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UNDERSTANDING COST ESCALATION IN NUCLEAR REACTOR CONSTRUCTION PROJECTS

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ABSTRACT

This work seeks to evaluate overnight construction costs (OCC) and lead time escalation of nuclear reactors from 1955 to 2016. To this end, a comprehensive database of commercial Light Water Reactors (LWR) was developed and a statistical analysis was conducted. Findings reveal that there is significant delay in lead time, especially for the last generation reactors constructed from 2010's. This results in the escalation of capital costs rather than a decline. Average OCC of newer reactors are 60% higher than the ones implemented in the earlier stages of the nuclear era. This suggests a negative learning curve effect for both OCC and lead time, which threats the market and financial sustainability of current and future nuclear energy projects. Although this is a general trend, this negative effect is country specific and, thus, induced by national policies and regulatory frameworks. Therefore, the role of nuclear technology to cope with the decarbonisation of the power sector must be better evaluated, taking into account the real cost impacts of nuclear technology implementation.

INTRODUCTION

The glorious times of nuclear power are under pressure. In the early 60's and especially after the 1973 oil embargo, the nuclear power installed capacity increased steadily. However, since the 1990's, the pace of new constructions has stagnated given low oil prices and safety concerns after the nuclear accidents in Three Mile Island (1979) and Chernobyl (1986). In the aftermath of the Fukushima Dai-ichi accident (2011), several countries have revised their nuclear policies and reinforced new regulatory requirements for new operating reactors (Aoki and Rothwell, 2013; Huenteler et al., 2012; NRA, 2013; Portugal-Pereira et al., 2014; Vivoda, 2012). This results in riskier projects of nuclear technology in terms of cost escalation (Sovacool et al., 2014a).

The hypothesis underneath this work is that, unlike other energy technologies, nuclear energy can actually lead to high overnight construction costs (OCC) and long lead times given the uncertainty associated with tighten safety procedures and increasing complexity of last generation reactors. Over time, nuclear technology has become more complex, which raised construction and operation and maintenance (O&M) costs. Also, environmental licences and public acceptance are major reasons for construction delays and, consequently, overrun costs. This suggests a negative learning curve of nuclear technology, i.e., accumulated experience results in a capital cost escalation rather than a decline.

Several studies in the literature looked at learning curves for nuclear power and attempted to evaluate the effects of main cost drivers (Grubler, 2010; IEA, 2015; Jamasb, 2007; Kahouli, 2011; Koomey and Hultman, 2007; Kouvaritakis et al., 2000). However, learning curves are influenced by a vast range of factors and it is difficult to isolate specific learning effects (Lovering et al., 2016). Berthélemy and Escobar Rangel (2015) provide an econometric analysis of nuclear reactor construction costs in France and in the United States based on overnight cost data. The study concludes that, contrary to other energy technologies, innovation leads to increasing lead costs. In same line, Sovacool et al. (2014) investigate the frequency and magnitude of cost and time overruns occurring during the construction of electricity projects built over time, and concluded that nuclear reactors are the riskiest technology in terms of mean cost escalation as a percentage of budget and frequency. Cooper (2014) also evaluates nuclear power costs over time and concludes that most recent cost projections for new nuclear reactors are, on average, over four times as high as the initial nuclear reactors.

Lovering et al. (2016) also assessed the experience curve of nuclear reactors, but conclude that there is a positive effect learning curve of nuclear technology development. Similarly, IEA and NEA reports also show that nuclear power costs have dropped over time and will decline or remain flat in future (IEA, 2015; Varro and Ha, 2015).

While relevant to the field, existing literature of nuclear power costs has mainly focused on reactors implemented in the USA and France, which account for 1/3 of the World operable reactors. Currently major construction of nuclear reactors occurs in emerging countries, mainly China, South Korea and India. Lovering et al. (2016) extended the analysis to these markets, but focus on overnight construction costs, which do not reflect contingences and escalation of lead time during construction.

The state of the existing literature highlights the need for an analysis of the historical experience and trends of nuclear costs in order to assess the effect of time escalation, increasing safety measures and regulatory procedures as main proxies of escalation of costs in the nuclear technology.

In this context, this work seeks to analyse OCC of operable light water reactors (LWR) and to assess key factors that result in a negative learning curve, including increasing complexity of technology, improved passive safety measures, tighten sectorial regulatory procedures, delay in environmental licences, and public acceptance disapproval, especially after the Fukushima Dai-ichi accident.

Starting from a comprehensive characterisation of operable LWR reactors, this study updates and extends the OCC of Grubler (2010) and Lovering et al. (2016), assessing the learning effect on capital costs and lead time through statistical analysis of pool data series.

ANALYTICAL FRAMEWORK

To assess the OCC and lead time of nuclear reactors, this work encompasses two stages, entailing: (i) design of a database of World nuclear reactor projects, and (ii) statistical analysis of the OCC and lead time of reactors over time.

Database of existing nuclear power plants and planned future projects

From the starting point of IAEA power reactor information system (PRIS) (IAEA, 2016), a comprehensive list of nuclear power reactors has been collected. This encompasses over 660 reactors, including phased-out, operable, under construction and planned nuclear reactor projects from 1955 to 2016. The database covers key technological parameters, namely the net nominal capacity (GW), the capacity factor (%) and reactor technology and model, as well as OCC ($\text{US\$}_{2010}$/kWh), lead time (years), and operation starting year.

Reactors were than aggregated by technology type, model, operational status, country, decade of operation starting, and multiple- and single unit plants. This aims to assess relevant statistical parameters that dictate the trend of OCC and lead time from the early nuclear era during the decade 1960 to present days.

Worldwide several nuclear reactor technologies have been developed, namely LWR, pressurised heavy water reactors (PHWR), gas-cooled reactors (GCR), and fast-breeder reactor (FBR). Over time, however, the nuclear sector has converged towards the LWR technology, which accounts for more than 2/3 of operable reactors around the World (IAEA, 2016). For this reason, among the overall 661, only LWR, i.e., pressurised water reactors (PWR) and boiling water reactors (BWR) units have been assessed. Furthermore, the statistical analysis excludes pilot and demonstration reactors, as "first of a kind" reactors are not necessarily representative of commercial reactors. Also, only operable reactors were assessed due to consistence of available data for OCC. This reduces the database to 232 reactors, equivalent to 35% of total World reactors.

The geographical scope of the database includes OECD countries, former Soviet countries and emerging economies. Reactors were classified by technology generation according the construction year, including Generation I, II, and II+.

Statistical analysis of overnight construction costs and lead time

In project management literature, OCC is defined as the construction costs as a project was implemented straightaway during day working hours and overnight. Therefore, this cost indicator is not sensitive to lead time delays and consequently financial costs, financial structure of projects, interest rate during construction period and public subsidies. Although these parameters are tremendously relevant to estimate the total direct costs of energy of megaprojects, such as nuclear power plants (NPP) (Lovering et al., 2016), the developed methodology does not consider financial costs. This is however subject of future research work.

Lead time, on the other hand, refers to time difference between the construction start time and the commercial operation time, when the reactor is connected to the grid after the initial test phase.

These two indicators (OCC and lead time) have been subject of a statistical analysis. For the statistical tests of the data series the software package @RISK 7.0 from Palisade (2015) has been applied to identify the probability distribution function that best fits the data.

RESULTS AND DISCUSSION

Figure 1 and Figure 2 illustrate the evolution of OCC ($\text{US\$}_{2010}$/kW) and the lead time of selected PWR and BWR units from the early nuclear era to nowadays. Both figures present a trend line for indicative purposes.

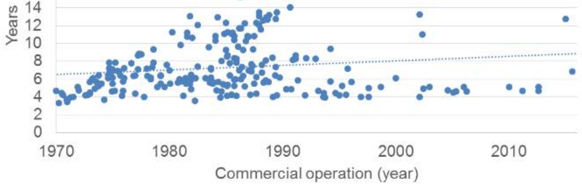

Figure 1. OCC of PWR and BWR units (US$2010) (all data series trend line in blue; minimum values trend line in red).

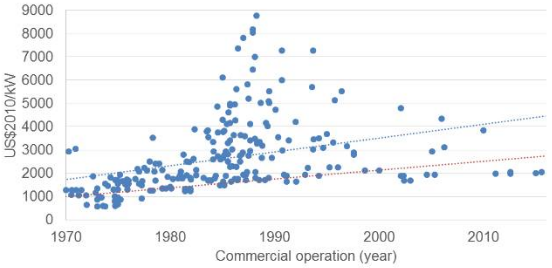

Figure 2. Lead time of PWR and BWR units (years).

Results reveal a general increasing trend of OCC and lead time from the 1970's to the 2010's. Although data are very disperse and this trend can be influenced by extreme high values, it can be observed that the minimum values tend to follow a similar trend, suggesting a negative learning curve effect. This negative effect is particularly evident for the USA for both OCC and lead time. Data for France show also this negative learning curve effect for OCC, although much less evident then for the USA, but remarkably pronounced for the lead time.

On the other hand, Japan's reactors show a fairly stable lead time, nonetheless with evidence of OCC escalation among the analysed years. Yet, it is important to highlight that the evaluated data series (until 2015) do not reflect the on-hold nuclear projects, idle reactors and retrofitting costs in the aftermath of the Fukushima Dai-ichi accident. For instance, the Hamaoka nuclear power plant, operated by Chubu Electric Power Co, was requested to implement more resistance tsunami breakwater walls at a cost of JPY 400 billion (US$ 3.7 billion) (Esteban and Portugal-Pereira, 2014; NRA, 2013; World Nuclear Association, n.d.). Furthermore, the 12 planned new nuclear reactors, totalising 4.1 GW, are unlike to be operating in the future, given the sceptical public opinion regarding nuclear safety in Japan (Portugal-Pereira et al., 2014).

The only exception of increasing trends goes to Germany with positive learning effects for both OCC and construction time. Nevertheless, a limited number of reactors restricted to the 1980's reduces significantly its influence in the overall analysis.

The USA along with Japan and Germany are the countries presenting the highest average OCC with the USA showing the highest standard deviation and the highest lead time. In fact, in the USA there is a large dispersion in the standardisation of reactor design. Therefore, the benefits on "learning by doing" are not evident. In the case of Japan, high OCC are related to institutional costs and extra safety measures requested in a highly seismic country, such as Japan.

OCC and lead time indicators seem to follow a similar distribution, giving rise to the hypothesis that these parameters may be related. The correlation coefficient between OCC and lead time for data series is 0.48, which may be considered a value on the border of "weak" to "significant" correlation (Suomalainen et al., 2015). It can be justified by the increasing complexity of the nuclear technology resulting in escalation of lead time, higher OCC, possible overruns and additional financing costs.

An interesting outcome is the positive significant correlation (0.51) between lead time and the reactor size, corroborating Berthélemy and Escobar Rangel (2015) results. The average construction time for small reactors (<900 MW) is 5.2 years, with a standard deviation of 1.4. Large reactors (>900 MW), on the other hand, present a lead time of 8.1 years, and a standard deviation of 3.3, which translates into higher uncertainty and consequently higher OCC. As for OCC, the correlation with reactor size is positive but weak (0.22), which shows that relying on the OCC for the evaluation of large reactors can be a too optimistic approach. The importance of financial costs incurred during the construction time is a relevant factor not to be neglected on a realistic planning and evaluation exercise.

Figure 3 and Figure 4 corroborate the similar shape of probability distribution function (pdf) of OCC and construction time series as both of them can be adjusted to log-normal function. Although a high concentration of values can be found around the average, the positive long right tale shows a high dispersion of the database and the probability of reaching a construction time or an OCC higher than the corresponding average is more than 35%. This distribution shape represents energy projects with highly risk parameters, such as nuclear reactors.

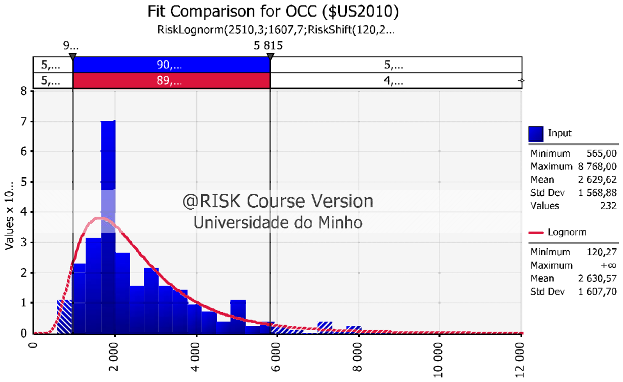

Figure 3. Pdf for OCC of PWR and BWR nuclear reactors ($USD 2010).

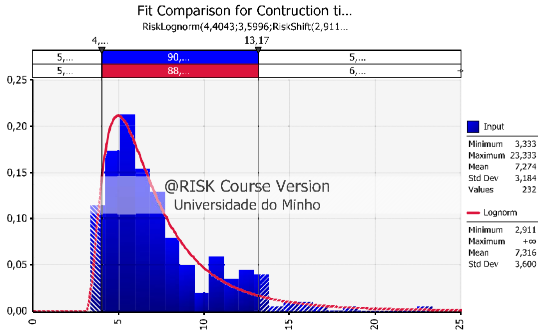

Figure 4. Pdf for construction time of PWR and BWR nuclear reactors ($USD 2010).

CONCLUDING REMARKS

The accumulated experience of the nuclear reactor technology does not translate necessarily a positive learning curve. Over time, there is a trend of more complex reactors with safer passive systems, tighten regulatory procedures, which suggest higher OCC and longer lead time. This work sought to evaluate the effects of these parameters in the OCC and lead time of nuclear reactors from 1955 to 2016. To this end, a comprehensive database of commercial LWR reactors was developed and a statistical analysis was conducted using the @Risk project risk management software.

Results showed that there are significant delays in lead time, which increases over time, especially for the last generation reactors constructed from 2010's. This leads to escalation of OCC rather than a decline. Average OCC of newer reactors are considerably costlier than the ones implemented in the earlier stages of the nuclear era. This finding suggests that the nuclear technology is significantly costlier than other low-carbon alternatives and takes too long to be implemented. This threats the market and financial sustainability of future and current nuclear energy projects. Therefore, nuclear technology is not at the forefront to cope with climate change mitigation strategies to contribute to decarbonizing the power sector.

Although the outcomes of this study are intended to bring the relevance to policy makers and the nuclear sector in the energy debate, this study presents preliminary results of ongoing research. Future work intends to expand the developed methodology beyond operable reactors in order to include phased-out, under construction and planned nuclear reactors. Furthermore, future analysis will include evaluation of financial costs, as a strategy to evaluate meaningful direct construction costs of nuclear reactors.

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