Energy Policy 82 (2015) 118–130

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

Nuclear reactors' construction costs: The role of lead-time, standardization and technological progress

Michel Berthélemy [a,b,*], Lina Escobar Rangel [b]

[a] Institut de technico-économie des systemes énergétiques (I-tésé), Commissariat a l'Energie Atomique, Université Paris Saclay, 91191 Gif-sur-Yvette Cedex, France

[b] Centre d'Economie Industrielle, École des Mines de Paris, PSL Research University, 75006 Paris, France

HIGHLIGHTS

- This paper analyses the determinants of nuclear reactors construction costs and lead-time.
- We study short term (coordination gains) and long term (learning by doing) benefits of standardization in France and the US.
- Results show that standardization of nuclear programs is a key factor for reducing construction costs.
- We also suggest that technological progress has contributed to construction costs escalation.

ARTICLE INFO

Article history:
Received 15 November 2014
Received in revised form
10 March 2015
Accepted 15 March 2015

Keywords:
Nuclear construction cost
Nuclear new build
Learning by doing
Standardization

ABSTRACT

This paper provides an econometric analysis of nuclear reactor construction costs in France and the United States based on overnight costs data. We build a simultaneous system of equations for overnight costs and construction time (lead-time) to control for endogeneity, using change in expected electricity demand as instrument. We argue that the construction of nuclear reactors can benefit from standardization gains through two channels. First, short term coordination benefits can arise when the diversity of nuclear reactors' designs under construction is low. Second, long term benefits can occur due to learning spillovers from past constructions of similar reactors. We find that construction costs benefit directly from learning spillovers but that these spillovers are only significant for nuclear models built by the same Architect–Engineer. In addition, we show that the standardization of nuclear reactors under construction has an indirect and positive effect on construction costs through a reduction in lead-time, the latter being one of the main drivers of construction costs. Conversely, we also explore the possibility of learning by searching and find that, contrary to other energy technologies, innovation leads to construction costs increases.

1. Introduction

1.1. Toward a nuclear renaissance?

By January 2015, the World Nuclear Association (WNA, 2015) lists 69 reactors *under construction* in 15 countries. This level of new builds represents a record for the nuclear industry since 1987. However, it remains limited compared to the *nuclear renaissance* forecasts that have been envisioned since the late 1990s. This is despite the fact that many factors that should support a nuclear expansion are still valid today: increasing energy demands in emerging countries, the need to reduce fossil fuel dependence, and the increased awareness of the dangers resulting from climate change. In spite of this positive environment, it is yet to be seen if a rapid expansion of nuclear power is possible and – more importantly – economically viable.

If we take a closer look to the list of nuclear reactors *under construction*, there are reasons to question the view that ongoing projects could spur a rapid expansion of nuclear power – or will even be completed. As pointed out in the *World Nuclear Industry Status Report* (Schneider and Froggatt, 2014), 8 of these reactors have been under construction for more than 20 years, 1 for 12 years and 49 have already face significant construction delays.

This situation is not new for the industry as the construction of nuclear reactors has been characterized by lengthy lead-times (due to construction delays), in particular in western countries. For instance, Schneider and Froggatt (2014) notice that the average construction time of the last 37 reactors that started since 2004 is 10 years. This is twice what is usually announced by nuclear

* Corresponding author.
E-mail addresses: michel.berthelemy@cea.fr (M. Berthélemy), lina.escobar_rangel@mines-paristech.fr (L. Escobar Rangel).

http://dx.doi.org/10.1016/j.enpol.2015.03.015

vendors and significantly longer than the 3 and 6 years period to build a combined cycle gas plant and a coal plant, respectively.

In addition to concerns about construction delays, a key challenge for nuclear new-build remains the economic viability of building these reactors. In particular, according to IEA (2010), upfront construction costs account between 60% and 80% of nuclear power levelized costs. This means that any unexpected increase of those costs can significantly undermine nuclear reactors profitability and can lead to abandon ongoing construction projects.

In particular, concerns regarding the competitiveness of new 'Gen III' nuclear technologies have emerged in the United States (US) over the last decade due to an increase in construction costs expectations. For instance, cost expectations per kilowatt and in 2014 USD increased between 2003 and 2009 from USD2631 (Base case in Parsons and Du, 2003) to USD4567 (Parsons and Du, 2009; Rosner and Goldberg, 2011).

The ongoing constructions of first of a kind European Pressurized Reactor (EPR) reactors in Europe have further contributed to revising expected costs of nuclear new build in OECD economies. Despite Finland and France past successes in building nuclear reactors, projects in both countries face significant cost overruns. In France, the construction of Flamanville 3 unit is almost 3 times more expensive than initially planned (EUR3 billion in 2009 versus EUR8.5 billion in 2012). The reactor should also not be operational before 2016, which represents nearly a doubling in lead-time from 5 to 9 year (World Nuclear News, 2012).

Past cost over-runs, multiple upward cost revisions and ongoing delays represent important barriers to nuclear new-build and limit countries where reactors can be installed. Consequently, more than 60% of new build projects are located in countries where governments play a central role as investor in the power sector.[1] This is the case in China, where the three national nuclear utilities are largely or entirely state-owned. Similarly, in Russia and South Korea, nuclear reactors under construction are designed and owned by the state-owned Rosenergoatom Corporation and Korea Electric Power Corporation (KEPCO), respectively.

For countries considering nuclear new-build, many have postponed their programs due to financing difficulties (e.g. Poland, United Kingdom (UK)). In addition, even in countries with lower financial constraints, upfront investment costs have been a key driver to select reactor design. For instance, according to Schneider and Froggatt (2014) the United Arab Emirates (UAE) chose a less technologically advanced Korean design over France's EPR due to lower construction costs and shorter construction lead-times.

In that respect, one can argue that any future expansion of nuclear power in both mature and new entrant countries will to a large extent depend upon the ability to identify potential factors that could reduce both construction costs and lead-times.

1.2. Existing literature on nuclear power plants construction costs and lead-times

The existing economic literature provides mixed evidence about the determinants of nuclear construction costs and lead-times, partly due to a lack of comparable and reliable data. Most of the econometric studies focus on US reactors and tend to attribute construction costs escalation to a lack of standardization, an increase in complexity of new reactors, and safety related regulatory interventions following the Three Mile Island (TMI) nuclear accident.

A number of authors argue that experience gained by US nuclear vendors led to the design of bigger and more complex reactors that took longer to build and required closer regulatory oversight (Komanoff, 1981; Zimmerman, 1982; Rothwell, 1986; Cantor and Hewlett, 1988; Cooper, 2012). It is also argued that the heterogeneity of the US nuclear fleet and the multiplicity of vendors contributed to the absence of learning by doing gains. David and Rothwell (1996) argue that the lack of standardization in the US nuclear fleet entailed a *ballooning* of construction costs, whereas positive learning effects are found by Cantor and Hewlett (1988) and McCabe (1996) for projects managed directly by utilities.

In the case of the French nuclear program, data on construction costs were only published in 2012 (Cour des Comptes, 2012). Previous cost data in Grubler (2010) are based on extrapolations of annual investment expenditures of the utility EDF, and rejected the existence of learning by doing. Conversely, using the actual construction costs Escobar-Rangel and Leveque (2012) find evidence of cost reductions due to learning effects within specific reactor models.

1.3. The contributions of this paper to the economic literature and the nuclear energy policy debate

In this paper, we investigate the role of lead-times, standardization and learning opportunities on nuclear reactors' construction costs, using historical cost data from US and France. This choice is motivated by the fact that the two countries have followed different paths in terms of industrial structure and technological diversity. For instance, while in the US a number of firms have acted as Architect–Engineer (A–E) and/or vendors of nuclear reactors, these roles have been the responsibility of the utility EDF and Areva (formerly Framatome) in France, respectively. Similarly, while both countries have built Pressurized Water Reactors (PWR), France has implemented fewer technological variations compared to the US.

Hence, by looking at French and US experiences together one can benefit from sufficient heterogeneity in the data in order to test robust research hypotheses on the role of industrial structure and disentangle it from other factors. In particular, unlike other papers, we distinguish between short and long term potential benefits of standardization and explore the possible effects of learning by searching (i.e. innovation) on construction costs, given the importance of public R&D expenditures on nuclear power.

The rest of the paper is organized as follows: Section 2 presents the model, main hypotheses regarding learning effects and the data. Section 3 presents and discusses our results on construction costs and lead-times in France and the US and also provides some robustness tests for lead-times using a larger dataset. Section 4 concludes by discussing the relevance of our findings for current and future nuclear new-build policies.

2. Methods: econometric framework, main hypotheses and data

2.1. Econometric framework for construction costs and lead-times in nuclear power

Many firms are usually involved in the construction of a nuclear power plant. First, an electricity generation firm (hereafter the utility) places an order for the construction of a nuclear reactor and selects a specific design offered by a nuclear vendor. Once the design is chosen, the construction is managed by an Architect–Engineer (A–E) firm who is in charge of engineering, procurement and construction. This involves supervising and coordinating the constructor, the nuclear steam supply system manufacturer, the turbine manufacturer, as well as a number of subcontractors. The allocation of firms' responsibilities may differ between projects and, for instance, it is possible that the utility decides to act as A–E (as it is the case in France and sometimes in the US).

Rothwell (1986) develops a structural model to represent the involvement of multiple firms in the construction of a nuclear

[1] Authors calculations based on IAEA PRIS database.