally with other major construction projects for key commodities such as steel and cement.

Specifically in the UK, Harris et al. (2012) warn that a new build programme would likely be congested, with potentially eight reactors under construction at the same time during the early 2020s. During this same period India and China will, by themselves, be increasing current global nuclear construction rates by around 60%. This may well place further pressure on supply chains, increase construction costs and jeopardise timing plans.

Final observations

Whilst contemporary cost estimates have been rising since the mid-2000s, in part reflecting a new appreciation of the realities of nuclear construction, expectations for future nuclear costs are that they will gradually fall over the next few decades. Nevertheless, nuclear's track record is characterised by uncertainty and MacKerron (2006)'s warning that appraisal optimism is a real risk remains true today.

Nuclear projects appear to be particularly prone to cost uncertainty and surprises but this is likely to be especially true for any capital project which can have a lead time of a decade or more – long planning and construction durations inevitably mean more time during which cost shocks can arise. Harris et al. (2012) caution that the cost estimates the UK government is currently relying on fail to take into account that the scope and complexity of nuclear plants can cause project durations to last more than 14 years. This in turn exposes projects to a range of pressures that impact final costs.

Given the example of nuclear's tendency for forecast overconfidence, Koomey Hultman (2007) argues more generally that any projection assumptions that deviate significantly from historical experience need careful documentation and justification, especially if those estimates are used to support policy proposals.

Grubler (2009) goes further, suggesting that the true cost of a technology as large and complex as nuclear might in fact be unknowable ex ante. If this is correct, “this would severely limit conventional deterministic economic calculus and decision making (e.g. cost minimization) models”. In any case, Grubler (2010) advises that forecast analysis should probably begin with the engineering rule of thumb that large-scale construction projects tend to always cost two to three times the original estimate. Significantly, nuclear energy is not the only large-scale, complex technology to which this engineering rule might apply: other generating technologies such as coal-based IGCC with CCS, for example, could be candidates as well.

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