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Proceedings of the 13th International Conference on Manufacturing Research (ICMR2015)

FISSION POSSIBLE: UNDERSTANDING THE COST OF NUCLEAR POWER

Amritpal Singh Agar[1] & Yee Mey Goh[2]
Wolfson School of Mechanical & Manufacturing Engineering
Loughborough University
Leicestershire
LE11 3TU, UK
[1]a.s.agar@lboro.ac.uk
[2]y.goh@lboro.ac.uk

Linda Newnes
Department of Mechanical Engineering
University of Bath
Bath
BA2 7AY, UK
l.b.newnes@bath.ac.uk

Martin Goodfellow
Rolls-Royce Civil Nuclear
Derby
DE21 7XX, UK
Martin.Goodfellow@Rolls-Royce.com

ABSTRACT

The cost of nuclear power has been debated ever since the build of the first plant at Calder Hall. Despite crippling construction delays in the 1970s and 80s, nuclear new build is again considered to meet both future demand growth and CO2 reduction targets. UK suppliers could produce around 45% of the high value components, with the potential to enter international export markets. Initially estimated at £9bn, to £16bn after Fukushima, with the most recent estimate at £24.5bn, Hinkley Point C will be the pilot build for new nuclear. The question remains, can the UK build a nuclear power station economically? The research aims to provide a methodology for estimating the cost of future nuclear build projects. This paper will review cost drivers for historic nuclear build, prior to and after their construction. Based on this analysis the paper will critique the current methodology and provide direction for the research.

Keywords: Nuclear, cost, estimation.

1

INTRODUCTION

Nuclear reactors were first built in the UK in the 1940s, primarily for military applications. From the 1950s to the 1980s the Government-run Central Electricity Generating Board (CEGB) pioneered the construction of nuclear reactors for civil purposes. Following privatization of the UK electricity market in the 1990s there has been no new installed nuclear capacity. At the time of writing Edf Energy are on the brink of investing in a Pressurized Water Reactor (PWR) to be built at Hinkley Point C, Somerset. There is little consensus over the projected cost of building new nuclear reactors in the UK, a liberalized market.

2 This paper will review the three major nuclear build eras in the UK, and the understanding gained from each programme regarding the cost drivers and accuracy of the estimates produced. A section is then dedicated to the key literature regarding the cost drivers of nuclear new build in the UK. Finally possible areas of future work and possible directions for the research are presented.

GENERATION ONE: THE MAGNOX PROGRAMME

The first generation of commercial nuclear power construction in the UK took place between 1955 and 1972, with the building of eight Magnox stations totalling 4.8GW of electrical capacity (**Green 1995**). Early cost estimates showed a preference for gas graphite reactors, and research was progressing on this technology in both the UK and France (**Cowan 1990**). France abandoned gas reactors in the late 1960s reverting to the US-developed PWR technology.

As the first of the Magnox stations came online, the belief was still very much that ‘bigger is better.’ **George** (**1960**) estimated that nuclear construction for a Magnox station would cost £40million, more than double the cost of a conventional coal fire power station. Over the 20 year lifetime of the power station the cost per unit was estimated at 0.66p/kWh. In this estimate, the major cost driver was seen as the cost of fuel. Other cost drivers were considered including electrical output, length of the amortisation period, rate of interest, load factor, and the value of plutonium.

Pipe (**1969**) showed how based on the experience of the build of coal fire power stations in the 1950s nuclear power would see a reduction in costs due to increasing station size. Throughout the 1950s and 1960s, it was believed that learning by doing would see a major reduction in the cost of nuclear power, in much the same way that capital costs in other industries had experienced (**Cowan 1990**).

Sandford (**1965**) found that two-thirds of the actual costs were associated with the initial capital charges, due to rising interest rates. Earlier expectations that nuclear and conventionally produced electricity would be comparable in cost were wrong. **Sweet** (**1990**) argued that the actual cost of capital for building the first generation of nuclear reactors was much higher than accounted for, as capitalization of interest was not included during construction and, due to overruns, this was a substantial cost.

Green (**1995**) used the CEGB annual accounts to infer the total cost of the Magnox programme. By including decommissioning estimates from the experience of the closing of Berkeley power station, a total cost of 3.3p/kWh was arrived at in 1989 money. During construction it was difficult to ascertain whether future NOAK (nth of a kind) capital costs would reduce due to lessons learned from FOAK (First of a kind) stations, or due to a greater installed capacity in each successive build driving the average cost curve down (**Sandford 1965**).

An analysis was conducted by **Jeffrey (1982)** as to whether there was an opportunity cost, in real terms, to building Magnox reactors rather than more coal-fired power stations. It was shown that the value of nuclear power over coal was dictated by coal fuel costs, and that adjusting the existing assumption of coal price to the actual price resulted in an investment loss of £450million over the lifetime of a 1000MW nuclear power plant.

3 AGR VERSUS PWR

From 1966 to 1978, while some of the Magnox fleet was still under construction, the CEGB ordered 7 twin Advanced Gas-cooled Reactors (AGRs) (**Chesshire 1992**). It was estimated that an additional 2000MW(e) of installed capacity from AGRs would be ordered each year, with nuclear eventually providing 70% of the UK’s electricity mix (**Bainbridge & Farmer 1971**).

The AGR, it was believed, would “produce substantially cheaper electricity than the Magnox stations” (**Mounfield 1967**) as well as being lower cost when compared with conventional power stations. The FOAK station, Dungeness B, was estimated to cost 0.46p/kWh, with the CEGB then assuming that NOAK versions would reduce generating costs by 20% overall. Searby (**1969**) estimated that the cost of a twin AGR reactor would be 0.56p/kWh. This was based on an assumed electrical efficiency of 41%, which was never achieved by AGR technology.

Estimating methods were used as investment decisions based on the “minimum total cost of meeting future power demand” (**Bainbridge & Farmer 1971**). The CEGB used the “total system cost” method to determine the least cost and most secure supply generating technology for investment (**Pipe 1969**). **Bainbridge & Farmer** (**1971**) described a parametric cost method which compared the start-up and operating costs (including projected fuel costs) of various types of power stations in order to determine the best choice. The cost drivers were believed to be the relative price of fossil fuels, the price of extracting and processing uranium fuel (including the fabrication stage), and also the level of maturity/rate of advancement in nuclear reactor design.

Actual Cost Drivers

The lack of detailed design work prior to commercialization of AGR technology lead to severe technical problems, and commensurate time delays, which added over 50% (£1000million) to the estimated cost of the construction programme (**Rush *et al.* 1977**). Figure 1 shows the time for construction for each of the stations in the UK nuclear reactor fleet. The early Magnox stations built in the 1950s were much smaller in size when compared with those built in the 1960s, with the larger stations also having longer
3.1 construction times.

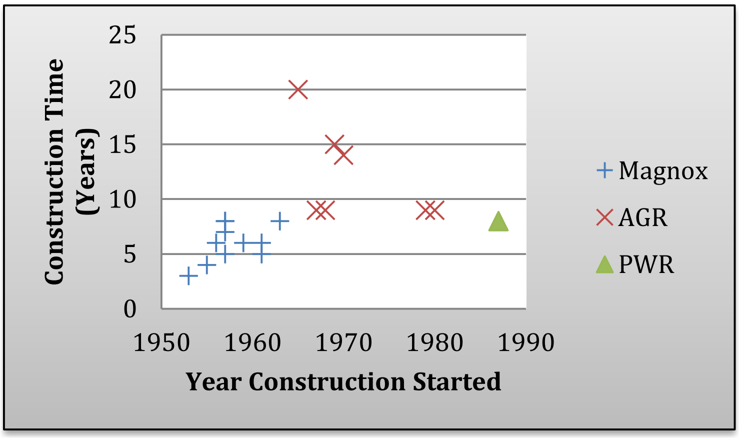

Figure 1: Construction of the UK Nuclear Reactor Fleet

In the Electricity Supply Industry's (ESI) review of cost drivers for nuclear and conventional power stations, the main variable was determined to be the cost of fuel, whilst for nuclear power, the cost of capital was the most significant cost driver (**Sweet 1990**).

A third generation of nuclear reactors was a non-indigenous technology, the PWR. At the time of the Sizewell enquiry, when the PWR was competing with the AGR, the supply chain in the UK was fully operational and able to deliver high value and complex primary reactor components for a new AGR (**Franklin 1984**). Given this situation, it was believed that the heavy losses sustained in the early AGR programme, could have been recuperated in later orders as a result of the learning curve.

Originally there were plans for a fleet of 10 PWRs, to be built from 1982 to 1992 (**Chessire 1992**). **Pearce & Jones** (**1980**) produced an estimate of the capital cost for a PWR fleet of 15GW. In 1980 prices this was at around £600/kW. It was also estimated that, for a plant that would begin construction in 1983 the capital cost became £1096/kW. This priced Sizewell B at approximately £1.64billion. However significant amounts of redesign and a length public enquiry led to only 1 station, Sizewell B, which began operating in 1995, costing around £3.2billion.

It was believed that had the CEGB proceeded with plans to license and construct a further 6 PWRs (by the year 2000), that this "would allow the retention and maintenance of manufacturing infrastructure, and the supply chain required to build nuclear power stations" (**ACOST 1988**). **Green** (**1986**) argued that by the 1980s the AGR fleet had developed such that it was an "established design", comparable with the PWR technology being considered. In addition, he argued that the design of the PWR being considered was still unique to the UK.

In order for a UK manufacturer to have the required investment criteria to build the Reactor Pressure Vessel, a minimum of 5 reactors would need to have been ordered (**ACOST 1988**). Since privatization, there has been no construction of new nuclear power stations in the UK, and only one PWR has ever been built.

PWR: THE NEXT GENERATION

Following the 2006 Energy Review, there was a renewed interest in nuclear power, with Edf Energy presenting a modern, large PWR technology, to be built at Hinkley Point C. Known as the EPR, it is a similar design to that being built at Olkiluoto (Finland) and Flamanville (France). Though groundworks have started on site at Hinkley Point, a final investment decision has not been made, with much debate about the estimated cost, as well as financing options. There are a multitude of investors, including Areva, China General Nuclear Corporation and China National Nuclear Corporation. The delay to the investment decision for Hinkley Point C has already led to an estimated completion date of beyond 2024 (**Gosden 2015**).

In the UK market the cost of electricity for new nuclear has been shown to be around £100/MWh for FOAK and £65/MWh for NOAK. **Harris *et al*** (**2013**) estimated that this could be as high as £175/MWh if the construction period was assumed to be 14 years rather than 7 (as generally used for estimating), and by assuming a 40 year operational life for the station (rather than the expected lifetime of up to 60 years for an EPR). Prior to construction the estimated overnight capital cost for Olkiluoto was £1050/kW, with Flamanville estimated at £900/kW (**Kennedy 2008)**. 4 years into the construction period the cost of Olkiluoto was then estimated at £3200/kW, whilst Flamanville was estimated at £2100/kW (**Thomas 2010**).

The **IAEA** (**1971**) report looked at a cost estimate method for a generic PWR plant built in any country around the world. Using a regression analysis of the past experience of nuclear build in the United States, the method assumed cost reductions associated with economies of scale, and technological advancement over time. The **IEA** (**2010**) compiled LCOE estimates from countries with existing nuclear programmes, and these are summarised in Figure 2. Some of the studies presented a range of estimates based on changing assumptions related to the overnight construction cost, whereas other studies presented a single-value estimate. It was also identified that a general upward trend in the LCOE over the time period is observable, particularly evident in the three UK estimates.

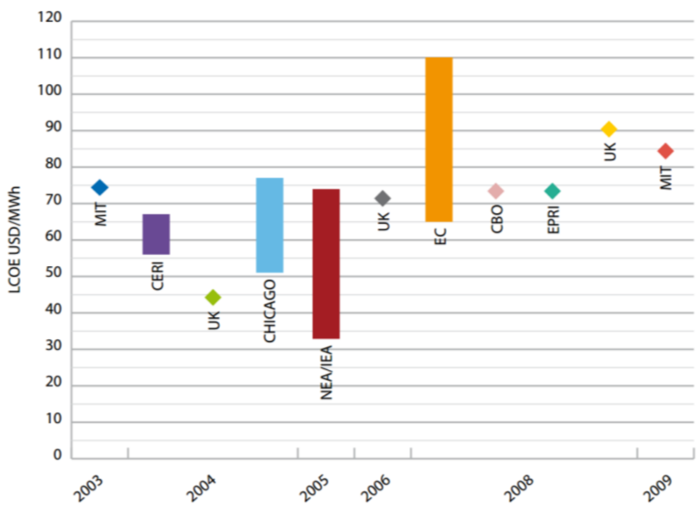

Figure 2: Levelised Cost of Electricity Estimated from Various Studies (**IEA 2010**)

"If the electricity price is equal to the levelised average lifetime costs, an investor would precisely break even on the project" (**IEA 2010**). The same method was used to compare the economics of various power generation plant (**OECD 1986**). This included a provision of 10% of the initial investment cost for decommissioning and interest accrued during construction of 5% per annum. It was found that if coal prices were lower, the advantage of lower operating costs of a nuclear power station were reduced. The follow up report (**OECD 1989**) showed that investment costs were dependent on the discount rate used, the cost of fossil fuel prices, capital cost of the power plant, and the operations and maintenance costs for the stations.

Linares & Conchado (**2013**) provide a critique on the use of the LCOE method to determine the cost of nuclear power in a liberalised market. Using a generation-expansion model they estimated a break-even overnight cost of £2100/kW. This method does not include the cost of dismantling, nor does it take into account supply chain availability.

4.1 Expected Cost Drivers

Generally there is agreement over the main components of the cost of nuclear power: capital construction; O&M; fuel; dismantling and site remediation. However, the variability of cost estimates around operational reliability, size, site preparation requirements, supply chain availability and knowledge, and the probability of construction overruns leads to a range of estimates (**Thomas 2010; Kessides 2010; Harris *et al* 2013; Lehtveer & Hedenus 2015**).

Locatelli & Mancini (**2012**) discussed using historical, similar megaprojects as a method of providing a reference based forecast. Giving the example of the nuclear build at Olkiluoto, key cost drivers included the capability of engineers and the supply chain. Although a lot more data is available regarding the cost of PWRs in general, **Kessides (2010)** identifies that reliable future cost data is based on directly related experience. Due to a lack of new nuclear build activity worldwide there is little actual experiential based cost data available.

5 CONCLUSIONS AND FUTURE WORK

Early in the civil nuclear programme it was believed that the main drivers were the cost of fuel, relative to conventional generation, and the rate at which reactor technology was likely to develop and mature. During the construction of the Magnox fleet it was thought that through increasing the size of the nuclear reactor there were economies of scale to be gained. This lead to the AGR programme, for which costs were estimated to be equivalent to conventional power stations. The drivers then became centred on capital costs and it was evident that the actual cost of UK nuclear was heavily influenced by construction delays, regulatory changes, resolution of design flaws, and commensurate modifications to the reactor design late in the build phase.

Multiple methods have been used to estimate the cost of nuclear power stations, producing a LCOE over the life of the power station. There is, however, no consensus over what the significant cost drivers may be, and how much each variable influences the LCOE. A variety of cost drivers have been identified. These could change over time with changes in technology or socio-economic policy.

In order to understand the cost of new nuclear, a significant amount of useful and relevant data is required on previous build projects. There is also an opportunity to investigate costing techniques used for major infrastructure projects in similar-scale industrial development. To develop a cost model for the build of new nuclear reactors in the UK, or one which describes the likely cost of any type of nuclear reactor, a detailed understanding is required of the major variables that will drive the cost, and on what factors may affect the impact of each variable.

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