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Historical construction costs of global nuclear power reactors

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HIGHLIGHTS

- Comprehensive analysis of nuclear power construction cost experience.
- Coverage for early and recent reactors in seven countries.
- International comparisons and re-evaluation of learning.
- Cost trends vary by country and era; some experience cost stability or decline.

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ABSTRACT

The existing literature on the construction costs of nuclear power reactors has focused almost exclusively on trends in construction costs in only two countries, the United States and France, and during two decades, the 1970s and 1980s. These analyses, Koomey and Hultman (2007); Grubler (2010), and Escobar-Rangel and Lévêque (2015), study only 26% of reactors built globally between 1960 and 2010, providing an incomplete picture of the economic evolution of nuclear power construction. This study curates historical reactor-specific overnight construction cost (OCC) data that broaden the scope of study substantially, covering the full cost history for 349 reactors in the US, France, Canada, West Germany, Japan, India, and South Korea, encompassing 58% of all reactors built globally. We find that trends in costs have varied significantly in magnitude and in structure by era, country, and experience. In contrast to the rapid cost escalation that characterized nuclear construction in the United States, we find evidence of much milder cost escalation in many countries, including absolute cost declines in some countries and specific eras. Our new findings suggest that there is no inherent cost escalation trend associated with nuclear technology.

1. Introduction

Studies by the Intergovernmental Panel on Climate Change and the International Energy Agency have identified nuclear power as a key technology in reducing carbon emissions (IPCC, 2014; IEA, 2014). Today, nuclear energy makes up one-third of global low-carbon electricity, and countries with the lowest carbon intensities depend heavily on low-carbon sources of baseload power: nuclear and hydroelectric. Yet the high cost of nuclear power in developed countries has slowed its deployment, as low-carbon nuclear power cannot compete with cheaper fossil fuels, especially in deregulated power markets. Additionally, cost estimates for future nuclear energy are among the most important inputs to energy system models and climate mitigation scenarios (Leibowicz et al., 2013; Bosetti et al., 2015; Barron and McJeon, 2015).

Several analyses of historical nuclear cost trends have pointed to escalating costs for nuclear power plants over time, raising doubts about whether nuclear can become cost competitive (Bupp and Derian, 1978; Hultman et al., 2007; Cooper, 2014). However, past studies have been limited in their scope, focusing primarily on cost trends in the 1970s and 1980s for the US (Komanoff, 1981; Koomey and Hultman, 2007) and France (Grubler, 2010; Escobar-Rangel and Lévêque, 2015). These studies represent 26% of the total number of nuclear power reactors completed in the world and only look at two of the 31 countries that generate electricity from nuclear power today.

The US and France may not be representative of broad cost trends, as they suffered first-mover disadvantages of deploying an evolving technology (Jamasb, 2007). More importantly, the US and France built most of their reactors over 30 years ago. The last

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reactor to come online in the US began construction in 1978. The limited scope of the existing literature on nuclear costs is further limited by the industry wide disruption caused by the Three Mile Island accident in 1979. Of the 100 US reactors included in previous studies, half were under construction and had not yet received operating licenses when the accident occurred. Given the event's potential effect on construction costs, there is a need to study the cost experience of a wider sample of countries and eras in nuclear power history.

In addition to the US and France, the UK, Germany, Japan, Canada, and the USSR were all building nuclear reactors during this time period. When the US and Western European countries stopped building nuclear power in the 1990s, several other countries continued to build out their nuclear fleets in East and South Asia and Eastern Europe. In particular, large fleets of standardized reactors were built in Japan, South Korea, India, and more recently in China. While a handful of studies note the low cost of reactors in these regions today (Du and Parsons, 2009; IEA, 2010), there is little analysis of historic cost *trends* in these countries.

This study extends and reassesses the literature by collecting and analyzing cost data from a broader set of countries and time periods. We focus our analysis on the real Overnight Construction Cost (OCC) of completed plants because it is both the dominant component of lifetime costs for nuclear power, and the cost component that varies most over time and between countries. The metric OCC includes the costs of the direct engineering, procurement, and construction (EPC) services that the vendors and the architect-engineer team are contracted to provide, as well as the indirect owner's costs, which include land, site preparation, project management, training, contingencies, and commissioning costs. The OCC excludes financing charges known as Interest During Construction. Further details on OCC can be found in Section 3.2.

We expand the scope of analyses to include the costs of 32 US and eight French reactors built prior to 1970. Beyond the US and France, we collect complete cost histories for Japan, South Korea, West Germany, Canada, and India (153 reactors in total). To summarize, our study provides costs for a full set of reactors in seven countries, covering builds from 1954 through projects that had been completed by the end of 2015, covering costs for 58% of all power reactors ever built globally.

2. Literature review

Experience curves, progress ratios, and learning rates are all methods of analysis that were originally used to compare innovation and advancement across aircraft manufacturing firms (Wright, 1936), and have since been employed to analyze development of a broad range of technologies including power plants (Zimmerman, 1982; Joskow and Rose, 1985). Since nuclear power plants are complex infrastructure projects – not a product that rolls off an assembly line – a range of factors go into the final cost. To isolate learning effects for a specific reactor developer, many studies have used regression models to isolate for a theoretical learning-by-doing based on a manufacturer or architect-engineer firm's progress.

Cantor and Hewlett (1988) summarized four such regression studies that attempt to isolate the effects of learning, economies of scale, and regulatory changes on Overnight Capital Costs of US reactors. They found that individual firms experience learning, but that the increased size of plants and increased regulation led to longer lead times and higher overnight costs, thus offsetting any learning-by-doing effect.

Kouvaritakis et al. (2000); Jamasb (2007), and Kahouli (2011) also derived learning rates for nuclear construction costs for the OECD and EU. They found that learning-by-searching, ie, improvement through R&D, can have an important effect. Berthélemy and Escobar-Rangel (2015) performed a regression analysis to isolate hypothetical cost drivers, including learning effects, using a combined data set of French and US reactors. They find that standardization of reactor designs is key for decreasing lead times and costs, and that innovation can actually lead to higher capital costs and longer lead times.

While these studies calculate theoretical learning rates for specific developers and construction firms, it is difficult to truly isolate learning effects when so many other factors were changing at the same time as firms potentially gained experience. Jamasb (2007) demonstrated how incorporating multiple factors – such as technological improvements due to research and development – changed the learning-by-doing rate significantly. Clarke et al. (2006); Söderholm and Sundqvist (2007), and Pan and Köhler (2007) warned against using learning curves beyond the scope of a manufacturing firm, since there are many drivers of cost reductions that are unrelated to replications or experience. These drivers include market demand, supply chain, labor relations, research and development, and regulation.

Given these conflation issues – and in the absence of any causal framework – a simpler method is to look at historical cost trends for reactors built within a specific country over time or by cumulative deployed capacity; this metric is often referred to as an experience curve. Such analysis can be likened to industry-wide or country-wide learning and can shed light on the combined effect of developer experience, learning-by-doing, and the accumulation of other time-related cost drivers. Analyzing the historical experience in this way has been a common approach to help understand the prospects and challenges of nuclear power. Past studies (Thomas, 1988; MacKerron, 1992; Koomey and Hultman, 2007; Escobar-Rangel and Lévêque, 2015) have documented dramatic cost escalation and have identified the presence of "negative learning-by-doing," suggesting an "intrinsic" or inevitable increase in costs (Grubler, 2010). These results have played a role in informing integrated assessment modellers and policy makers (Neij, 2008; Junginger et al., 2008; Harris et al., 2013; Azevedo et al., 2013).

The phenomenon of cost escalation has been interpreted as a lack of learning in the traditional sense of firm-level production, but the studies have deployed a broader use of the term to describe a theoretical country-level, industry-wide learning. Experience curves may not be able to isolate firm-level learning, but they can be useful in highlighting differences between the experiences across countries or during different phases of reactor development within a single country. Importantly, experience curves do not provide a causal explanation of cost drivers for nuclear power (or other energy technologies), but can help quantify historic trends and lead to future case studies or econometric studies.

Despite these constraints, the single-factor learning curve methodology has been commonly and broadly applied in studies of nuclear cost trends, due to the availability of data and its ease of use (Jamasb, 2007). Of particular note, Grubler (2010) analyzed the historical costs of nuclear power for France and the US, and concluded that nuclear power construction costs "invariably exhibited negative learning" and "forgetting by doing," citing an increase in system complexity for nuclear power construction, which was hypothesized by Lovins (1986), Bupp and Derian (1978), and Komanoff (1981). Additionally, Grubler (2010), using Fig. 1, observed a "rhythm of cost escalation" for both the US and France, describing 20 GW and 50 GW as "threshold levels" at which cost escalation "accelerated" and "skyrocketed."

Regardless of the methods used to analyze cost trends, the existing literature mainly ignores cost data in several dominant and emerging nuclear countries. The data analyzed for 99 US