# The economics of nuclear power : four essays on the role of innovation and industrial organization

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## To cite this version:

Michel Berthélemy. The economics of nuclear power : four essays on the role of innovation and industrial organization. Economics and Finance. Ecole Nationale Supérieure des Mines de Paris, 2013. English. NNT : 2013ENMP0022 . pastel-00875147

HAL Id: pastel-00875147
https://pastel.hal.science/pastel-00875147

Submitted on 21 Oct 2013

ParisTech
INSTITUT DES SCIENCES ET TECHNOLOGIES
PARIS INSTITUTE OF TECHNOLOGY

MINES
ParisTech

École doctorale n° 396 : Economie, Organisation, Société

## Doctorat ParisTech

# THÈSE

**pour obtenir le grade de docteur délivré par**

## l'École nationale supérieure des mines de Paris

**Spécialité " Economie et Finance "**

*présentée et soutenue publiquement par*

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le 20 septembre 2013

# The Economics of Nuclear Power: Four Essays on the Role of Innovation and Industrial Organization

# L'Economie de l'Energie Nucléaire: Quatre Essais sur le Rôle de l'Innovation et de l'Organisation Industrielle

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# Acknowledgements

I would like to start by thanking my supervisor François Lévêque who has guided my work during these last three years and has made this PhD thesis possible. I have benefited at Mines ParisTech from a privileged research environment and I would like to thank Antoine Dechezleprêtre, Matthieu Glachant, Yann Ménière and Magnus Söderberg for many comments and advice on my work.

I would like to thank my fellow PhD students at Cerna for comments during doctoral seminars and making work fun, and in particular Justus Baron, Charlène Cosandier, Arnaud de la Tour, Henry Delcamp, Damien Dussaux, Lina Escobar Rangel, Marine Lefort, Gabrielle Moineville and Paula Restrepo. I also wish to thank Sesaria Ferreira for administrative support, especially when something went wrong.

My research has further benefited from a three-month stay at the University of Cambridge Electricity Policy Research Group (EPRG), and I would like to thank them for welcoming me during my stay. In particular, I wish to thank Pierre Noël, Michael Pollitt and David Newbery for their advice and comments on my work and Andrew Pruitt for administrative support.

I also wish to thank my family and my friends for their support.

Finally, thank you Kate for enduring me during these last three years and for pro**o**f-reading (twice) this entire PhD thesis.

# Preface

This PhD thesis was funded through a scholarship from Mines ParisTech and is part of a research program at Mines ParisTech on the economics of nuclear power led by François Lévêque and financially supported by EDF. The opinions expressed in this thesis do not necessarily reflect those of EDF. This thesis contains four empirical papers which have been presented at a number of conferences and seminars.

The first Chapter, *What drives innovation in nuclear reactor technologies? An empirical study based on patent counts*, has been presented at the 5th Atlantic Workshop on Environmental and Energy Economics, Toxa, Spain (25-27 June 2012) and the 4th IAEE French Workshop, Paris, France (6 July 2012). It is currently under revise and resubmit with *Energy Economics*.

The second Chapter, *Innovation, Learning by Doing Opportunities and Nuclear Reactors Performance*, has been presented at the 12th IAEE European Energy Conference, Venice, Italy (9-12 September 2012), the 4th IAEE Swiss Workshop, ETH Zurich, Switzerland (12 October 2012), the 11th Doctoral Conference, University of Cambridge, Judge Business School, UK (3 December 2012) and the French Economic Association (AFSE) Annual Conference, Aix-en-Provence (24-26 June 2013).

The third Chapter, *Measuring the effect of persistent treatments: Evidence from restructuring the US nuclear power sector*, is co-authored with Magnus Söderberg (Assistant Professor of Economics at Mines ParisTech) and has been presented at the EPRG seminar, Electricity Policy Research Group, University of Cambridge, UK (11 March 2013) and the Cerna Seminar, Mines ParisTech (24 April 2013). This Chapter is an earlier draft version of the paper and the latest version with Damien Dussaux (PhD candidate at Mines ParisTech) includes a more general section demonstrating our empirical strategy using Monte Carlo simulations. This section is not included in the thesis as I have had limited input in it.

The fourth Chapter, *Nuclear reactors construction costs: The role of lead-time, standardization and technological progress*, is co-authored with Lina Escobar Rangel (PhD candidate at Mines ParisTech) and has been presented at the 5th IAEE French Workshop, Paris, France (5 July 2013).

Further, in addition to these four papers, I have co-authored three others papers dealing with the regulation of nuclear safety and the international market for nuclear power plants. These papers are not included in this PhD thesis because of their more policy oriented nature. These papers are available upon request:

- Berthélemy, M. and Lévêque, F. (2011), "Korea nuclear exports: Why did the Koreans win the UAE tender? Will Korea achieve its goal of exporting 80 nuclear reactors by 2030?, *Report for EDF*.

- Berthélemy, M. and Lévêque, F. (2011), Harmonising nuclear safety regulation in the EU: which priority?, *Intereconomics - Review of European Economic Policy*, Vol. 46 (3) pp. 132-137.

- Berthélemy, M., Iezhova, V. and Lévêque, F. (2012), The expansion of the russian nuclear power industry abroad, *Report for EDF*

# Table of Contents

# List of Figures

## Chapter 1

## Chapter 2

## Chapter 3

## Chapter 4

# List of Tables

## Chapter 1

## Chapter 2

## Chapter 3

## Chapter 4

## Appendixes

# Introduction

## 1. Context

The nuclear power industry has experienced profound structural changes since its early days in the 1950s where it was initially considered to be *"too cheap to meter"* (Lewis Strauss, Chairman of the US Atomic Energy Commission, 1954). Today, repeated cost over-runs for nuclear reactor construction projects in mature OECD countries have raised concerns about the economic competitiveness of this technology. Between the 1950s and today, three major nuclear accidents (Three Mile Island (TMI) in 1979, Chernobyl in 1986 and Fukushima in 2011) and concerns about the legacy of nuclear waste have led to significant changes in public opinion, and nuclear accident externalities have taken a central place in the policy debate.

In spite of these factors, the idea of a nuclear renaissance has been regularly evoked in the press since the early 1990s (Nuttall, 2005). Today, nuclear power still represents 18% of OECD countries' electricity production[1] mix and 69 nuclear reactors – accounting for 63 GWe of potential installed generation capacity – are under construction worldwide[2]. These nuclear new-build projects essentially take place in emerging countries such as China and India, but constructions, albeit in a smaller number, are also under way in mature nuclear countries such as the US or France. This represents a significant shift in the global market for nuclear reactors towards emerging countries with lower level of expertise in nuclear power. For instance, the International Energy Agency (IEA, 2012) estimates that about 300 GWe of new nuclear generation capacity could be installed between 2012 and 2035, with more than 70% located in non-OECD countries. This would represent a 53% growth rate of worldwide nuclear generation capacities, compared to 370.5 GWe of installed capacities today and taking into account expected capacity retirements (114 GWe).

However, while nuclear renaissance has never taken place at the scale that was suggested, several countries are still considering the nuclear option. For instance, as of July 2013, 99

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[1] IEA Monthly Energy Statics, available at: http://www.iea.org/stats/surveys/elec_archives.asp.
[2] IAEA PRIS database, Restricted access available at: http://prisweb.iaea.org/PRISStatistics.

nuclear reactor new-builds are planned worldwide[3]. This reflects the fact that in parallel to the negative externalities associated with nuclear accidents, nuclear power also represents important positive externalities, at least from the perspective of policy makers. In particular, it does not emit $CO_2$ and it does not lead to security of supply constraints due to the even distribution of uranium resources on Earth. Finally, it produces large scale and base-load power generation in a world where primary energy demand is expected to grow by 35% between 2010 and 2035 (IAE, 2012).

This conflict between potentially large positive and negative externalities means that the policy debate on nuclear power is, to say the least, passionate. The aim of this PhD is not to take position on this debate or to follow a normative approach. Rather, we aim to adopt a positive approach based on empirical evidence and econometrics.

In particular, as the outlook for nuclear new-build is characterised by the emergence of countries often with limited or no expertise in nuclear power technologies (Carlisle et al., 2008), it is critical to understand if and how national innovation may impact the economic competitiveness and safety of nuclear power. In parallel, the policy debate on nuclear suffers from a lack of empirical evidence in the economic literature and more work is also needed on the impact of industrial structures – such as different levels of vertical integration of firms, the level of concentration in the industry, or the location of multiple reactors on the same site – on economic and safety performance. For instance, nuclear power might be the only energy technology where the existence of learning by doing for construction costs is still debated between authors (Grubler, 2010; Escobar Rangel and Lévêque, 2012).

This focus on innovation and industrial structures is further motivated by the history of the nuclear industry which is characterised by the diversity of national strategies for its development, both in terms of technological paths and industrial structure. These two elements form the cornerstone of nuclear programs and are particularly important due to the increasing returns for the adoption of a technology (Cowan, 1990) and the long time horizon of nuclear projects which can take up to a century between the initial planning process, the construction of a reactor, its operating lifetime, and finally its decommissioning. These long time horizons and increasing returns mean that sub-optimal decisions regarding technology and industrial structure can lead to technological lock-in and strong inertia of industrial structures respectively, with significant impacts on the economic and safety performance of this technology.

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[3] IAEA PRIS database.

For example, Cowan argues that this might have been the case for the adoption of Light Water Reactors (LWRs) in many OECD countries, whereas other potentially superior technologies, such as Graphite Gas Reactors (GGRs), could not penetrate the market for nuclear reactors due to this lock-in effect. Similarly, inertia in industrial structures can also be observed from the lack of entry into and exit from this sector, or the existence of long term contracts for nuclear fuel. Hence, this PhD thesis analyses how national strategies in terms of technological paths and industrial structure settings impact the economic competitiveness and the safety performance of nuclear reactors in order to better understand the conditions of success for future nuclear projects.

# 2. Innovation, technological paths and nuclear power

Compared to other energy technologies, the economic literature has provided limited evidence on the role of innovation in nuclear power technologies. This can be explained by the fact that nuclear technologies were initially secret/confidential (Lowen, 1987), leading to difficulties in quantifying and observing innovation in nuclear technologies. This means that few empirical analyses exist on the impacts of innovation in nuclear power (Corderi and Lin, 2011)[4] or the determinants of innovation effort in this field, and the existing literature focuses on descriptive evidence concerning specific innovation programs from an engineering and technology policy perspective (OECD/NEA, 2007).

To understand the role of innovation in nuclear power and the diversity of technological paths, one needs to take into account the fact that nuclear power is a technology which emerged from military programs and, in particular, nuclear submarines (Cowan, 1990). This led to significant government control and support for the development of nuclear technologies.

For instance, according to the International Energy Agency[5], public R&D expenditures for nuclear fission still represents 26% of OECD countries' public R&D spending for energy technology (with 4.52 $\text{USD}_{2012}$ billion), down from 38.6% in 2000 (with 4.2 $\text{USD}_{2012}$ billion) and 43% in 1990 (with 5.47 $\text{USD}_{2012}$ billion). Nuclear technology is also characterised by

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[4] Cordeli and Lin (2011) look at the return to R&D for nuclear fuel. However, this study takes place at a macro level and examines nuclear fuel technology jointly with coal and petrol technologies.

[5] Available at: http://data.iea.org

significant government control, with a few countries leading the market for nuclear reactors. This concentration of innovation activity in a few countries (i.e. France, Germany, Japan, Russia and the US) can partly be explained by the sensitivity of certain nuclear technologies, such as enrichment technologies, owing to concerns regarding proliferation of radioactive materials (DeLeon, 1979).

Consequently, there remain large heterogeneities in the level of national knowledge capabilities, and a number of civil nuclear programs have benefited from international technology transfers. This was notably the case for France which decided to adopt the US Pressurised Water Reactor (PWR) in the 1970s through a technology transfer agreement with the US firm Westinghouse. This also applies to many European countries such as Belgium, Germany and Sweden (with the notable exception of the UK), as well as Asian countries such as Japan, South Korea and more recently China.

However, the French example also highlights the fact that following international technology transfers many countries have tried to develop their own technology and most of the aforementioned countries have followed this path to varying degrees. This raises the question of the economic and safety benefits that one may expect from developing national knowledge capabilities, as well as the extent to which international technology transfer can substitute national innovation effort. This question is particularly policy relevant as many countries currently considering the construction of nuclear reactors (e.g. Vietnam, Turkey, or the United Arab Emirates) have little or no experience in nuclear technologies.

The close ties that nuclear has with government-led incentives (e.g. public R&D expenditures) also raises the question of the determinants of innovation effort, as one might wonder if the development of nuclear technologies is only the outcome of government support. For instance, beyond the traditional drivers of innovation such as technology-push and demand-pull, one may further argue that innovation in nuclear reactors has been influenced by safety regulation. This is important as it implies that safety regulation may also contribute to technological progress, in accordance with the Porter (1995) hypothesis regarding environmental technologies.

# 3. Industrial structure and nuclear power

The industrial structure of the nuclear sector also differs between countries. In particular, there exist large variations in terms of ownership, vertical integration, market regulation, the number of firms in national industry, or the experience of these firms in the construction and operation of nuclear reactors.

Compared to innovation and technological change, the industrial structure of the nuclear sector is easier to observe for economists and most of the existing literature on the economics of nuclear power has focused on classical questions in industrial organisation, such as the impact of ownership on operating and maintenance costs (Pollitt, 1996), managerial structure within nuclear power plants and outages (Rothwell, 1996), the existence of economies of scale for the construction costs of larger reactors (Krautmann and Solow, 1988), or the impact of learning by doing opportunities and standardization of nuclear reactors on operating performance (Joskow and Rozanlski, 1979; Lester and McCabe, 1993; David and Rothwell, 1996) and construction costs (Rothwell, 1986; Zimmerman, 1982). In addition, the impact of changes in nuclear safety regulation, following the TMI nuclear accident, on profitability (Rust and Rothwell, 1995) and safety (David et al., 1996) has also been studied.

The recent literature has focused on the liberalization of electricity markets in the US, with the creation of wholesale markets and the divestiture of generation and supply activities, and their impacts on economic performance (measured in terms of availability factor) of nuclear reactors (Zhang, 2007; Davis and Wolfram, 2012), as well as safety (Hausman, 2012).

The French and the American nuclear industries have often been used to highlight this diversity of industrial structures (Lester and McCabe, 1993). On the one hand, the French have a highly concentrated and vertically integrated industry with one state owned utility, *Electricité de France* (EDF), operating nuclear reactors and acting as Architect-Engineer (A-E) for the construction of those reactors, and one firm, Areva (formerly Framatome) in charge of nuclear reactor design as well as the front and back-end of the nuclear fuel cycle. On the other hand, the US has experienced the opposite situation with multiple vendors and operators, at least for the construction and operating stage.

While the existence of multiple firms might have first been thought to foster competition, this has led to a lack of standardization and learning by doing opportunities and it is generally considered to be one of the factors leading to cost over-runs in the US (McCabe, 1996). Similarly, early comparisons between France and the US for the operating performance of reactors (Lester and McCabe, 1993) have supported the hypothesis that coordination gains can also be expected once reactors have been built, in particular at the site level through learning by doing spillovers when multiple reactors are built on the same site.

However, this empirical evidence remains scarce and often controversial. As aforementioned, Grubler (2010) claims negative learning by doing for construction costs in France, whereas Escobar Rangel and Lévêque (2012) find the opposite. Similarly, there is no recent evidence on the effect of aging nuclear reactors on operating performance. This lack of clear empirical analysis blurs the policy debate on the competitiveness and safety of nuclear power and calls for more empirical investigations.

In addition, the industrial structure of the nuclear sector is influenced by ownership and economic regulation. In particular, the nuclear sector – along with other electricity generation technologies – has been profoundly impacted by electricity market liberalization and privatization over the past three decades. Despite significant transition costs, the privatization of the UK electricity utility is considered to have improved the operating performance, measured in terms of load factor, of British nuclear reactors (Newbery and Pollitt, 1997). Furthermore, the introduction of wholesale electricity markets, and the divestiture of generation and distribution activities, have been considered in the US to improve the operating performance of existing reactors (Davis and Wolfram, 2012).

These changes in market regulation mean that, if the US nuclear reactors were underperforming compared to international standards in the late 1970s and 1980s, this trend has since been reversed and the liberalized US nuclear sector now achieves high performance standards in terms of availability. In fact, these recent changes in the performance of the US nuclear power sector highlight that electricity market deregulation might have been a way for the US to escape from the technological lock-in previously mentioned, considering that the US nuclear reactors operating performance has now caught up and outweighs other nuclear reactors technologies in the world.

# 4. Methodological approach and structure of the PhD

As previously mentioned, this PhD thesis follows a positive approach which aims at better understanding the role of technological paths and industrial structure settings on the economic and safety performance of nuclear reactors using econometric models. In addition, the structure of the PhD is based on a paper format, where four papers (or chapters) focus on different questions related to the role of innovation and industrial structures in the nuclear power sector.

Chapter one studies the determinants of innovation in nuclear power technologies and in particular the importance of the traditional technology-push / demand-pull paradigm, along with the role of nuclear safety regulation, to foster innovation in nuclear power technologies. This work is based on patent data and patent citations as measures of innovation effort and quality respectively, and on data on nuclear reactor inspections and corrective actions to capture nuclear safety regulation.

Chapters 2 and 3 investigate how innovation and industrial structure settings impact the economic and safety performance of existing reactors, using outage data. Chapter 2 focuses on the economic and safety performance of nuclear reactors based on outage data from reactors in operation in 12 OECD countries between 1970 and 2008. It studies the role of the origin of innovation, by differentiating between national and foreign innovations, and the role of industrial structure to foster learning spillovers between reactors for improving performance. Chapter 3 focuses on the US nuclear reactors between 1994 and 2008, and analyses how the deregulation of the US electricity market has impacted the performance of reactors. It focuses on two major reforms of the electricity market: the creation of wholesale market and the divestiture of nuclear reactors with the vertical unbundling of electricity generation and supply activities.

Finally, Chapter 4 analyses the role of standardization of nuclear reactor programs, construction time and innovation on the construction costs of nuclear reactors in France and the US between 1970 and 2002, using a unique dataset on overnight construction costs in the two countries.

A key feature of this thesis is the collection of a large variety of micro level data on innovation activity, operating performance, industrial structure and construction costs.

These data are generally collected at the annual and reactor level and cover a large number of countries, as well as a fairly long time period going back to the 1970s for performance data, and to the 1930s for patent data.

Chapters 1, 2 and 4 make different use of patent data to measure innovation effort. We built an original database on fission nuclear reactors technologies patents using the European Patent Office (EPO) Patstat database. The definition of the relevant patent classifications is based on a new classification of climate change technologies which encompasses a sub-classification for nuclear power. This classification provides access to relevant patent data at a worldwide level since the first patent application for nuclear reactors in 1939. In addition, we collect extensive data on patent characteristics such as application and grant year, patent citations, application country and country of residence of the innovator.

This dataset is then used in different ways in the three chapters. As previously mentioned, in Chapter 1 we analyse the determinants of innovation whereas in Chapters 2 and 4 these data are used as explanatory variables.

Similarly, a large variety of data has been collected on industrial structures and performance over the course of this PhD. In particular, we make extensive use of outage data in Chapters 2 and 3 in order to measure performance using reactor level statistics on outage characteristics. These data are collected from the International Atomic Energy Agency (IAEA) Power Reactor Information System (PRIS) database and enable us to distinguish between economic and safety performance using planned and unplanned outages respectively. The PRIS database is set at a worldwide level with annual data going back to 1970 and allows further access to nuclear reactor technical characteristics and the different firms involved in the construction and operation of reactors. These more general data on industrial structures, collected essentially from the PRIS database, and other institutional sources, have been used to varying degrees in the four Chapters.

Finally, the four papers use different, albeit classical, econometric models in order to test for causality and measure the magnitude and significance of explanatory variables. However, we should also stress that this PhD makes more general contributions in Chapter 3 about econometrics methodology concerning the treatment effect of endogenous variables.

# 5. The contributions of the PhD

The contributions of the four Chapters of this PhD thesis can be divided into three sets of findings on *(i)* the determinants of innovation in nuclear power technologies; the role of innovation and industrial structure settings on *(ii)* existing nuclear reactors operation and *(iii)* the construction costs of nuclear reactors.

It is important to note that some of these findings are the result of collaborative work with other researchers who should be acknowledged. Chapter 3 is co-authored with Magnus Söderberg (Associate Professor of Economics at Mines ParisTech)[6]. Chapter 4 is co-authored with Lina Escobar Rangel (PhD Candidate in Economics at Mines ParisTech).

## On the determinants of innovation in nuclear power technologies

In Chapter 1, we present an empirical analysis of the determinants of innovation in commercial nuclear reactor technologies, based on patent data in 12 OECD countries between 1974 and 2008, and show how government-led incentives and nuclear safety regulation impact the incentives for innovation and the quality of innovation, measured using patent forward citations (i.e. subsequent citations by other patents).

Firstly, the empirical analysis confirms the descriptive insights into the positive role of demand-pull (measured in terms of Nuclear Power Plant (NPP) construction at home and in the rest of the world) and technology-push (measured in terms of public R&D expenditures) on nuclear power innovation. These policy drivers also have some positive long term impacts on innovation through the stock of knowledge which emphasizes the existence of a strong first-mover advantage in countries' nuclear technologies developments. Our results also show that political decisions (measured in terms of cancellation of NPP construction) have a negative impact on innovation. The latter result can be interpreted as one of the consequences, along with a fall in NPP orders, of the TMI and Chernobyl accidents on nuclear reactor innovation.

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[6] We are currently working on a revised version of this paper where Monte Carlo simulations demonstrate under which conditions our empirical strategy of using the predicted values of a survival model produces stronger instruments. These simulations are mostly performed by Damien Dussaux (PhD Candidate at Mines ParisTech) and, as such, are not included in this PhD thesis.

Secondly, our results demonstrate the first part of the Porter (1995) hypothesis which states that environmental (in our case safety) regulation impacts innovation activity which, in turn, improves performance. We find that the level of monitoring (measured by the average number of inspections per reactor) has a positive impact on innovation. This result can be interpreted as the positive effect that regulatory enforcement has on the incentive to innovate in order to comply with safety standards.

Thirdly, our results show the importance of taking into account the value of past and present innovation (measured by the count of forward citations). We find that technology-push and national demand-pull lead to relatively more valuable innovation than foreign demand-pull. This result can be explained by the fact that diffusion of nuclear innovations takes place initially in the home country of the innovator who will start by patenting its most valuable innovations.

## On the role of innovation and industrial structure for operating performance

Chapters 2 and 3 study the role of innovation and industrial structures – with a focus on learning by doing opportunities and market regulation – on the economic and safety performance of nuclear reactors.

### *On innovation, learning by doing opportunities and operating performance*

In Chapter 2, we study the role of innovation and learning opportunities on nuclear reactors' economic and safety performance in 12 OECD countries between 1970 and 2008. We define economic and safety performance based on planned and unplanned outages respectively, using annual data at the reactor level. Furthermore, while these measures remain proxies, we show that unplanned outages remain closely related to other safety performance indicators used by the US Nuclear Regulatory Commission.

The results provide robust and significant evidence of the importance of the stock of innovation and learning spillovers. In particular, we show that both innovations from national and foreign innovators are important in improving nuclear reactors' economic performance, but that international technology transfers do not have an impact on safety performance. At a time when funding for nuclear R&D is declining, this result shows that it may be in the interest of the nuclear industry to foster international technology transfers in order to maintain knowledge within the industry, and by extension nuclear reactors' economic performance.

However, national innovations remain necessary for safety performance, which can be explained by the fact that these innovations reflect the national knowledge capabilities of the country where a reactor is located. In that respect, our results stress the potential limit of international technology transfer programs on a turn-key basis, as these programs tend to be developed without associated national R&D capabilities.

Our results provide the first comprehensive analysis of learning by doing since the development of commercial nuclear reactors as the period studied covers 40 years of operation in 12 countries. Overall, we show that the improvements in economic and safety performance due to learning by doing are limited in terms of magnitude and concentrated in the first 5 to 7 years of operation for economic and safety performance, respectively. However, safety performance deteriorates at a much slower rate than economic performance and the cumulative effect of age on safety remains positive up to at least 40 years of operation. In addition, one may also argue that reactors' life extension programs may at some point reverse this trend, as they will usually include the replacement of major components such as steam generators.

In accordance with the existing literature (Lester and McCable, 1993), WEalso find that nuclear reactors benefit from spillovers effects, measured by reactor-years of operation of other reactors at the site level, but not from other reactors operated by the same firm but located on a different site. This result shows that learning opportunities are essentially limited to the experience of the site manager both for economic and safety performance. From a policy perspective, it also shows that efficiency gains achieved by a utility such as EDF in France might not be due to operating a large number of reactors but to locating several reactors on the same site.

### *On the (de)regulation of electricity markets and operating performance*

In Chapter 3, we focus on the restructuring of some of the American states' electricity markets and its impact on nuclear reactors economic performance. In particular, taking advantage of the heterogeneity between states and reactors in terms of the exposure to market reform, we investigate how the introduction of a wholesale market and the forced divestiture of vertically integrated utilities during the 1990s and 2000s have impacted nuclear reactors' availability.

Owing to the endogeneity of market interventions, a general contribution to the econometric literature made in this Chapter 3 is that instruments based on proportional hazard models are conceptually more appropriate when measuring the effect(s) of discrete government interventions that persist over time. We show that when endogenous variables are discrete and subject to inertia, using the predicted values of a survival model produces stronger and more precise instruments compared to OLS, 2SLS or the predicted values of a Probit model.

As the treatment of endogeneity often represents a shortcoming of many empirical studies dealing with electricity market restructuring (Kwoka, 2008), we argue that this approach could be replicated in the context of many structural policy interventions where policy inertia substantially reduces the risk of reversal following the reform, but also in the context of other economic decisions with the same properties (e.g. mergers, investment decisions).

Building on this approach, our findings show that the divestiture of nuclear reactors in the US has led to a substantial improvement in the economic performance of divested nuclear reactors in the US between 12% and 14%, whereas wholesale market creation is not found to have changed the incentives to reduce outage level. In addition, the results highlight that divestiture has been particularly effective in improving the performance of nuclear reactors with the highest outage track record.

Taking into account potential increases in operation and maintenance costs associated with divestiture, our back of the envelope estimate (based on Davis and Wolfram, 2012) shows that, at wholesale market prices, divestiture has led to USD 3.5 billion annual revenues for the US nuclear sector. In addition, considering the merit order of nuclear plants compared to fossil fuel plants in the US, this improvement in performance also has a significant impact on $CO_2$ emissions.

### On the role of innovation and industrial structure on construction costs

Finally, Chapter 4 studies the short and long term benefits of nuclear reactors standardization and the impact of the stock of knowledge on the construction costs of nuclear reactors in the US and France between 1966 and 2002 using overnight construction costs data.

We build a system of equations to control for endogeneity between costs and lead-time, using the expected demand of electricity as an instrument for lead-time. The endogeneity between lead-time and construction costs could be motivated from the fact that the nuclear operator maximizes the net present value of nuclear reactor, leading to a simultaneity problem between lead-time and cost. We further control for input prices and the possibility of structural breaks following major nuclear accidents, and distinguish between short term and long term potential benefits of nuclear reactor standardization. Short term benefits are defined as the instantaneous gains based on the diversity of nuclear reactors currently under construction, whereas long term benefits represent learning by doing spillovers from similar reactors.

We show that short term gains from standardization have a positive impact on construction costs through a reduction in lead-time, the latter being one of the mains drivers of construction costs in France and the US. This result is also confirmed for a range of other OECD countries with heterogeneous nuclear programs and can be explained by the fact that the diversity of nuclear reactor models can lead to delays caused by supply line constraints or delays due to increased workload for the nuclear safety regulator. For instance, nuclear safety authorities with limited resources will have to monitor the construction of several nuclear models with different designs and safety systems.

From a policy perspective, as liberalised electricity markets will tend to apply higher discount rates to nuclear new-build's projects appraisal, we further argue that standardization of nuclear reactors will be a key criterion for the economic competitiveness of merchant nuclear reactors.

At the same time, we demonstrate that learning by doing spillovers are also conditional on the standardization of nuclear programs, given that learning by doing spillovers only take place through reactors of the same model built by the same Architect-Engineer (A-E) firm. Concerning the role of the A-E firm, we also show that vertical integration of the utility and the A-E firm reduces construction costs, which can be explained by a reduction in the asymmetric information of the utility regarding costs. For instance, when a utility acts as the A-E firm it directly interacts with the different firms involved in the construction of the reactor and can gain more information on their costs.

In parallel, we also find that innovation in the nuclear industry – using patent data –increases construction costs, reflecting the fact that innovation increases the complexity of nuclear reactors, for instance in terms of the number of safety systems. This result is contradictory to the pattern in other energy technologies where innovation contributes to costs reductions but can be explained by the importance of safety regulation in the nuclear power sector which improves safety performance (Chapter 2), at the expense of an increase in construction costs.

* * *

We conclude this thesis with a policy discussion on the general implications of our results for the role and nature of innovation in nuclear power and on the industrial structure settings which favour the short and long term competitiveness of nuclear power. Paths for future research avenues on the economics of nuclear power are also suggested.

# Chapter 1:

# What drives innovation in nuclear reactor technologies? An empirical study based on patent counts.

## Abstract

This paper studies the evolution of innovation in nuclear reactor technologies between 1974 and 2008 in 12 OECD countries and assesses to what extent nuclear innovation has been driven by economic incentives, political decisions and safety regulation considerations. We use priority patent applications related to nuclear power generation as a proxy for innovating activity. Our results highlight that nuclear innovation is partly driven by the conventional paradigm where both demand-pull, measured by Nuclear Power Plant (NPP) constructions in the innovating country and in the rest of the world, and technology-push, measured by Research and Development (R&D) expenditures specific to NPPs, have a positive and significant impact on innovation. In contrast, we show that changes in policy support for nuclear power following the Three Miles Island and Chernobyl nuclear accidents, measured by NPP cancellations, have a negative impact on nuclear innovation. Finally, we find that nuclear safety regulation has an ambivalent effect on innovation. On the one hand, regulatory inspections have a positive impact on innovation. On the other hand, regulatory decisions to temporarily close a NPP have an adverse impact on innovation.

# Résumé

Cet article étudie l'évolution de l'innovation dans les technologies des réacteurs nucléaires entre 1974 et 2008 dans 12 pays de l'OCDE, et évalue dans quelle mesure l'innovation nucléaire a été stimulée par les incitations économiques, les décisions politiques et les considérations de réglementation de sécurité nucléaire. Nous utilisons les demandes de brevets prioritaires en matière de production d'énergie nucléaire comme proxy pour l'activité innovante. Nos résultats mettent en évidence que l'innovation nucléaire est en partie soutenue par le paradigme classique où la demande, mesurée par les centrale nucléaire en construction dans le pays de l'innovation et dans le reste du monde, et les dépenses de Recherche et Développement (R & D) spécifiques aux centrales nucléaires, ont un impact positif et significatif sur l'innovation. En revanche, nous montrons que les changements de politique de soutien à l'énergie nucléaire à la suite des accidents nucléaires de Three Miles Island et de Tchernobyl, mesurés par les annulations de centrales nucléaires, ont un impact négatif sur l'innovation nucléaire. Enfin, nous constatons que la réglementation de sûreté nucléaire a un effet ambivalent sur l'innovation. D'une part, les inspections réglementaires ont un impact positif sur l'innovation. D'autre part, les décisions réglementaires de fermer temporairement une centrale nucléaire ont un impact négatif sur l'innovation.

# 1. Introduction

The empirical economic literature on the determinants of technological change in clean technologies, and in particular low carbon energy technologies, has been growing rapidly for the past two decades. Considering the importance of energy saving and alternative forms of energy in fostering climate change mitigation, and the role of technological change in reducing mitigation cost, this literature has studied how economic and regulatory incentives have an impact on the pace and direction of innovation.

The aim of this paper is to assess how nuclear innovation has evolved and has been induced by government-led incentives, and the characteristics of the nuclear industry, through for instance political shocks and nuclear safety authority regulation, since nuclear reactor technologies entered the commercial stage. Very little attention has been devoted to the innovation taking place in nuclear reactors' technologies despite the fact that nuclear power generation encompasses a significant share of the electricity mix of developed countries and plays a role in climate change mitigation scenarios. In 2010 (World Nuclear Association, 2012), nuclear power provided 13.5% of the world's electricity consumption, 24% of electricity consumption in OECD countries, and 34% in the European Union. In the 2010 IEA Blue Scenario, nuclear power generation was expected to become the first electricity source by 2050 with 24% of worldwide electricity consumption, contributing to 7% of the climate change mitigation effort to curb overall carbon emission by 50% compared to 2007 (IEA, 2010).

Innovation in nuclear power is significant both in terms of competiveness and safety margins of Nuclear Power Plants (NPPs). For instance, the OECD Nuclear Energy Agency (OECD/NEA, 2007) highlights the role of innovation in nuclear reactors for improving NPPs' competitiveness through, for instance, an increase in operation and maintenance efficiency (e.g. nuclear fuel rod reliability), more standardized designs or an increase in the NPPs' lifetime. Innovation has also enabled improvements in NPPs' safety margins both in terms of the expected probability of a major accident (e.g. automatic scrams in case of technical failure) and the potential impact beyond the NPP in the event of a major accident (e.g. core catcher). The recent Fukushima nuclear accident has called for a revision of NPPs safety margins. While some safety margins improvements may originate from organizational changes within the nuclear industry (David et al., 1996), and from changes of the international framework on nuclear safety regulation (Berthélemy and Lévêque, 2011), one may expect that incremental technological change will also have to play a central role in order for nuclear power to remain a competitive energy source.

This paper follows the empirical body of literature on the determinants of innovation in energy technologies and on the role of environmental regulation as a channel for environmental innovation. In energy technologies, Newell et al. (1999) and Popp (2002) show, respectively, that the direction and the pace of innovation in energy saving technologies has been induced by changes in energy prices and is also impacted by the quality of the stock of knowledge available to innovators. Johnstone et al. (2008) highlight that policy instruments supporting the diffusion of renewable energy sources (e.g. feed-in tariffs, obligation or green certificates) play a significant role in spurring innovation in these technologies. More recently, Dechezleprêtre and Glachant (2013) and Peters et al. (2012) study the determinants of innovation in the wind and solar modules industries, respectively, and show that innovators do not only respond positively to national demand-pull policy, but also to spillovers from foreign demand-pull incentives.

In parallel, numerous authors have explored the link between environmental regulation and innovation. Porter and Van der Lindle (1995) argue that compliance with environmental regulation may be a key channel for spurring new innovation and in turn for improving firms' competitiveness. Jaffe and Palmer (1997) find that Pollution Abatement and Control Expenditures (PACE) have a positive impact on US firms' R&D expenditures but have no incidence on patent application. Brunnermeirer and Cohen (2003) argue that environmental innovation in the US manufacturing industry is induced by the level of PACE and regulatory enforcement, but do not find a significant effect for the latter. In addition, based on survey data and a discrete choice approach, Horbach (2008) finds evidence that environmental innovation in German firms is induced by environmental regulation.

Following this literature, innovation effort in nuclear reactors is measured using priority patent applications in 12 OECD countries with commercial NPPs between 1974 and 2008. These specifications of the panel dimensions allow us to focus solely on the commercial area of the nuclear industry, as well as on the stage of the nuclear fuel cycle where innovation results essentially from industry. For instance, we do not consider innovation in fast breeding reactors which originates from public research centers and has not yet reached the commercial stage.

The results show that the positive impacts of public R&D expenditures and national NPP constructions on nuclear innovation are found to be larger when priority patents are weighted by foreign citations, indicating that these incentives are channels which induce relatively more valuable innovations. In contrast, policy shocks, measured by the decision to cancel NPP construction, are found to have a negative impact on innovation in nuclear reactors. Finally, we find that the nuclear safety regulation has an ambivalent impact on innovation. On the one hand, the level of monitoring, measured in terms of the average number of inspections per NPP, has a positive effect on innovation. On the other hand, decisions to temporarily close NPPs because the operator does not comply with the safety regulation have a negative effect on innovation. This can be explained by the fact that non-compliance may originate from a lack of resources which will in turn have a negative impact on innovation.

The next sections of this paper are organized as follows. Section 2 provides a descriptive overview of the evaluation of the innovation system for nuclear reactors and shows how the control over nuclear reactor technologies has gradually been passed to the private sector. Section 3 presents various datasets used for our analysis and addresses the methodological approach used to measure innovation. Section 4 presents a descriptive overview of the trends of innovation in nuclear power. Section 5 presents the econometric model and the results. Finally, Section 6 concludes and suggests paths for future research.

# 2. The nuclear innovation system

The early days of the nuclear innovation system can be described as a technology sector which originated under strict government control and planning along with centralized research centers and a strong culture of secrecy (Cowan, 1990). For instance, in the US, the creation of the Atomic Energy Commission (AEC), in charge of both military and civil research for nuclear technologies, was a direct extension of the World War II *Manhattan Project* and shared much in common with this war project in terms of military control and secrecy culture (Lowen, 1987). However, by the mid-1950s and with the prospect of the development of civil applications for nuclear, involvement of private corporations had been rapidly growing with the notable predominance of the US firms Westinghouse and General

Electric, for the development of reactor designs (Joint Congressional Committee on Atomic Energy, 1952).

The rapid involvement of private corporations has not been the sole attribute of the US nuclear industry, and private corporations were later to be involved in the commercialization of NPPs in most of the western European countries (DeLeon, 1979), either through public-private partnerships (e.g. Framatome) or international cooperation (e.g. Euratom). This involvement of the private sector, which initially took place at the construction stage of the first generation of NPPs, rapidly shifted toward the development of new nuclear reactor designs by the late 1960s (OECD/NEA, 2007).

The commercial stage of nuclear power has also been characterized by the importance of international technological transfers, originating essentially from the US toward a large number of countries (e.g. France, Germany, Japan, and Korea), with the notable exception of the United Kingdom (UK). A number of countries have since adapted and improved these NPP designs to create national reactors (e.g. the APR-1400 Korean reactor is based on a design initially transferred by the US firm Combustion Engineering).

Hence, the nuclear reactors innovation system has evolved from a significant governmental control framework toward a system where most of the incremental innovation originates from the private sector. However, government control remains strong at other stages of the nuclear fuel cycle and in particular at the back-end stage (i.e. waste treatment and long term storage), for technologies facing high proliferation risks (e.g. isotope enrichment technologies) or with long term deployment horizons (e.g. fast breeding reactors). In that respect, the scope of our analysis is limited to conventional nuclear reactor innovations in market economies between 1974 and 2008, in order to focus on nuclear technologies and on the period where private corporations became more involved at the innovation stage. This limit to the scope of our analysis is especially important in limiting endogeneity risk in our empirical analysis between public R&D expenditures and innovation.

Nevertheless, innovation in nuclear reactors is not only the outcome of private corporations. Public research laboratories can still actively be a part of the innovation system, essentially through public-private partnerships, such as the Commissariat à l’Energie Atomique (CEA) and Areva in France. More importantly, innovation activity is to a large extent influenced by nuclear safety regulation, as well as government support for nuclear energy and it is important to take their actions into account when studying innovation in nuclear reactors.

# 3. Data

## 3.1. Nuclear power patents

Patent data are commonly used to measure and track innovative activity and their advantages and limitations have been extensively discussed in the economic literature (OECD, 2009). Firstly, the main attribute of patent data over other data sources, such as R&D expenditures, is that patents are *ex post* indicators of the innovation effort. Secondly, patent data are available at a disaggregated level and allow the tracking of where and when patents originated in most of the countries in the world and their relevant technological field. Thirdly, patent analyses can be refined through the use of indicators to measure the value of a patent, either through the use of forward patent citations made for a specific patent, the size of patent family or patent renewal information (Van Zeebroeck, 2010).

The use of patents as indicators still faces a number of limitations. Patents are only one of the alternatives for protecting an innovation. In particular, patents grant a temporary exclusion right over a specific innovation in exchange for the public disclosure of this innovation and some innovators may prefer to keep innovation secret. Innovators may also choose to protect innovation through product complexity or know-how. The propensity to patent may vary among technological sectors, countries and over time. Whilst this effect does introduce a bias when presenting descriptive statistics on patents, the use of country and time fixed effects, along with focusing on only one technological sector, mitigates this problem in econometric analysis.

More importantly, nuclear patents have received specific treatment compared to the rest of the intellectual property rights system. Nuclear energy patents encompass the unique attribute, along with defense related technologies, that a patented innovation can be classified and remains *de facto* secret for a period of time. In addition, some nuclear energy patent legislations do enable the preemption of firms' patent rights to the benefit of government agencies, through compulsory licensing, if the innovation is thought to be of benefit to the general interest[7]. If the impacts of these specific legislations on the incentives to patent and to innovate have been extensively pointed out by legal scholars (Newman and Miller, 1947; Joint Congressional Committee on Atomic Energy, 1959), it is generally

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[7] For instance, this provision for nuclear related patents' compulsory licensing is present in the US 1954 Atomic Energy Act.

recognized that these features have gradually faded away, as private enterprises became more involved in the development of nuclear technologies and needed intellectual property rights to secure the economic benefits of their innovations (Hamann, 1962). Hence, it is reasonable to argue that patent secrecy is not a problem for our analysis, as it starts in 1974 where many reactor technologies had already been transferred to other countries.

When using patents to measure innovation, one needs to be able to assess which patent classification classes are relevant to the analysis. In that respect, our empirical work has largely benefited from the creation, by the EPO, of a new classification specific to climate change related technologies which includes a technology class specific to nuclear fission reactors "Y02E30". Using this classification, we retrieve relevant patent applications between 1938[8] and 2008 in the 12 countries studied in our analysis, using the EPO/OECD World Patent Statistical Database (Patstat), in order to build our innovation dependent variables, knowledge stocks based on previously patented innovations and the forward citations of these patents. In the end, our dependent variable includes 7,999 priority[9] patent applications between 1974 and 2008.

### 3.2. Data on nuclear power plants construction and cancellation

Data on nuclear power plant construction are retrieved from the International Atomic Energy Agency (IAEA) Power Reactor Information System (PRIS) database. This database includes general information on all the NPPs in the world since 1970, and information on the dates when the construction of a NPP starts, finishes or is cancelled. It also includes information on reactors' energy capacity and technical characteristics. Moreover, the PRIS database provides detailed information on causes and durations of the nuclear reactors' outages at the country level.

Using this database we retrieved information on the dates when the construction of NPPs started and their capacity (in MWe). We also collect data on the date of NPP construction cancellation, i.e. NPPs whose construction began but was not finished due to government or utility decisions. Our dataset includes 237 NPPs whose construction started between 1974 and 2008 in the 12 countries studied, with a total capacity of 241 GWe. In parallel, 141 NPPs' construction started during this same period in the rest of the world, with a total capacity of

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[8] 1938 is the year where nuclear fission was discovered by German scientists, Otto Hahn and Fritz Strassmann.

[9] By priority patent we refer to the first application made for a patent. In particular, we do not consider the extensions made to a patent abroad.

116 GWe. These NPP constructions have essentially taken place in Russia (25 NPPs), China (22 NPPs), Ukraine (21 NPPs) and India (16 NPPs). Finally, out of the 237 NPPs whose construction started during the period, 51 were cancelled, representing a total capacity of 51 GWe. These NPP cancellations took place in the US (41 NPPs), Germany (6 NPPs) and Spain (4 NPPs).

### 3.3. Data on nuclear power plants inspections and on outages due to regulatory decisions

We use the PRIS database to collect data on NPP outages and characteristics. Outages are available at the country and year level and include information on their causes (e.g. refueling, inspection, technical failures), the systems impacted (e.g. steam generator, turbine), the total duration and the electricity generation loss resulting from these outages. More specifically, we are interested in NPP outages resulting from inspections made by the nuclear safety authority or from the nuclear safety authority decision to temporarily close a NPP due to non-compliance with the safety standards.

These measures of nuclear safety regulation follow the empirical literature on environmental regulation where the number of inspections (Brunnermeier and Cohen, 2003) and non-compliance events (Muehlenbachs et al., 2011) at industrial installations are used to measure environmental regulation stringency. In the case of nuclear safety regulation, outages resulting from inspections are used as a proxy for nuclear safety monitoring, while outages resulting from non-compliance with the safety regulation are used to capture nuclear operators' non-compliance with safety standards. However, this latter variable should be interpreted with caution as it may also reflect increases in the rate of non-compliance detection or increases in nuclear safety standards stringency (Feinstein, 1989).

These two variables are expressed in each country in terms of the annual average number of outages per reactor for both types of outages. Whilst taking into account outage duration could be a way to refine the analysis, this measure would introduce a bias as nuclear operators take advantage of inspections to undertake refueling and maintenance work. In the end, our dataset includes 11,034 outages resulting from inspections and 484 outages resulting from nuclear safety regulators decisions.

### 3.4. Data on public R&D expenditures and national GDP

Data on public R&D expenditures were collected from the International Energy Agency (IEA) energy technology R&D database. These data are available from 1974, (with a few missing years for some countries which were not reported to the IEA) for all the IEA member states, and include disaggregated information on R&D expenditures for nuclear fission. In particular, we were able to extract information specific to nuclear reactors' public R&D expenditures, and exclude expenditures covering other stages of the nuclear fuel cycle[10].

Finally, we collect data on countries' annual GDP using the World Bank data, measured in $USD_{2010}$ dollar current price and adjusted for purchasing power parity.

# 4. Innovation and diffusion of nuclear reactor technologies

### 4.1. Distribution of nuclear reactor patents

This section presents the distribution of nuclear patents specific to nuclear reactors between 1974 and 2008. Figures 1.1 and 1.2 present, respectively, the trend in priority patent applications between 1974 and 2008, and their distribution among the 12 countries[11] studied in our empirical model. The choice of country studied is based on a number of criteria: firstly, data on R&D expenditures in nuclear reactor technologies are only available for OECD countries; secondly, we are only interested in countries with commercial NPPs; and thirdly, in order to provide meaningful results we need to study countries with an intellectual property law system in place throughout the period[12]. As Figure 1.1 highlights, nuclear reactor patents have followed a decreasing trend over the period studied, in particular since 1984, ranging from 371 patent applications in 1984 to 82 in 2005. The distribution of these patents among countries shows that innovation essentially took place in

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[10] We consider public R&D expenditures specific to "Light water reactors", "Other converter reactors", "Other nuclear fission" and "Unallocated nuclear fission".

[11] Namely: Belgium, France, Japan, South Korea, the Netherlands, Spain, Sweden, Switzerland, Canada, Germany, the UK and the US.

[12] For instance, even if we could have access to public R&D expenditures in Russia or China, we would not keep them in our panel study as the notion of property rights has historically been very distinct in these countries compared to Western European countries or to the US.

the US, France, Japan and German as these four countries represent 90% of our sample. Note that this trend is the opposite of what is happening in other energy technologies.

**Figure 1.1: Trend in patent applications in nuclear reactor technologies**

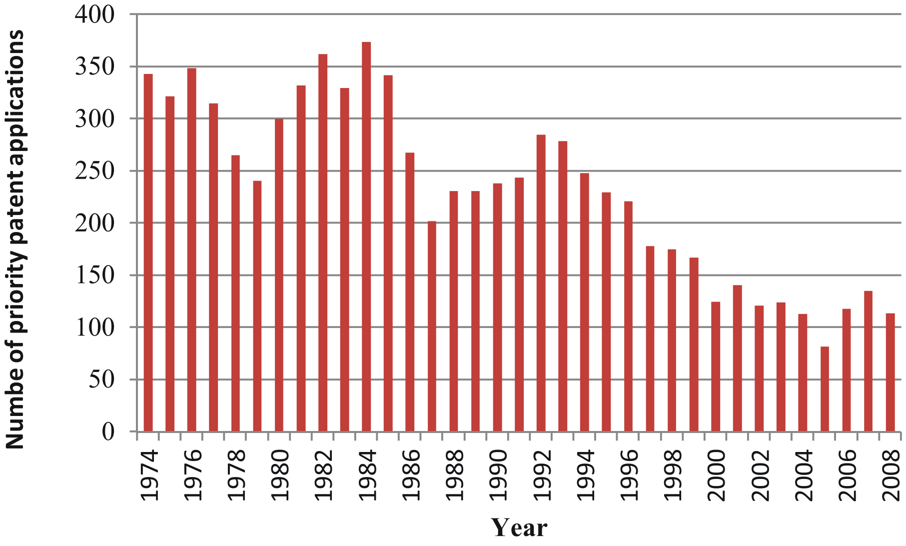
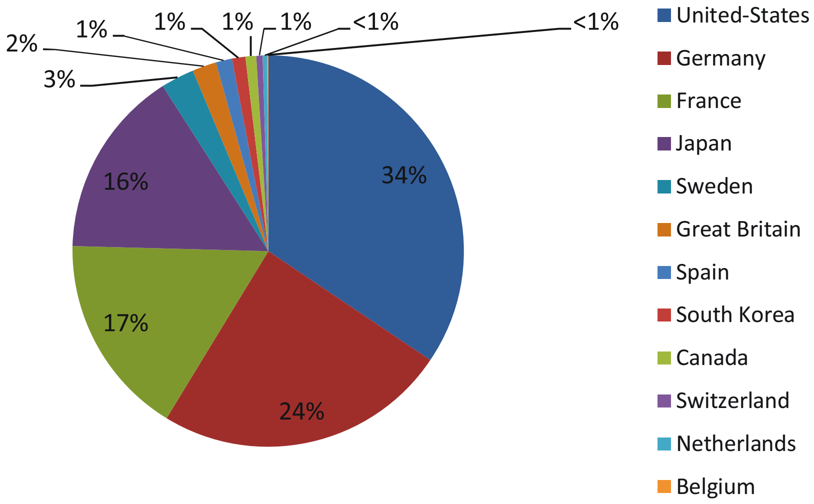


**Figure 1.2: Distribution of patent applications among countries (1974 – 2008)**



If we focus on the main firms and public research organizations[13] applying for patent protection, we observe that firms represent the vast majority of innovators, which is also characterized by few, large organizations. Figure 1.3 presents the top 20 innovating organizations in our sample and shows that the nuclear innovation system is highly concentrated, as the top 20 organizations represent 70% of our dataset with 5,771 patent

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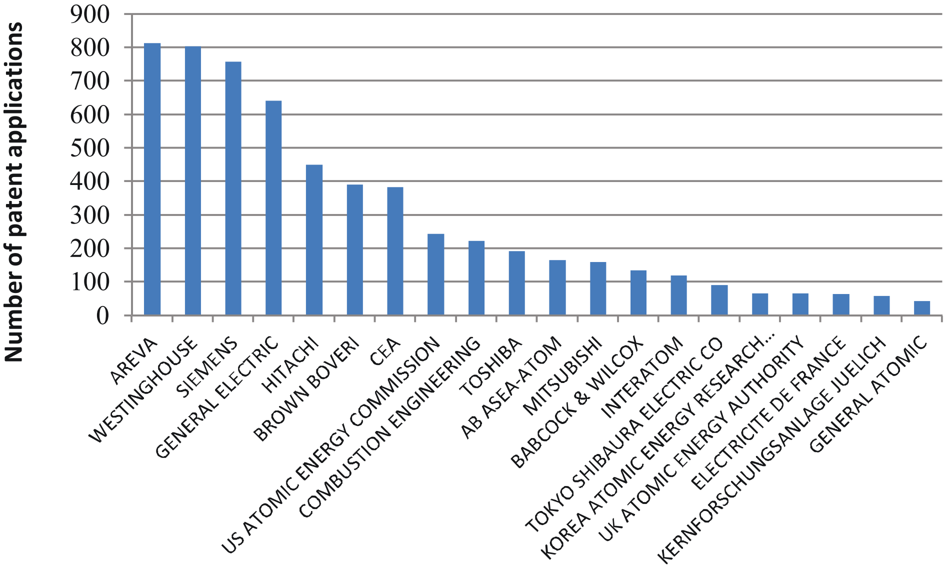
[13] Organizations' names were retrieved by aggregating firms with their main subsidiaries. For instance, AREVA regroups Framatome, Cogema, Technicatome, FBFC, Cezus, Zircotube, etc.

applications. In particular, Areva, Westinghouse and General Electric represent more than 25% of all the innovating organizations. Moreover, private firms represent 88% of these 20 organizations and more than 90% of all the organizations.

**Figure 1.3: Top 20 innovating organizations in nuclear power (1974 – 2008)**



Finally, innovation in nuclear reactor technologies is also characterized by the importance of foreign patenting. In other words, innovators do not only seek patent protection in their home country but will also extend these patents abroad[14], suggesting that foreign markets opportunities are important for nuclear reactor innovators. In our nuclear patents dataset, international inventions, i.e. innovations that have been extended in at least one other country (Dechezleprêtre et al., 2011), account for about two thirds of all the nuclear reactor patents and are patented, on average, in 4.8 countries. As Table 1.1 shows, this propensity to seek patent protection abroad is a feature of most of the countries studied and is directed both toward OECD and non-OECD countries.

This propensity to export patents varies across countries as, for instance, Spain exports only 3.7% of its patents abroad while Sweden exports 98.7% of its patents. Moreover, countries tend to export their patents more toward other OECD countries than non-OECD countries. For example, South Korea exports 93.5% of its patents toward OECD countries but only 30.4% toward non-OECD countries. However, patent exports toward non-OECD countries

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[14] The 1883 Paris Convention, which most of the countries of the world have now ratified, allows innovators to extend their domestic patent to other countries. Moreover, innovators have a 12 month priority right during which they can use the first filing date of a patent as the effective date for patent protection in another country.

remains an important feature of nuclear reactor patents as on average 38.2% of the patents are exported toward these countries, implying that market opportunities are not only sought in OECD countries but also in the rest of the world. In particular, the top four non-OECD countries where patent protection has been sought by innovators in the countries studied are China, South Africa, Russia and Brazil. The fact that patent applicants seek patent protection in these countries is not without importance for our empirical analysis, as it supports the hypothesis that nuclear developments in these non-OECD countries is important to for nuclear innovators.

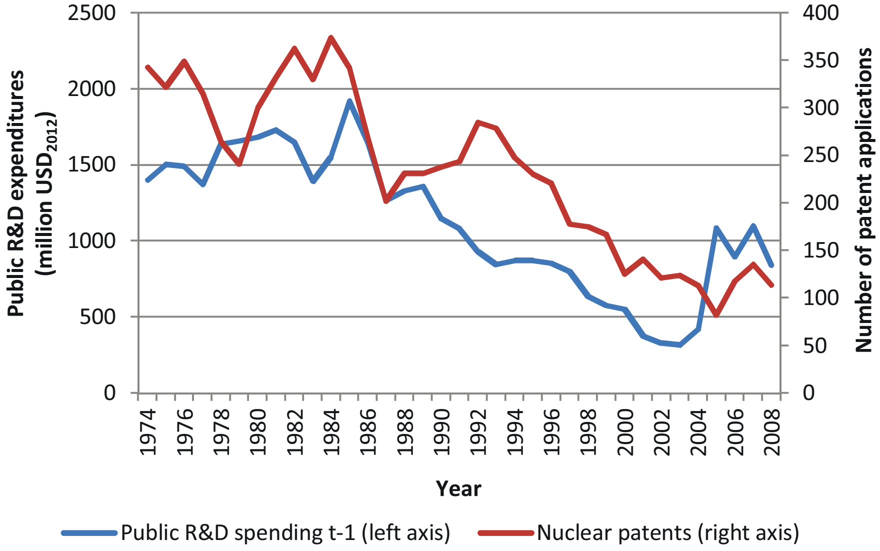
**Table 1.1: Patent export rate for the 12 OECD countries between 1974 – 2008**

| | **Overall** | **OECD** | **non-OECD** |
|---|---|---|---|
| Spain | 3.7% | 3.7% | 2.8% |
| United Kingdom | 40.1% | 40.1% | 13.0% |
| Canada | 41.1% | 39.7% | 24.7% |
| Netherlands | 44.8% | 44.8% | 20.7% |
| Germany | 49.3% | 46.1% | 28.8% |
| Japan | 53.2% | 51.5% | 18.4% |
| United States | 66.2% | 65.4% | 44.2% |
| France | 72.0% | 70.1% | 59.9% |
| Belgium | 87.5% | 87.5% | 75.0% |
| Switzerland | 92.9% | 92.9% | 47.6% |
| South Korea | 94.6% | 93.5% | 30.4% |
| Sweden | 98.7% | 98.7% | 69.6% |
| **Average** | **60.7%** | **59.1%** | **38.2%** |

### 4.2. Innovation activity, public R&D expenditures and NPP constructions

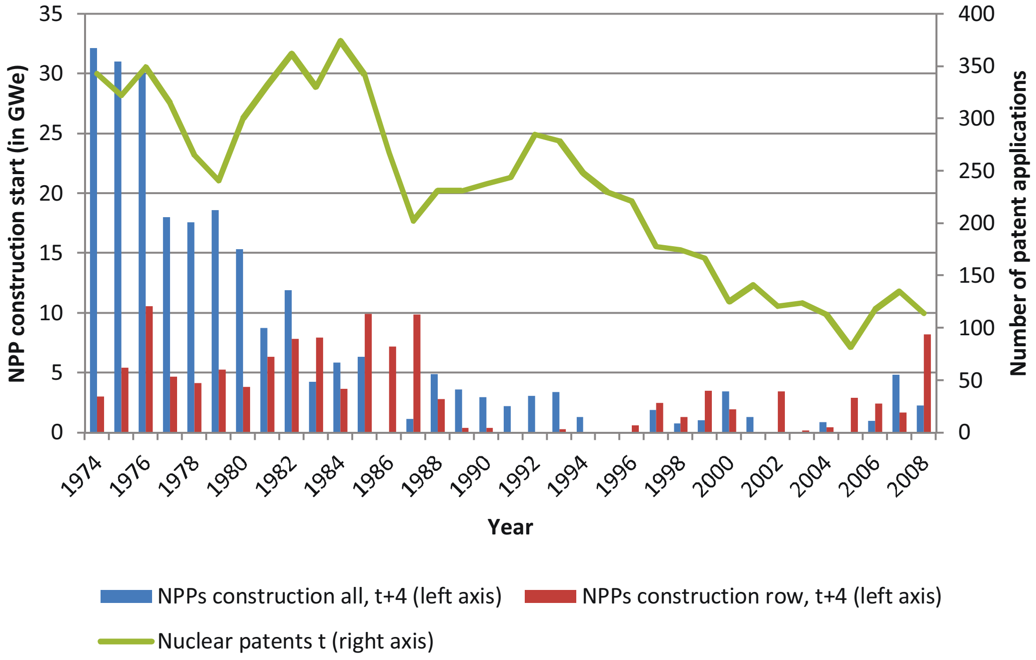
Before turning to the econometric analysis, Figures 1.4 and 1.5 highlights the trends in and correlations between innovation and technology-push (public R&D expenditures) and demand-pull (NPP construction), respectively. As Figure 1.4 shows, public R&D expenditures specific to nuclear reactors have followed a declining trend over the period studied with a peak of nearly 2 billion USD in 1985 and a trough of 300 million USD in 2003. Expenditures have since been increasing over the last few years with an increase of 63% between 2003 and 2008. Both variables are highly correlated with a correlation coefficient of 78% between public R&D expenditures and innovation.

Figure 1.4: Nuclear patent applications and public R&D expenditures



Similarly, as Figure 1.5 shows, nuclear reactor innovations and NPP constructions in the innovating countries and in the rest of the world aggregated among countries are also correlated, with a correlation coefficient of 32% and 40%, respectively, when a four year lag is taken for NPP constructions. More importantly, we observe that during the beginning of the period, the decline in NPPs in the innovating countries was compensated by an increase in NPP construction in the rest of the world which could be interpreted as an explanatory factor for the slow increase in innovation in the innovating countries during this period.

Figure 1.5: Nuclear patent applications and NPP construction



# 5. Empirical model and results

## 5.1 Main hypotheses and variables specifications

As aforementioned in Section 3, patent data can be used in a number of ways as a measure of innovation. A common measure of innovation is to consider the row count of priority patent applications in one country at time $t$. We also introduce a second measure of innovation which takes into account the quality of the patent through the count of forward citations[15] received by these patents within the next five years (van Zeebroeck, 2010), such as:

$$. \; eightedPatent_{i,t,T} = \sum_{s=t}^{t+T} \sum_{j \in J(s)} C_{i,j} \tag{1.1}$$

$WeightedPatent_{i,,T}$ is the number of forward citations received by patents filed by innovators in country $i$ published in year $t$ within $T$ years since its publication. $C_{i,j}$ is a dummy variable which is equal to 1 if application $j$ is citing application $i$, and 0 otherwise. $J(s)$ is the set of all applications published in year $s$. We set a value of T = 5, a value commonly used in the literature, to treat application years in a consistent manner and the last four years of our sample are censored to avoid truncation bias. Note that the use of time and country fixed effects in our sample allows us to control for unobservable changes in the propensity to patent over time and between countries. Using these two measures of innovation we are able to assess how the impact of policy incentives may vary when the quality of innovation is introduced.

Public R&D expenditures $RD_{i,t}$ are used to capture technology-push incentives. Similarly to Popp (2002) and Dechezleprêtre and Glachant (2013), we use current expenditures at time $t$ to explain innovating activity during the same period. While the presence of public organizations in our patent dataset could create an endogeneity problem, we do not consider this to be an important bias in our analysis as they represent a minority of the patent applicants (less than 10%), and most of the public organizations in the nuclear industry generate a large share of their revenues from public-private partnerships. This feature of

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[15] Forward citation count is made at the family level, i.e. we count the number of citations that the priority patent and its extensions abroad receive. Moreover, we do not consider inter-industries knowledge spillovers and, as such, account only for citing patents relevant to nuclear reactor technologies.

public organizations is especially strong for nuclear reactor technology development (OECD/NEA, 2007). More importantly, the hypothesis concerning endogeneity between public R&D expenditures and patents is based on the argument that the allocation of public R&D expenditures among technological sectors is based on the innovation potential (i.e. patenting activity) of each sector. It is reasonable to argue that this assumption does not hold for the nuclear sector, where the decision to fund nuclear research programs remains a strategic choice for governments, rather than a competitive allocation process between energy technologies based on the potential for new innovations.

In parallel, NPP constructions in the innovating country $CAP_{i,t+4}$ and in the rest of the world (RoW) $CAP.RoW_{i,t+4}$ measured in MWe, are used to capture demand-pull incentives. The construction of NPPs in the rest of the world, with respect to each country $i$, is used to capture the spillovers that foreign nuclear programs have on national innovation. As shown in Table 1.1 (Section 4), international patents are filed in both OECD and non-OECD countries, which highlights that international market opportunities are important to innovators.

In addition, it is important to take into account the long term planning process which takes place before the construction of a NPP and the fact that the construction time of a nuclear reactor can vary extensively between 5 and 10 years. In that respect, it is necessary to consider the date when the construction of the NPP starts and not the date when construction is completed. While limited empirical evidence exists for the lag between innovation and diffusion of nuclear reactor technologies, Lor (2008) shows a four year delay between patent applications and technology transfer agreements for CEA nuclear patents. Based on this evidence, we decide to follow a four year lag for our demand-push variables. We also decide not to build a model of innovators' expectations and measure these demand-pull variables in terms of the NPP capacity (in MWe), as the long term planning process implies that, beyond official forecasts, the nuclear industry usually has a good foresight into future constructions.

One may also expect that, policy shocks, and in particular political decisions to revisit NPPs construction programs, can adversely impact innovation activity as innovators expect a lower return on their innovation. In practice, these political events have emerged largely as consequences of the Three Miles Island (TMI) and Chernobyl accidents (in Ukraine), in the US and Germany, respectively. We attempt to measure the impact of political decisions through the number of NPPs whose constructions started but were never completed (in

MWe) at time $t$ ($Cancelled_{i,t}$). While this variable remains an imperfect measure of political shocks since the decision not to complete NPP construction can originate both from the government and the utilities; Delmas and Heiman (2001) show that US utilities' decisions not to finish NPP constructions following the TMI accident were directly influenced by changes in the US government's attitude toward nuclear power. Moreover, we argue that this measure of a political shock is a better proxy than using dummy variables for the TMI and Chernobyl accidents, as it captures the propagation of these accidents within the nuclear industry over time and between countries.

Nuclear safety regulation is also a key characteristic of the nuclear industry. Finding a suitable proxy for nuclear safety stringency is a difficult task since nuclear safety regulation includes many dimensions (OECD/NEA, 2007). As aforementioned, our approach to nuclear safety is to consider that it is constituted by two components: ($i$) NPP monitoring activities and ($ii$) NPP outages resulting from the nuclear operator failure to comply with safety standards. Nuclear safety monitoring, measured by the average annual number of regulatory inspections per reactor in one country ($Inspection_{i,t}$), is used to capture the level of nuclear safety monitoring. This approach to nuclear safety regulation is similar to the measure of environmental regulation developed by Brunnermeier and Cohen (2003) and is based on the argument that *ex ante* stricter monitoring of NPPs increases the incentive for nuclear operators to comply with nuclear safety standards.

The second component, aims to capture the effect of *ex post* regulatory action if the nuclear operator does not comply with the safety regulation. As aforementioned, it is measured by the average annual number of outages per reactor in one country resulting from a decision made by the nuclear safety authority ($Reg.outage_{i,t}$). Whether nuclear safety regulation can spur innovation in nuclear technologies remains essentially an empirical question as, beyond the well-known Porter hypothesis, one might expect other factors to have a negative impact on innovation. For instance, while non-compliance with safety standards may encourage new innovation to comply with regulation, it may also reflect a lack of resources for nuclear operators which, in turn, may lead to fewer innovations. Note that this hypothesis of resource constraints is consistent with the fact that non-compliance events could also reflect increases in the rate of non-compliance detection or more stringent nuclear safety standards.

Finally, we take into account the stock of knowledge available to inventors in country $i$ at time $t$. This captures the *"building on giant's shoulders"* effect, in other words todays' innovation is based on the stock of previous innovation. This effect is important from a policy perspective as it indicates that policy incentives do not only induce current innovation, but also have long running impacts and may induce a first-mover advantage, where countries with early nuclear programs can maintain a comparative advantage as nuclear innovators, compared to late comers. It is measured through the discounted stock of previous patents since 1939 in country $i$, and a discount factor $\delta$ captures the fact that innovation from the period $t-1$ would be more useful to todays' innovation than innovation from $t-2$. Similarly to equation (1.1), we build two distinct variables. Equation (1.2) is a simple discounted stock of knowledge and equation (1.3) is a discounted stock of knowledge weighted by forward patent citations, made with a five year window, to take into account the quality of the knowledge $CIT_{i,T,t-k}$ available to innovators as defined in equation (1.1). We take a 10% discount factor to reflect the empirical literature evidence of knowledge depreciation (Peri, 2005).

$$Know_{i,t} = \sum_{k=1}^{\infty}(1-\delta)^k N_{i,t-k} \tag{1.2}$$

$$Weighted.Know_{i,t} = \sum_{k=1}^{\infty}(1-\delta)^k\, CIT_{i,T,t-k} \tag{1.3}$$

As with our dependent variable, time fixed-effects allow us to control for unobserved temporal evolutions that may influence the propensity to patent innovation. Similarly, country fixed-effects control for unobserved country characteristics in terms of innovation usefulness.

### 5.2. Empirical framework

Our empirical approach follows a simple panel data approach where fixed effects are introduced for the time and country dimensions of the panel. As patent data have over-dispersed distributions and arise from counting the number of patents, OLS estimators are biased and it is necessary to use count data models. We use a Poisson regression[16] to capture this specificity of our data and as Poisson estimator for panel data, unlike Negative Binomial estimator, allow one to control for heteroskedasticity as well as to cluster the standard error, leading to more robust estimators (Cameron and Trivedi, 2010). This model is estimated using maximum likelihood. Two model specifications are estimated, one where the row

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[16] Regression results with Negative Binomial estimator, without clustering, can be found in Appendix 1 and show that our results are robust with respect to the choice of estimator.

number of patent applications is used as the explanatory variable, and the other where patent applications are weighted by patent citations as defined in equation (1.1). We apply a log-linear transformation to the right side of our equations such as:

$$Patent_{i,t} = \exp(\alpha_1 \ln.Know_{i,t} + \alpha_2 \ln.RD_{i,t} + \alpha_3 \ln.CAP_{i,t+4} + \alpha_4 \ln.CAP.row_{i,t+4} + \alpha_5 \ln.Cancelled_{i,t} + \alpha_6 \ln.Inspection_{i,t} + \alpha_7 \ln.Reg.outage_{i,t} + \alpha_8 \ln.GDP_{i,t} + \eta_i + \theta_t + \varepsilon_{i,t}) \tag{1.4}$$

$$Weighted.Patent_{i,t} = \exp\big(\alpha_1 \ln.Weighted.Know_{i,t} + \alpha_2 \ln.RD_{i,t} + \alpha_3 \ln.\mathrm{CAP}_{i,t+4} + \alpha_4 \ln.CAP.row_{i,t+4} + \alpha_5 \ln.Cancelled_{i,t} + \alpha_6 \ln.Inspection_{i,t} + \alpha_7 \ln.Reg.outage_{i,t} + \alpha_8 \ln.GDP_{i,t} + \eta_i + \theta_t + \varepsilon_{i,t}\big) \tag{1.5}$$

Where, $\eta_i$ and $\theta_t$ are country specific and time specific fixed-effects, respectively[17]. $\ln.GDP_{i,t}$ is used to control for countries' economic activity. The explanatory variables follow the notation presented in Section 5.2. The panel model is unbalanced as public R&D expenditures data are not available for the whole period in some countries (41 observations out of 408 are missing). However, this feature of our data is mitigated by the use of country and time fixed-effects and we have no reason to suspect the missing variables to be correlated with the idiosyncratic error term $\varepsilon_{i,t}$. Descriptive statistics for the panel data are presented in Table 1.2.

**Table 1.2: Descriptive statistics**

| Variable | Mean | Std. Dev. | Min | Max |
|---|---|---|---|---|
| $Patent_{i,t}$ | 21.1 | 32.0 | 0 | 151 |
| $Weighted.patent_{i,t}$ | 34.2 | 69.9 | 0 | 410 |
| $Know_{i,t}$ | 219.7 | 261.9 | 0 | 902.4 |
| $Weighted.Know_{i,t}$ | 321.2 | 543.7 | 0 | 2525.6 |
| $RD_{i,t}$ | 105.1 | 147.8 | 0 | 681.6 |
| $CAP_{i,t+4}$ | 381.1 | 1462.9 | 0 | 19256 |
| $CAP.row_{i,t+4}$ | 8354.7 | 8207.5 | 0 | 39426 |
| $Cancelled_{i,t}$ | 139.5 | 999.4 | 0 | 13189 |
| $Reg.outage_{i,t}$ | 0.033 | 0.079 | 0 | 0.66 |
| $Inspection_{i,t}$ | 1.06 | 0.448 | 0 | 4 |
| $GDP_{i,t}$ | 1613.6 | 2329.1 | 130.7 | 11670.8 |

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[17] We perform the Hausman test for model specification, and reject the null hypothesis that unobserved heterogeneity is uncorrelated with the explanatory variables, hence supporting the choice of country fixed-effects over random effects.

### 5.3. Empirical results

Estimation results of equations (1.4) and (1.5) are presented in Table 1.3. Robustness checks are provided in Appendix 1 and show that our results are robust when a Negative Binomial estimator and different specifications of our explanatory variables are used, and when the panel is restricted to fewer countries.

Estimations from models (1) and (2) show that innovations in nuclear reactors are driven both by technology-push and demand-pull incentives. As these models use a log-linear transformation, coefficients can be directly interpreted as elasticities. Our results show that public R&D expenditures are the main policy driver of innovation in nuclear reactors as, for instance in model (1), a 10% increase in public R&D expenditures is estimated to lead to a 0.7% increase in innovation in nuclear reactors. Similarly, the results for national and foreign demand-pulls confirm the insights from Figure 1.5: NPP construction abroad has been a substitute to national NPP construction programs for encouraging innovation in nuclear reactors. Moreover, our estimates indicate that NPP construction abroad has a higher impact on innovation than national NPP construction. This result may arise from the fact that innovators have a higher propensity to patent innovation induced by foreign demand-pull, as patent protection may be more important for an innovator to protect their innovation abroad compared to in their home country. This result is also consistent with the organization of the market for nuclear new-build, where competition between vendors essentially takes place on the international market for NPPs rather than on domestic markets.

Table 1.3: Estimated coefficients of the Poisson fixed-effect regressions

| | **Model 1** | **Model 2** |
|---|---|---|
| **Dependent variable** | $Patent_{i,t}$ | $Weighted.Patent_{i,t}$ |
| ln. $Know_{i,t}$ | 0.423 ** | - |
| | (0.207) | |
| ln. $Weighted.Know_{i,t}$ | - | 0.274 ** |
| | | (0.134) |
| ln. $RD_{i,t}$ | 0.072 ** | 0.125 *** |
| | (0,030) | (0,025) |
| ln. $CAP_{i,t+4}$ | 0.059 *** | 0.078 *** |
| | (0.012) | (0.014) |
| ln. $CAP.RoW_{i,t+4}$ | 0.122 *** | 0.143 *** |
| | (0.023) | (0.004) |
| ln. $Cancelled_{i,t}$ | -0.056 *** | -0.042 * |
| | (0.019) | (0.023) |
| ln. $Reg.outage_{i,t}$ | -0.612 *** | -0.341 |
| | (0.149) | (0.240) |
| ln. $Inspection_{i,t}$ | 0.463 ** | -0.253 * |
| | (0.182) | (0.153) |
| Observation | 309 | 309 |
| Control for GDP | Yes | Yes |
| Country FE | Yes | Yes |
| Time FE | Yes | Yes |

Note : ***, ** and * indicate that results are significant at 1%, 5% and 10% confidence levels, respectively. Robust-clustered standard errors are reported in brackets.

Comparisons between models (1) and (2) also provide valuable insights as to whether technology-push and demand-pull incentives lead, not only to more innovation, but also to more valuable innovation. In that respect, our results show that public R&D expenditures and installed capacity in the innovating countries have a stronger impact when the quality of innovation, measured by forward patent citations, is taken into account. This result shows the central role of technology-push in nuclear reactor innovation, as this has both a larger impact on innovation and is also found to induce relatively more valuable innovation between models 1 and 2.

In parallel, the impact of NPP construction abroad is not found to vary much when the quality of innovation is considered, but the impact of NPP construction at home is greater when the value of innovation is considered. This result highlights that these two dimensions of demand-pull may channel different kinds of innovation in the sense that national demand-pull leads to relatively more valuable innovations than foreign demand-pull. This effect could be explained by the fact that patent protection may be more important abroad than in the home country. Furthermore, this result could arise because innovators tend to first implement their innovation in NPP construction in their home country, before exporting this technology abroad. Hence, innovators will start by patenting their most valuable innovations induced by national demand before patenting less useful innovation induced by international demand.

We find that the stock of knowledge has a strong positive impact on innovation with an elasticity of about 4% in model (1) and 2.7% in model (2). Hence, policy incentives do not only impact current innovation but also have some long running incidence through the stock of knowledge which in turns spurs on future innovation. In other words, there exists a strong first-mover advantage for innovation in nuclear reactor technologies.

These results also show that political decisions, measured by the decision to cancel NPP construction, have a negative impact on nuclear reactor innovation. In particular, cancellations essentially took place following the TMI and Chernobyl accidents, in the US and Germany respectively, and can be interpreted as one of the consequences of these severe nuclear accidents on innovation.

Our results also provide important insights into the role of nuclear safety regulation on innovation. In particular, they show that nuclear safety monitoring, measured by the average number of inspections per reactor, has a strong positive impact on innovation. This result provides evidence supporting the Porter hypothesis, where the level of safety monitoring increases the incentives for firms to comply with nuclear safety regulation, which encourages innovation in nuclear reactors. In contrast, we find that *ex post* outages resulting from non-compliance of nuclear operators with nuclear safety standards has a negative impact on innovation. We do not argue though that this result should be interpreted as a sign that nuclear safety regulation has some negative effects on innovation. Rather, it underlines the fact that the nuclear operator did not comply with the safety standards, which can arise due to a lack of resources resulting in a reduced innovation effort.

Consequently, one might also argue that these events may lead to some eviction effects, as companies delegate more resources towards compliance with the safety standards, to the detriment of innovating activities. The fact that non-compliance events have no incidence on patents weighted by citations in model (2) is also consistent with this hypothesis: with fewer resources, nuclear innovators decide not to patent the least valuable innovations, but will still patent the more valuable innovations which receive more forward citations.

# 6. Conclusions

In this paper, we present an empirical analysis of the determinants of innovation in conventional nuclear reactors based on patent data in 12 OECD countries between 1974 and 2008. To the best of our knowledge, this paper is the first empirical investigation into innovation determinants in nuclear related technologies.

Firstly, our empirical analysis confirms the descriptive insights into the positive role of demand-pull (measured in terms of NPP construction at home and in the rest of the world) and technology-push (measured in terms of public R&D expenditures) on nuclear power innovation. These policy drivers also have some positive long term impacts on innovation through the stock of knowledge which emphasizes the existence of a strong first-mover advantage in countries' nuclear technologies developments. In contrast, our results also show that political decisions (measured in terms of NPP construction cancellation) have a negative impact on innovation. The latter result can be interpreted as one of the consequences, along with a fall in NPP orders, of the TMI and Chernobyl accidents on nuclear reactor innovation.

Secondly, our results apply part of the predictions of the Porter hypothesis to the role of nuclear safety regulation in nuclear innovation. We find that the level of monitoring (measured by the average number of inspections per reactor) has a positive impact on innovation. This result can be interpreted as the positive effect that regulatory enforcement has on the incentive to innovate in order to comply with safety standards. We find that when nuclear operators do not comply with safety standards and have their reactors temporarily closed by the safety authority, the impact on innovation is negative. We argue that this result may reflect the fact that nuclear operators do not comply with safety standards due to a lack of resources, which may directly, or through an eviction effect, lead to fewer innovations.

Thirdly, our results show the importance of taking the value of past and present innovation into account (measured by the count of forward citations). We find that technology-push and national demand-pull lead to relatively more valuable innovation than foreign demand-pull. This result can be explained by the fact that the diffusion of nuclear innovations takes place initially in the home country of the innovator, who starts by patenting its most valuable innovations.

In light of the recent Fukushima nuclear accident in Japan, it is worth noting that our results show that the impact of this accident may have ambivalent impacts on nuclear innovation. On the one hand, similarly to the TMI and the Chernobyl accidents, it can be anticipated that the Fukushima accident, through a revision of NPP orders around the world, will lead to a reduction in innovation effort in nuclear reactor technologies. On the other hand, the Fukushima accident has also led to a number of safety inspection "stress tests" in many nuclear countries and, in line with our empirical results, it can be anticipated that these safety inspections will stimulates some innovation in safety related nuclear technologies.

In that respect, these results call for future research into both the measure of safety regulation and the direction of nuclear innovation, as one might argue that safety regulation could play a role in both the pace and the direction of innovation, for instance by increasing the research effort to improve NPP safety margins. In particular, it stresses the need to differentiate innovations in nuclear reactors between those in favour of more competitive reactors, and those in favour of an increase in NPP safety margins. Key word searches based on patent abstracts could be a way of addressing this issue.

This also calls for future research into the interplay between innovation in nuclear reactors and the performance of both existing and future reactors. For instance, do these innovations lead to spillover effects in existing reactors or do they only influence future reactors' performance? Furthermore, our empirical analysis studies innovation jointly aimed toward more competitive and safer NPPs, and only addresses one of the dimensions of nuclear safety regulation. For instance, one could argue that the NPP licensing process has important effects on nuclear industry incentives to innovate, as new innovations may have to undertake long and uncertain regulatory reviews before being embedded into nuclear reactors (Cohen, 1979).

# Chapter 2:

# Innovation, Learning by Doing Opportunities and Nuclear Reactor Performance

## Abstract

This paper investigates the role of learning by doing and innovation on nuclear reactors operating economic and safety performance, measured by energy loss resulting from different outages. Incremental innovation is introduced through discounted stocks of patents, reflecting knowledge capabilities, and we distinguish between patents filed by national and foreign innovators. Our results indicate that learning by doing is concentrated during the first five years of operation and remains limited in terms of magnitude. This learning is then outweighed by an aging effect, which outweighs the cumulative learning gains after 30 years for economic performance and more than 40 years for safety performance. The nuclear industry is also characterized by the significance of learning spillovers, which improve both economic and safety performance, and take place essentially at the site level. National innovation stock is found to have a positive impact on economic and safety performance, while innovations of foreign origin are found to have a positive impact on economic performance alone. The latter highlights the benefit of international technology transfer programs for the economic competitiveness of nuclear power. Conversely, safety performance is found to be driven only by national innovations, which suggests the importance of national knowledge capabilities to nuclear reactor safety performance, and the potential limitations of nuclear development programs solely based on international technology transfers.

# Résumé

Cet article étudie le rôle des effets d’apprentissage et de l'innovation sur la performance économique et de sureté des réacteurs nucléaires, mesurés par les pertes d'énergie résultantes de différentes pannes. L'innovation incrémentale est introduite à travers les stocks de brevets, qui reflètent les capacités de connaissance, et nous faisons la distinction entre les brevets déposés par les innovateurs nationaux et étrangers. Nos résultats indiquent que les effets apprentissage sont concentrés au cours des cinq premières années d'exploitation et restent limités en termes de magnitude. Cet apprentissage est alors contrebalancé par un effet de vieillissement, qui l'emporte sur les gains d'apprentissage cumulés après 30 ans pour la performance économique et plus de 40 ans pour la performance de sureté. L'industrie nucléaire se caractérise aussi par l'importance des externalités d'apprentissage, qui améliorent à la fois performances économique et de sureté, et ont lieu essentiellement au niveau du site. Le stock national d’innovation a un impact positif sur la performance économique et de sureté, tandis que les innovations d'origine étrangère ont seulement un impact positif sur la performance économique. Ceci met en évidence l'avantage des programmes internationaux de transfert de technologies pour la compétitivité économique de l'énergie nucléaire. A l’inverse, la performance de sureté bénéficie uniquement des innovations nationales, ce qui suggère l'importance des capacités de connaissances nationales et les limites possibles des programmes de développement nucléaire uniquement basés sur les transferts internationaux de technologies.

# 1. Introduction

The macroeconomic implications of learning by doing and innovation for improving economic performance and long term growth have received considerable attention since Arrow (1962) and Romer (1990), respectively. In parallel with these seminal works, a large body of the empirical literature has explored the role of these two factors, not only at the macroeconomic, but also at the firm level. In particular, learning by doing has received early empirical focus since, for example, Wrights (1939) in the aircraft industry, or Hirsch (1952) in the machine tool industry. An important emphasis of the literature is that, since knowledge encompasses the attributes of a public good, firms may benefit from important spillover effects. For instance, firms may learn not only from their own experience but also from that of their competitors and innovation may not only generate a return for the innovative firm, but for society at large. Moreover, the ability to capture these spillovers will depend upon market structures and regulatory and non-regulatory barriers that may slow down knowledge diffusion.

In energy economics, a segment of the literature has estimated the magnitude of learning by doing and learning by searching on energy technologies' cost reduction, in order to derive experience curves (e.g. Klaassen et al., 2005). However, this literature focuses on unit-cost reduction per MWe and has largely ignored the role of incremental innovation for these technologies' operating performance. In that respect, operating performance of energy technologies is particularly important for base-load technologies, such as nuclear power, where high fixed costs and low marginal costs imply - in particular for existing nuclear reactors - that changes in the availability of a nuclear reactor can have a large effect on its competitiveness. Similarly, while nuclear reactors' safety encompasses many dimensions, the ability of a nuclear operator to acheive a high safety performance can also be observed, to some extent, through outage events, which occur due to technical failures or other safety related events.

The aim of this paper is to study the impacts of innovation and learning by doing on nuclear reactors' economic and safety performance. We develop a panel data model based on nuclear reactors' performance data covering 343 nuclear reactors in 12 countries between 1970 and 2008. Throughout this paper, we will define nuclear reactors' performance as the duration of outages divided by the total potential generation during one year. The cause of outages will then allow us to distinguish between different types of performance.

The existing literature on the performance of nuclear reactors remains relatively sparse and is centered on the role of learning opportunities (Krautmann and Solow, 1988; Joskow and Rozanlski, 1979), and industry structure (Lester and McCabe, 1993). Lester and McCabe (1993) show that the standardization of the French nuclear industry has improved industry learning and led to higher performance, compared to the United States (US), with a more fragmented industry structure in terms of designs, vendors and operators. In addition, changes in energy market regulation may not be without incidence on nuclear reactors' economic and safety performance. For instance, Davis and Wolfram (2012) and Hausman (2012) show that nuclear reactors' divestiture following the US energy markets' deregulation, has increased these reactors' economic and safety performance, respectively.

However, beyond learning opportunities and market structure considerations, nuclear reactors' performance is reported to have benefited from two important features of the nuclear industry: (*i*) the importance of incremental innovations and (*ii*) the international diffusion of these incremental innovations through technology transfers.

Firstly, as a result of demand-pull and technology-push policies, the nuclear industry has generated a large and continuous flow of incremental innovations since the first generation of nuclear reactors (Chapter 1). Despite the absence of quantitative evidence on the role of innovative activity in nuclear reactors' performance, numerous descriptive examples[18] highlight the positive impact of innovation in improving both nuclear reactors' economic and safety performance (OECD/NEA, 2007). For example, new monitoring equipment and maintenance techniques have contributed to longer operating cycles with fewer refueling incidents contributing to enhanced economic and safety performance. The extent to which incremental innovations can have a positive impact on economic and safety performance is particularly relevant considering the share of nuclear power in public energy Research and Development (R&D) expenditures, and the debate on the social returns of nuclear public R&D. In particular, it is important to recall that innovation in nuclear reactors does not only result in economic and safety improvements for new-build reactors, but is also embodied by existing reactors either through retrofitting or upgrading of nuclear components.

Secondly, technology transfers have been present since the early days of commercial nuclear reactors (DeLeon, 1979). For instance, most of the OECD countries with commercial reactors

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[18] As an anecdotal example, the US Nuclear Energy Institute (NEI) recently reported on a patented innovation developed by Exelon, to reduce moisture in steam generators that improves both nuclear reactors' economic and safety performance. NEI (Summer 2012), Nuclear Energy Insight, see: www.nei.org/filefolder/insight_summer_2012.pdf

were characterized by important technology transfers from the US as they initiated their nuclear programs (Goldschmitd, 1980). While these international technology transfer programs may vary in scope, they imply that international technology transfers need to be taken into account when looking at nuclear reactors' performance. In addition, these international technology transfers are of considerable importance for nuclear technology policy, as they raise the question of whether a country initiating a civil nuclear program without national R&D capabilities, may still achieve high economic and safety performance with the transfer of innovation from another country.

Our results indicate that both national innovation and international technology transfers are important drivers of nuclear reactors' economic performance, but that only national innovation impacts reactors' safety performance. At the same time, while learning by doing essentially takes place at the reactor level, we find evidence of learning spillovers at the intra-site and inter-firm levels. The next sections are organized as follows: In Section 2, we review in more detail the existing literature on the role of innovation and learning by doing in energy technologies in general, and nuclear power in particular. Section 3 sets some stylized facts about nuclear reactors' performance, as well as presenting the data collected. Section 4 presents our empirical approach and main hypotheses. Finally, Section 5 presents and discusses the results and Section 6 concludes.

# 2. Literature review

This paper builds on different bodies of the energy economics literature dealing with (*i*) the role of innovation in the performance of energy sources, (*ii*) qualitative evidence of the role of innovation in improving nuclear reactors' performance, and (*iii*) the existing economic literature on the determinants of nuclear reactors' economic and safety performance.

## 2.1. Studies on the role of innovation in the energy sector

An important emphasis of the energy economics literature has recently been on the role of technological innovation in the energy sector, in particular as a tool for improving climate change policy cost-effectiveness. However, due to the difficulties of collecting and, more importantly, in matching data on firms' innovation and performance activities, there is relatively little empirical evidence on the impact of innovation on energy sector performance. The most directly related literature to our research topic can be found in the two factors learning curves approach, used to study energy cost reduction as a consequence of both learning by doing and learning by searching (e.g. Klaassen et al., 2005; Soderholm and Sundqvist, 2007).

Learning curves are often used to derive learning rates estimates from a doubling of energy capacity, which can later be used to calibrate energy economics models. An important finding of this empirical literature (Jamasb, 2007; Klaassen et al., 2005) is that omitting innovation effort in learning curves analyses will tend to over-estimate the contribution of learning by doing to cost reduction, and that innovation effort can have a large contribution to reducing costs. For instance, Jamasb (2007) reviews the overnight cost of different energy technologies[19] in OECD countries between 1980 and 1998, and finds learning rates for learning by doing and learning by searching in nuclear power of 37.6% and 23.8%, respectively, while omitting learning by searching tends to overstate the learning by doing rate (53.2%).

The role of innovation in the energy sector has also been studied in the literature on technological change and the environment. An extensive review of this literature can be found in Popp et al. (2009). In particular, Popp (2002) finds, using a stock of incremental innovations based on patent applications in 13 US energy-intensive industries between 1958 and 1991, robust evidence that about one third of the elasticity of energy consumption with respect to price is indirectly induced by innovation.

### 2.3. Studies on nuclear innovation development

Despite the importance of the nuclear power innovation system in terms of public R&D expenditures, little attention has been devoted to the study of the nuclear power innovation system. This can be explained by the fact that nuclear power emerged under tight government control, and in particular within the framework of military programs, which rendered difficult the collection of data and qualitative evidence. For instance, the first generation of Light Water Reactors (LWRs) in the US has been described as a by-product of the US nuclear submarine program "Nautilus" (Cowan, 1990), making it difficult to distinguish between military and civil developments.

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[19] Note that this study is based on the TECHPOL database gathered partly through expert opinions and used as parameters for energy forecasting in the POLES model.

Consequently, while the decision to develop commercial nuclear reactors was essentially the result of technology-push and demand-pull policies (Chapter 1), it has been argued that the choice of technology (e.g. light versus heavy water reactors) was the outcome of a technology lock-in (Cowan, 1990), where the early push for LWRs allowed this technology to benefit from increasing returns and prevented the penetration of other nuclear technologies. However, if the literature has stressed the relative inefficiency of current reactors compared to other reactor technologies, the impact of innovation on improving operating nuclear reactors' economic and safety performance has, to the best of our knowledge, never been studied.

Descriptive insights into the positive impacts of innovation programs supporting existing reactors can, however, be found in a report by the OECD/NEA (2007). In particular, the OECD stresses the potential for innovation in existing reactors that can be classified in three areas:

### *i. Operating and maintenance of plants*

This includes programs to increase nuclear fuel reliability and efficiency, to optimize fuel cycle lengths and to upgrade nuclear reactors' capacity. For instance, improvement of Instrumentation and Control (I&C) components is reported to play a central role in improving nuclear reactors' availability and safety performance (IAEA, 1999).

### *ii. Nuclear reactors lifetime management and safety*

Most countries are currently aiming to increase existing nuclear reactors' lifetime from 30 years to 50 or 60 years. As a result, managing aging nuclear reactors' components represents a growing challenge for the nuclear industry[20]. Moreover, programs to replace aging components also have to provide improved safety performance, as nuclear reactors have to comply with current and more stringent nuclear safety regulation compared to when the reactor was built. Needless to say, this process has recently come under greater scrutiny following the Fukushima nuclear accident.

### *iii. Nuclear reactors decommissioning and waste management*

This too represents key challenges for the nuclear industry. Nuclear reactors decommissioning includes techniques to reduce the cost and improve safety of

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[20] For instance, the PERFECT (Prediction of Irradiation Damage Effects in Reactor Components) research program, coordinated by Euratom in the EU, aimed at better understanding the aging of nuclear components as a result of irradiation conditions. See: http://cordis.europa.eu/search/index.cfm?fuseaction=proj.document&PJ_RCN=7516885

decommissioning with different approaches, such as immediate and differed dismantling or entombment currently being studied[21]. Radioactive waste management is focused on two main topics: (*i*) nuclear waste reprocessing technologies, and (*ii*) solutions for long term nuclear waste, both in terms of geological repositories and technology to contain the nuclear waste and prevent diffusion into the environment[22].

Hence, while decommissioning and waste management are beyond the scope of this study, it appears that part of the innovation effort taking place within the nuclear industry is oriented toward improving existing nuclear reactors' economic and safety performance. Moreover, this orientation is predicted to increase as nuclear operators aim to extend nuclear reactors' lifetime and are being asked to revise their safety margins in light of the Fukushima accident. As an illustrative, but not representative example, in 2005 the US Energy Power Research Institute allocated about 75% of its R&D effort to innovation relevant for currently operating nuclear reactors[23].

### 2.3. Studies on the performance of nuclear reactors

As aforementioned, the literature on the performance of nuclear reactors has essentially focused on the importance of learning by doing during nuclear reactor operation, but has excluded the role of innovation. In particular, Joskow and Rozanlski (1979), and Krautmann and Solow (1988) find, using data on nuclear reactors' monthly capacity factors, learning by doing effects both in the US and in other countries. They also find that some nuclear reactor designs perform better than others; notably Pressurized Water Reactors (PWR) compared to Boiling Water Reactors (BWR), as well as smaller units compared to larger ones.

Lester and McCabe (1993) provide a more general empirical framework where nuclear reactors' performance, measured by the annual availability factor, is not only impacted by their own experience but also from experience accumulated by the reactor vendor and operator, as well as by the other units located on the same site. Their findings show that,

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[21] UNEP (2012), UNEP Yearbook 2012 – Emerging issues in our global environment (Chapter 3), available at: http://www.unep.org/yearbook/2012/pdfs/UYB_2012_CH_3.pdf

[22] World Nuclear (July 2011), Radioactive Waste Management, see: http://www.world-nuclear.org/info/inf04.html

[23] The EPRI is the main industry research organization of the US nuclear operators. The OECD/NEA (2007) reports USD 86 million of research funding for nuclear development out of which 75% (USD 66 million) can be considered as relevant to currently operating reactors. A back of the envelope estimation on the share of the EPRI in the US nuclear R&D would indicate that the EPRI represents about one third of the total US private R&D in 2005 estimated at USD 274 million by the US National Science Foundation (NSF). NSF data are available at: http://www.nsf.gov/statistics/iris/

contrary to the US nuclear industry, nuclear reactors' performance in France has benefited from reactor design standardization combined with the localization of reactors on the same sites.

In addition, part of the literature has also studied nuclear reactors' performance in terms of outage risk, using survival models (David et al., 1996; Sturm, 1995). For instance, David et al. (1996) find, using a Cox proportional hazard model, a reduction in the risk of unplanned outages following the Three Miles Island accident in the US. They interpret this result as the consequence of nuclear safety regulation reforms following the accident. Similarly, Rothwell (1996) studies the impact of organization structure on the risk of outages and shows that more horizontal management structures have a positive effect on reactors' operation duration.

A more recent focus of the literature has been on the impact of ownership (Pollitt, 1996) and incentive regulation (Zhang, 2007) on performance. Zhang studies the effect of electricity restructuring on investor-owned Nuclear Power Plants' (NPPs) performance, measured by the annual capacity factor, between 1992 and 1998. Her findings show that incentive regulation programs, as opposed to rate-of-return regulation, along with electricity restructuring at the state level, lead to a significant and positive effect on NPPs' capacity factor. Davis and Wolfram (2012) study jointly the electricity restructuring and recent divestiture of nuclear reactor operators, that followed between 1990 and 2009, using monthly data of nuclear reactors' capacity factor as a measure of performance. Their results highlight that electricity restructuring and divestiture have increased nuclear reactors' capacity factor as a result of the reduction in the number of outage days per year. A striking result from their study is that the $CO_2$ emission reductions, induced by the efficiency gain following divestiture, exceed the contribution of wind and solar energy to climate change mitigation during this period.

Finally, Hausman (2012) shows that divestiture has not only increased reactors' capacity factor but has also had a positive effect on some of the nuclear reactors' safety aspects. In particular, she finds negative, but weakly significant impacts of divestiture on the number of fires and escalated enforcement actions[24].

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[24] Escalated enforcement actions are notice of violation and penalties imposed by the US Nuclear Regulatory Commission (NRC).

# 3. Data description and stylized facts

## 3.1. Data description

This paper is based on the construction and combination of two unique datasets. The first dataset is based on the International Atomic Energy Agency (IAEA) Power Reactor Information System (PRIS) database and collects information on nuclear reactors' annual production and characteristics between 1970 and 2009. The second dataset is based on the European Patent Office (EPO) Patstat database and collects information on patents specific to nuclear power in a number of countries between 1939 and 2008. We then use these patent data to build discounted stocks of incremental innovations variables based on patent applications by national and foreign innovators.

The scope of the study encompasses all the commercial Light Water Reactors (LWRs) that have been operating between 1970 and 2008 in 12 OECD countries[25]. These reactors represent 313 GWe or 79% of the worldwide nuclear capacity during this period and 8,139 or 63% of the worldwide cumulative experience in terms of reactor-years. The choice of countries is motivated by two factors: (*i*) the need to focus on countries with commercial reactors, and (*ii*) the need to study countries with comparable intellectual property rights regimes in place throughout the period, in order to provide meaningful comparisons of the stocks of incremental innovations variables based on patent data. The choice of period arises from the availability of reactor operation data since 1970 and the lag between the application for and the publication of a patent by the end of the period. Finally, we exclude graphite reactors (e.g. Gas-Cooled Reactors (GCRs)) as these types of reactors have significant technological differences compared to LWRs, leading to different patterns both in terms of technology adoption and output performance.

### *3.1.1. Data on nuclear reactors' operation and characteristics*

As aforementioned, we follow the previous literature on nuclear power's performance (e.g. Lester and McCable, 1993) and measure nuclear reactors' performance based on annual operation data at the reactor level. These production data are collected using the IAEA PRIS

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[25] Namely, Belgium, Canada, France, Germany, Japan, South Korea, the Netherlands, Spain, Sweden, Switzerland, the United Kingdom and the US

database[26] along with information on reactors' characteristics. Information on reactors' operation allows us to distinguish between proxies of economic and safety performance.

As nuclear energy is a base-load energy source, nuclear operators have a direct incentive to minimize the time during which a nuclear reactor is off-line. Nuclear reactors' unavailability factor measures the percentage of electricity generation that has not been produced due to outages compared to the maximum potential electricity generation during one year, and provides a representative measure of economic performance. In particular, it can be argued that it provides a more precise measure than the load factor, as the latter does not account for situations where a nuclear reactor is not generating electricity due to events beyond the plant manager's control, such as grid restrictions or environmental conditions.

Moreover, while information on causes of outage at the reactor level is not available, the PRIS database permits the distinction of planned and unplanned outages. Planned outages result mostly from maintenance, refueling and inspection activities[27]. These events represent 92% of worldwide planned outages between 1970 and 2009. Unplanned outages are essentially caused by technical problems or failures which are relevant to safety and these events represent 82% of worldwide unplanned outages during the same period[28].

Note that this measure of safety may not be without limitations as it does not capture safety events related to natural hazard risk, work radiation exposure or other events related to the risk of a nuclear accident but not leading to the plant being put off-line. However, the scientific and technical literature (Eide et al., 2005; IAEA, 2005) and the industry (WANO, 2011) argue that unplanned outages remain a good proxy for safety performance, to the extent that a large proportion of nuclear reactors' core damage risk originates from unplanned outages events, such as loss of coolant or back-up generators that may gradually lead to a major nuclear accident. In the end, our empirical analysis studies three measures of performance:

- The ***Unavailability Factor*** (UF) (i.e. planned and unplanned outages) as a general measure of the plant manager's economic and safety performance;

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[26] Available at: http://pris.iaea.org/public

[27] In order to minimize the duration of planned outages, maintenance, refueling and inspection activities usually take place at the same time. For instance, while refueling without maintenance exists in the PRIS database as an outage cause, it represents less than 1% of worldwide planned outages between 1970 and 2009.

[28] The remaining 18% mostly come from load-following. Note that load-following can also be considered as a safety relevant event and, as such, is not allowed by some nuclear safety regulators (e.g. in the US and Japan).

- The ***Planned Unavailability Factor*** (PUF) as a measure economic performance more specifically; and
- The ***Unplanned Unavailability Factor*** (UUF) as a measure of safety performance.

While other statistics on reactor (or even country) safety performance are not available at the same scale, one can still further investigate how unplanned outages may relate to other safety indicators. In particular, the US Nuclear Regulation Commission uses a variety of indicators to monitor safety, among which two are available over the 1999-2008 time period at the reactor level: initiating events[29] and fires.

Figure 2.1 and Table 2.1 below present descriptive evidence and regression estimates for the relationship of UUF with these two other safety indicators and show that UUF follows closely initiating events and to a lesser extent fires. In particular, OLS estimates show that the standard errors of both variables are very low.

**Figure 2.1: Comparison of three safety indicators in the US (1999 = 100)**

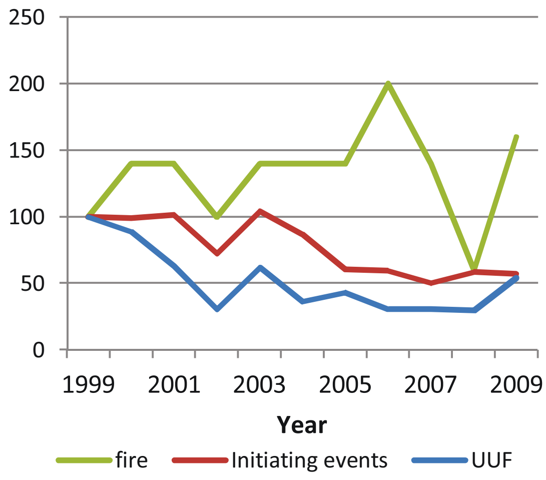

**Table 2.1: Regression estimates for the safety indicators**

| **Dependent variable** | **UUF** |
|---|---|
| Initiating events | 0.569 *** |
| | (0.019) |
| | [0.531 ; 0.608] |
| Fire | 0.416 *** |
| | (0.095) |
| | [0.228 ; 0.604] |
| **R-squared** | **0.45** |

Note: *** denotes significance at 1% level. The equation is estimated using OLS with robust standard errors in brackets.

In parallel, using the PRIS database, data are collected on nuclear reactors' technical characteristics, such as age, annual capacity (in MWe), site, and country localization, as well as the name of the operating firm. These data enable the construction of operation experience curves at the site, operator and country levels.

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[29] Initiating events are unplanned outages and, compared to the UUF, are count variables. As such, by comparing UUF and initiating events we can check how UUF, which depend both upon the number of initiating events and the length of these events, are closely related.

Operating experience curves are defined as discounted stocks (similar to equation (2.1) below) of reactor-year of operation from nuclear reactors at these three levels. Following the empirical literature (Perri, 2005), a 10% rate is applied. The rationale for discounting reactor-year of operation can be understood from practical examples. For instance, it is reasonable to expect that the later years of operation will be more relevant towards improving reactors' performance than early years. Similarly, one may also expect that if a reactor is permanently shut down, the relevance of its cumulative years of experience towards improving other reactors' performance will gradually diminish.

### *3.1.2. Data on the stocks of incremental innovations*

Data on innovations stocks are computed using patent data from the EPO Patstat database. Patent data are a common proxy for innovation activity and, compared to R&D expenditures, have the advantage of being *ex post* indicators of innovation activity, with information available at a disaggregated level. Another important advantage of nuclear patents compared to nuclear R&D expenditures is that the former is a narrower measure of incremental innovations which are more likely to be embodied within existing reactors. This characteristic of nuclear patents can be explained by the fact that intellectual property rights grant a temporary exclusion right (usually of around 20 years) to the innovator, meaning that there is little incentive to patent more radical innovations (e.g. Gen IV nuclear technologies), which will be developed after the patent protection expires.

Patents are also a rich source of information for tracking the flow of incremental innovations. In particular, patent family data are used as a measure of international technology transfer activity captured though the extension of a patent protection from one country to another (Dechezleprêtre et al., 2011). The limits of patent data as a measure of innovation activity and diffusion have been extensively discussed and a comprehensive review of the literature can be found in a recent OECD (2009) report. In particular, a patent is only one of the alternatives open to innovators to protect their innovation alongside secrecy, know-how and lead time, and the propensity to patent may vary between countries and over time.

Another potential limit of using patent data at a micro level arises from the difficulty of assigning a patent to a specific industry. In that respect, the collection of nuclear patent data is facilitated by a new patent classification (Y02E30) specific to nuclear fission reactor technology and developed by the EPO[30]. This classification enables a worldwide tracking of historical patents specific to nuclear fission reactors, with information on the application country, the innovator country of origin and the relation between priority patent applications (i.e. the first patent related to one invention) and the rest of the patent family (i.e. the extensions of the priority patent protection to other countries). Based on these data two stocks of innovations are built:

- A stock of innovations from national innovators, based on priority patent applications of innovators from country $c$;
- A stock of innovations from international technology transfers based on priority patent extended to country $c$.

The specification of the stocks of innovations variables follows the empirical literature and is based on a discounted stock of previously patented innovations in country $c$ at time $t$ as defined in equation (2.1) below ($KNOW_{c,t}$). The choice of country over firm level reflects the specificity of the nuclear industry where innovation results both from national R&D laboratories and firms. In addition, while most of the innovation effort results from nuclear reactor vendors[31], a reactor is likely to embody innovations resulting from other national and international innovators[32] during both construction and operation stages. In addition, it is important to note that collecting firm level patent data over a long time horizon in several countries would be a difficult task considering the evolving nature of firms (e.g. Joint ventures, mergers, etc.).

$$KNOW_{c,t} = \sum_{k=1}^{\infty} (1-\delta)^k Patent_{c,t-k} \tag{2.1}$$

### 3.2. Stylized facts

This section presents the trends in nuclear reactors' performance, as well as information on the evolution of the stocks of innovations variables and the nuclear industry structure. As Figure 2.2 below shows, reactors' operation performance followed a positive trend between

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[30] See : https://e-courses.epo.org/pluginfile.php/517/mod_resource/content/2/clean_energy_brochure_en.pdf

[31] Nuclear operators are marginally represented among patenting firms with the notable exception of Electricité de France (see Chapter 1).

[32] For instance, the first generation of PWRs reactors in France (CP0) were built by Framatome, but resulted essentially from technology transferred by the US firm Westinghouse.

1970 and 2008 in the 12 countries studied. Moreover, this improvement concerned both the economic (PUF) and safety (UUF) aspects of the performance of nuclear reactors.

### *3.2.1. Trend and heterogeneity between countries regarding economic and safety performance*

This positive trend in nuclear reactors' performance can be related to the increase in the number of operating reactors throughout the period, from 35 in 1970 to 323 in 2009. At the same time, one could argue that the downturn in performance (i.e. the increase in the PUF and UUF) since the early 2000s can be attributed to the aging of reactors, as for instance the average age of reactors increased from 7.6 in 1978 to 24.6 in 2008. As discussed in Section 2, part of the economic literature has explained this positive trend in performance by learning spillovers from other operating reactors, and has questioned the relation between the age and the performance of a nuclear reactor. However, for the latter, it is worth noting that the recent literature (e.g. Davis and Wolfram, 2012) does not focus on the aging effect[33] despite its policy relevance for countries with an aging nuclear fleet.

Beyond this overall trend in nuclear reactors' performance, it is important to stress that national reactors' performances are heterogeneous. As Tables 2.2 and 2.3 hereafter illustrate, reactor economic and safety performance differ among countries and reactor types. In particular, it is worth noting that South Korea and Switzerland appear to achieve high economic and safety performance, while Canada and the United Kingdom rank at the bottom for both measures of performance. An exception can be found in Japan where nuclear reactors show high safety but low economic performance.

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[33] The recent literature (Davis and Wolfman, 2012; Hausman, 2011) controls for the age of reactors with the use of age fixed-effects but does not report their values. An exception can be found in Zhang (2007) who includes reactors' age with a quadratic term. However, this study has a different scope as it aggregates a capacity weighted average age of reactors located on the same site.

Figure 2.2:Nuclear reactors' planned (PUF) and unplanned (UUF) unavailability factors and number of operating reactors between 1970 and 2009

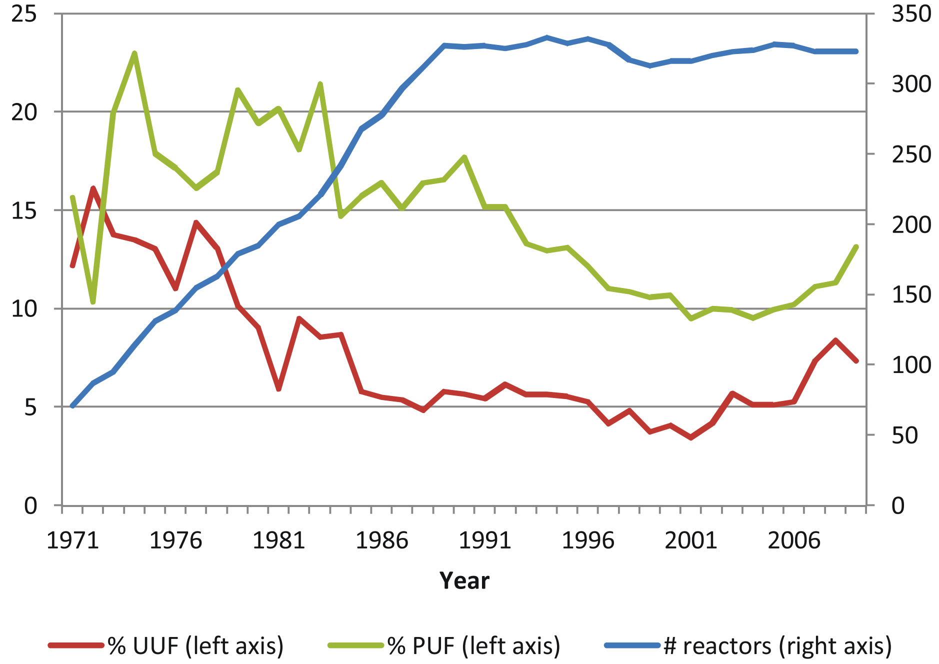

Figure 2.3: Distribution of nuclear reactors age between 1978 and 2008 (Total 1978 = 163 reactors, Total 2008 = 323 reactors)

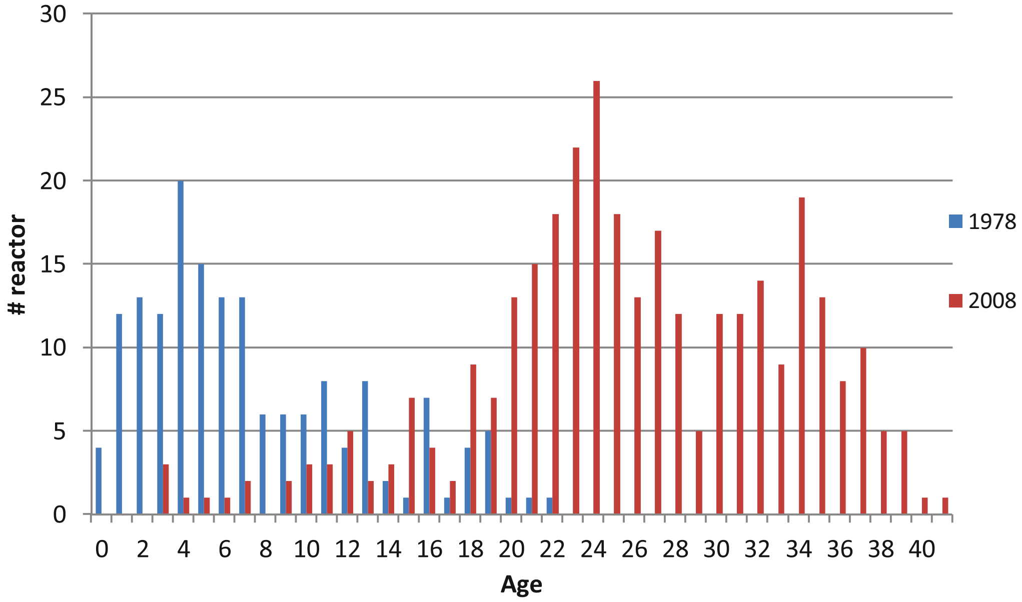

Table 2.2: Average UUF and PUF between countries (1970 -2009)

| **Country** | **UUF (in %)** | | **PUF (in %)** | | **Reactor-** |
|---|---|---|---|---|---|
| | **Mean** | **Std. Dev.** | **Mean** | **Std. Dev.** | **Years** |
| Belgium | 4.59 | 9.55 | 11.89 | 10.85 | 222 |
| Canada | 14.07 | 18.58 | 11.12 | 16.14 | 574 |
| France | 8.22 | 10.08 | 13.94 | 9.95 | 1,581 |
| Germany | 6.77 | 16.78 | 13.56 | 14.29 | 630 |
| Japan | 4.73 | 13.17 | 23.89 | 19.76 | 1,416 |
| South Korea | 1.40 | 3.40 | 11.46 | 8.22 | 333 |
| Netherlands | 3.85 | 8.00 | 11.38 | 7.08 | 62 |
| Spain | 5.60 | 10.26 | 12.56 | 11.17 | 267 |
| Sweden | 8.47 | 11.48 | 12.35 | 10.63 | 355 |
| Switzerland | 1.76 | 4.71 | 11.03 | 5.68 | 174 |
| United Kingdom | 9.14 | 13.22 | 16.70 | 16.35 | 1,122 |
| United States | 7.08 | 14.13 | 14.16 | 15.60 | 3,374 |
| **Average** | **7.19** | **13.41** | **15.24** | **15.34** | **10,110** |

Table 2.2 (above) illustrates that countries differ in experience, measured in terms of reactor-years of operation. In that respect, national economic and safety performance do not appear to be correlated with their experience (see correlation matrix in Appendix 2) as, for instance the US with ten times more reactor-years of experience compared to South Korea, achieves lower performance than the latter. These descriptive facts provide the insight that factors other than experience, such as technical characteristics, market structure considerations and the stocks of incremental innovations, may contribute to improving or reducing economic and safety performance.

In particular, it has been argued (Pollitt, 1996), that part of the improvement in the performance of nuclear reactors may have come from organizational changes within national nuclear industries. This means that existing studies on the performance of nuclear reactors, which focus on reactors located in the same country, may have confused learning by doing with organizational changes due to the timing of nuclear construction programs, leading to collinearity concerns between experience and time. This further strengthens the choice of our empirical framework where we look at a variety of countries with different timing for NPP construction programs.

Differences in terms of market structure are described in Table 2.3 (below). As the table shows, the industrial structure between countries is characterized by significant differences in terms of average reactor capacity, the number of operating reactors per site and per operator. For instance, while South Korean nuclear reactors are operated by a single operator on large sites, the US is characterized by few reactors per site and a multitude of operators. As aforementioned, one can argue that these market structure considerations are not without incidence on performance both directly, as a source of operating efficiency, and indirectly as reactors may benefit from learning opportunities from the experience of other nuclear reactors operated by the same operator or located on the same site.

**Table 2.3: Industrial structure between countries in 2008**

| Country | Mean Capacity (in MWe) | Reactors | Reactors per site | Reactors per operator |
|---|---|---|---|---|
| Belgium | 832 | 7 | 3.57 | 7 |
| Canada | 698.7 | 18 | 5.0 | 7.7 |
| France | 1088.4 | 58 | 3.5 | 58 |
| Germany | 1204.1 | 17 | 1.6 | 3.1 |
| Japan | 859.6 | 55 | 4.1 | 9.4 |
| Korea | 882.4 | 20 | 5.2 | 20 |
| Netherlands | 482.0 | 1 | 1 | 1 |
| Spain | 931.3 | 8 | 1.5 | 2.5 |
| Sweden | 899.6 | 10 | 3.4 | 3.4 |
| Switzerland | 644.0 | 5 | 1.4 | 1.4 |
| United Kingdom | 531.4 | 19 | 2.4 | 15.0 |
| United States | 967.5 | 104 | 1.8 | 12.7 |
| **Average** | **924.8** | **322** | **2.2** | **5.0** |

### *3.2.2. National versus foreign origin of innovation*

In parallel to market structure considerations, Figures 2.4 and 2.5 (below) present trends in countries stocks of incremental innovations between 1939 and 2008. Figure 2.4 presents the trends in national stocks of incremental innovations and Figure 2.5 shows the trends in the stocks of incremental innovations originating from international technology transfers. It is important to stress that, as information on the use of innovation in a specific reactor is not available, this measure of innovation stocks reflects knowledge capabilities in a country originating from national innovators and international technology transfers respectively. These figures are computed using a 10% knowledge depreciation rate, in accordance with the literature (Perri, 2005). Both figures illustrate that the stocks of incremental innovations in nuclear reactor technologies have been accumulated since the mid-1950s and have been, for most of the countries, decreasing since the early 1990s[34].

Figure 2.4 highlights that the US, Germany, France and Japan have large national stocks of knowledge over the whole period while, several counties such as Korea, Spain or Sweden have relatively low national stocks of knowledge. However, Figure 2.5 shows that this pattern is counter-balanced by the fact that the latter countries have benefited from large flows of international technology transfers, resulting in more homogenous trends in the stocks of incremental innovations generated by international technology transfers.

The latter result reflects the development of the nuclear industry where many new-entrant countries have benefited from large programs by receiving access to technologies developed in more technologically advanced countries (DeLeon, 1979). Similarly, it highlights that the empirical analysis of nuclear reactors' performance needs to take these international technology transfers explicitly into account when analyzing the impact of innovation on performance. Finally, the decline for most countries in both stocks of incremental innovations since the early 1990s needs to be viewed from the perspective of a recent slow decline in economic and safety performance (Figure 2.2). Hence, while the existing literature essentially points out that this performance trend can be attributed to aging reactors, one could argue that not taking innovation into account may lead to overestimating the impact of this aging effect.

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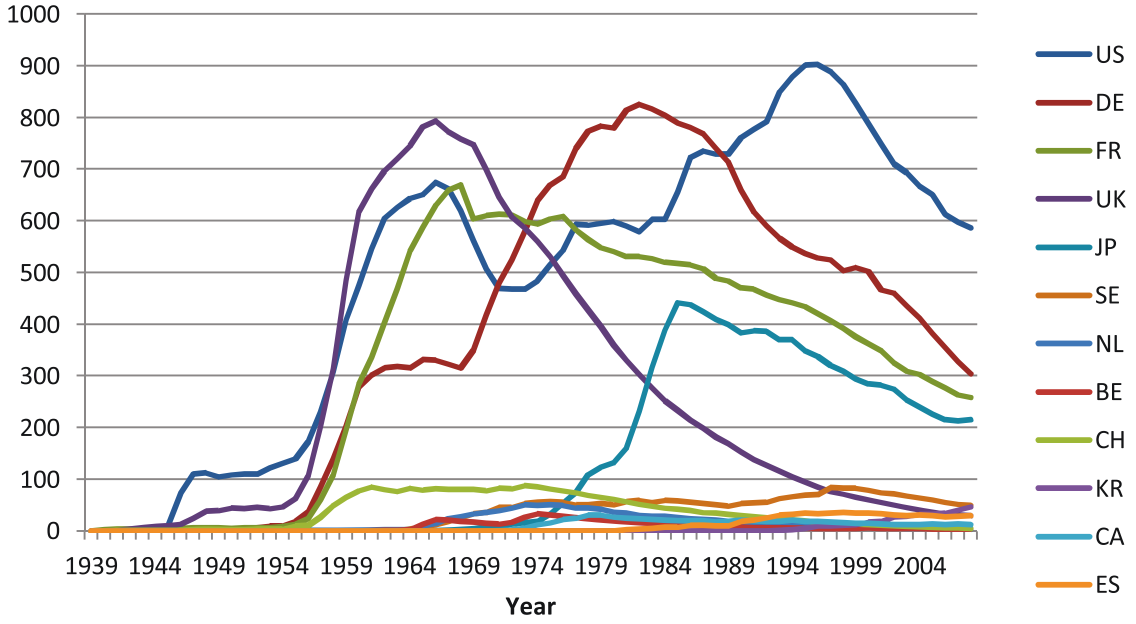
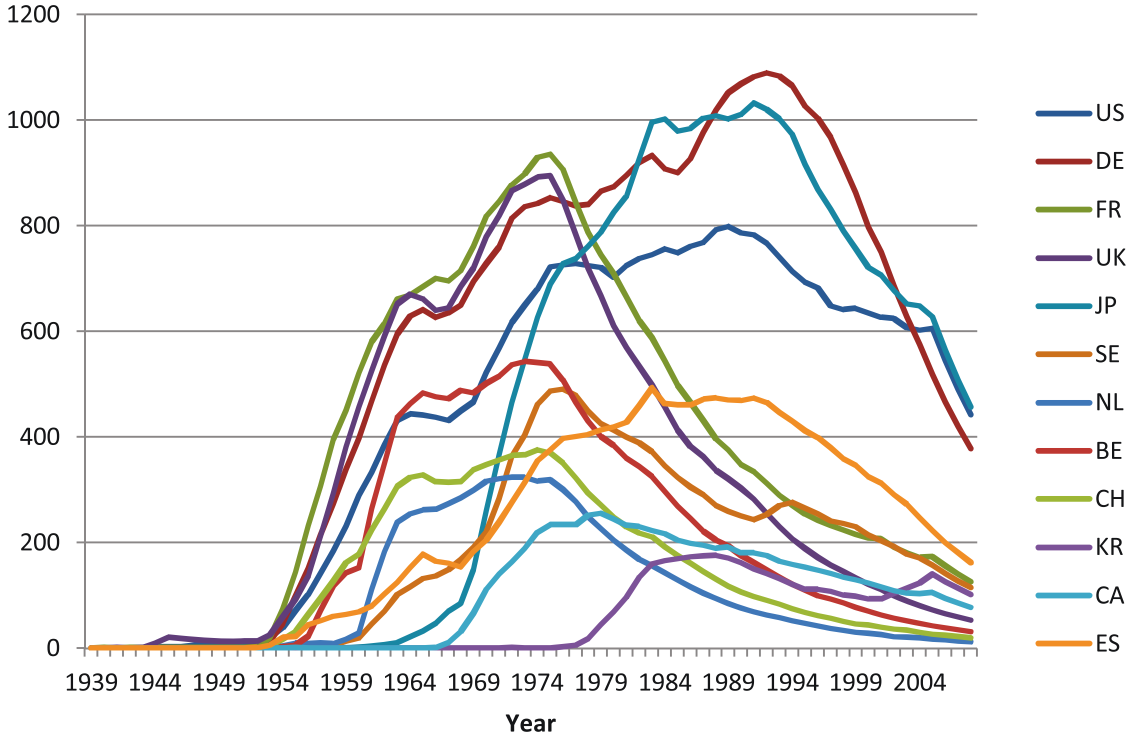
[34] This decrease in the stocks of knowledge can be essentially explained by the large decline in national public R&D expenditures and reactor construction in the innovating countries and abroad (Chapter 1).

## Figure 2.4: National stocks of incremental innovations in nuclear reactors technologies



## Figure 2.5: Stocks of foreign incremental innovations in nuclear reactors technologies



# 4. Empirical strategy

An important advantage of studying nuclear reactors' performance compared to other industries arises from the base-load nature of nuclear power generation. From an econometric point of view, this characteristic has the attribute that changes in nuclear reactors' performance will not be confounded with relative changes in demand. Similarly, a GWh of nuclear electricity is a homogenous good and is not affected by quality considerations that would have to be controlled for in other industrial sectors.

At the same time this paper is, to the best of our knowledge, the first to provide a comprehensive study of nuclear reactor performance in a panel model across different countries[35]. This level of analysis has the advantage of enabling us to explore the extent to which heterogeneity between countries characteristics may play a role in explained differences in economic (PUF) and safety (UUF) performance. More importantly, the differences between national nuclear programs' start dates have led to a large variation in the start of nuclear reactors' construction meaning that one can differentiate between learning by doing and time specific effects. This is particularly important as the technical performance of nuclear reactors has been reported to be poor at the beginning of the period studied (Pollitt, 1995 and 1996), and its improvement may have resulted both from traditional learning by doing and organizational changes, the latter being captured in the time control variables further presented below.

Taking these characteristics of nuclear power into account, our empirical strategy follows classical fixed-effect linear panel models where for each reactor $i$ at year $t$ the following model is defined:

$$Y_{ict} = \beta_0 + \beta_1 X_{it} + \beta_2 V_{ct} + \beta_3 W_{it} + \alpha_i + \eta_t + t * \varphi_c + \varepsilon_{it} \qquad (2.2)$$

Where $\beta_1$ and $\beta_2$ are, respectively, vectors of coefficients associated with vectors of time varying independent variables $X_{it}$ and $V_{ct}$ – associated with the learning by doing opportunities and knowledge capabilities, respectively – and further presented below. $\beta_3$ is a

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[35] Lester and McCable (1993) study nuclear reactors' performance in the US and France, but run the regression for the two countries separately. More importantly, Lester and McCable do not use reactor fixed-effects to control for unobserved heterogeneity between nuclear reactors (e.g. labour cost, safety regulation, etc.).

vector of coefficients associated with a vector of control variables $W_{it}$, and $\varepsilon_{it}$ is the error term and is assumed to be identically and independently distributed such as $\varepsilon_{it} \sim N(0, \sigma_{\varepsilon}^{2})$.

Fixed-effects are introduced to control for time fixed effects ($\eta_t$). $\alpha_i$ is a time invariant random variable to control for reactors' unobservable fixed-effects such as labour input, vintage, plant type, vendor and other unobserved time-invariant technical characteristics. Finally, we apply a log-linear transformation in order to derive elasticities for the variable of interest directly (i.e. excluding control variable for the industrial structure).

The choice of the Fixed-Effect (FE) estimator depends upon whether $X_{it}$ is correlated with the error term. If $X_{it}$ is correlated with $\varepsilon_{it}$, the FE estimator needs to be preferred over Random-Effect (RE) estimator in order to regain consistency. A robust version of the Hausman test[36] is performed and rejects the null hypothesis that the RE estimator is consistent at the 1% confidence level for the different performance indicators. This model specification is also consistent with the nature of nuclear power generation cost which is characterized by the predominance of initial construction costs over operation and maintenance costs[37]. However, FE estimator precludes the estimation of the effect of time invariant independent variables, leading to some loss of efficiency, in particular the country where a reactor is located. To mitigate for this effect, we introduce country-specific time trends ($t * \varphi_c$) in equation (2.1)[38] to control for changes in national nuclear safety regulation and other factors – such as organizational changes – impacting the operation decisions of plants' operators.

While the overall performance of nuclear reactors, measured by outages (UF) can be estimated directly, the distinction between planned (PUF) and unplanned outages (UUF), reflecting economic and safety performance, respectively, may give rise to endogeneity concerns owing to simultaneity between the two. These concerns may take place at two levels. Firstly, planned and unplanned outages are to some extent substitutes as, for instance, the duration of planned outage reduces the time within which unplanned outages may occur. Secondly, planned outages may reduce the probability of unplanned outages, as maintenance may diminish the probability of technical failures and *vice versa*.

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[36] Using the xtoverid command on Stata, see: http://ideas.repec.org/c/boc/bocode/s456779.html

[37] Construction cost typically covers around 60% of nuclear power levelized cost. In addition, Davis and Wolfram (2012) show that for the US nuclear plants, operation and maintenance costs are essentially proportional to generation.

[38] In particular, comparison between regression estimates with and without country-specific time trends show that this specification allows us to capture most of the between groups variation.

To address this endogeneity concern, one could use an Instrument Variable (IV) approach and consider using the lagged values of planned and unplanned outages as instruments of the respective endogenous variables. However, owing to serial correlation, these instruments $\boldsymbol{Z}$ would be invalid, meaning that $Cov(\boldsymbol{Z}, \varepsilon) \neq 0$. Another empirical strategy would consist of using the first difference of the lagged values as instruments. This strategy offers two advantages. Firstly, by taking the first difference, we remove the serial correlation problem and the concerns regarding the validity of the instruments. Secondly, one can argue that the current level of (planned / unplanned) outage may respond to previous changes in (planned / unplanned) outage level.  As the IV approach will lead to a loss in efficiency if the instruments are weakly correlated with the endogenous variables, we also report a range of statistical tests for weak identification and test the overidentifying restriction using the Hansen test.

In order to test for overidentifying restriction, we use the first two lagged of the first difference of the endogenous as specified according to equation (2.3) below, and a symmetric model specification is used to estimate the first stage of the unplanned outage regression. Equations (2.2) and (2.3) are estimated using the General Method of Moments (GMM) estimator.

$$\begin{aligned} UUF_{i,t} = \gamma_0 + \gamma_1 \Delta UUF_{i,t-1} + \gamma_2 \Delta UUF_{i,t-2} + \gamma_3 X_{i,t} + \gamma_4 V_{c,t} + \gamma_5 W_{i,t} + \alpha_i + \eta_t \\ + t * \varphi_c + u_{it} \end{aligned} \tag{2.3}$$

The empirical model introduces four different categories of independent variables: (*i*) reactors' technical characteristics, (*ii*) learning opportunities from other reactors, (*iii*) the stocks of incremental innovations of the nuclear industry induced by national innovation effort and international technology transfers, and (*iv*) control variables dealing essentially with structural changes.

### 4.1. Technical characteristics

Technical characteristics include the age ($AGE_{it}$ and $AGE2_{it}$) and capacity ($MWe_{it}$). Following the existing literature (Joskow and Rozanlski, 1979; Zhang, 2007) a quadratic term is introduced for age, as learning by doing at the reactor level may at some point be counter-balanced by an aging effect. The expected sign of the explanatory variable for reactor capacity is ambiguous: on the one hand larger reactors may benefit from economies of scale;

on the other hand, it is often reported that larger reactors are more complex to operate, leading to lower performance than smaller reactors.

## 4.2. Learning by doing spillovers

Learning spillovers may be facilitated through different channels: the localization of reactors on the same site ($LEARNSITE_{i,t-1}$), their operation by the same operator ($LEARNOP_{i,t-1}$) and finally their localization in the same country ($LEARNCNTRY_{i,t-1}$). Following Irwin and Klenow's (1994) study of the learning spillovers in the semiconductor industry, we define each learning curve as the difference between the experience accumulated at the level studied and the level immediately below. For instance, $INTRAFIRM_{i,t-1}$ is defined as the operating experience of reactors operated by the same operator but located on a different site, and $INTERFIRM_{i,t-1}$ as the operating experience of reactors located in the same country but operated by a different operator. In that respect, these learning spillovers should be interpreted as evidence of intra-site, intra-firm and inter-firm learning spillovers respectively. This measure of learning spillovers limits the risk of multi-collinearity and can be formalized in equations (2.4) and (2.5) as follows:

$$X_{it} = \beta_1 * \left(LEARNCNTRY_{i,t} - LEARNOP_{i,t}\right) + \beta_2 * \left(LEARNOP_{i,t} - LEARNSITE_{i,t}\right) + \beta_3 * (LEARNSITE_{i,t} - Age_{i,t}) \tag{2.4}$$

$$X_{it} = \beta_1 * INTERFIRM_{i,t} + \beta_2 * INTERSITE_{i,t} + \beta_3 * INTRASITE_{i,t} \tag{2.5}$$

## 4.3. Stocks of incremental innovations

Based on a unique dataset on nuclear reactor patents described in Section 3.1.2, two stocks of incremental innovations are built: (*i*) a stock of incremental innovations for national innovation ($NATKNOW_{c,t-1}$) in country $c$, based on priority patent applications and; (*ii*) a stock of incremental innovations for international technology transfers ($INTKNOW_{c,t-1}$), based on priority patent extensions from another country in country $c$. A one year lag is introduced to account for the delay between the patent application and the availability of the new innovation. As previously mentioned, these stocks of innovation reflect knowledge capabilities available in one country from national innovators and international technology transfers, respectively.

### 4.4. Control variables

We also introduce a set of controls variable to account for structural changes as well as differences between countries. We consider two potential structural breaks following the TMI and Chernobyl accidents. Note that these variables allow us to test for learning by accident (Davis et al., 1996). We further control for structural differences between countries using country specific time trends and controlling for the share of nuclear in the electricity mix, as one might argue that countries with a high share of nuclear power might not only use nuclear for base-load demand.

# 5. Results and discussion

Tables 2.5 presents the summary statistics of the data used (correlation matrix can be found in Appendix 2) and Tables 2.6, 2.7 and 2.8 present, respectively, the results for the three measures of nuclear reactors' performance using fixed-effects estimators. Note that a positive coefficient needs to be understood as a negative impact on performance. For each of the three measures of reactors' performance, different model specifications are presented and show the robustness of the estimates to the inclusion of explanatory variables. This is an important robustness check considering that many of the explanatory variables are stock variables leading to collinearity concerns. As a further robustness check we also try different values for the discount factor $\delta$ (5% and 15%)[39].

Concerning the treatment of endogeneity between planned and unplanned outages, the results from Tables 2.7 and 2.8 show that our instruments are strong over a range of statistical tests. For instance, the F statistic is above 200 and 30 for the unplanned and planned outages, respectively[40], and the size distortion based on the Kleibergen statistic and the Stock and Yogo (2005) critical values is systematically below 10%. In addition, the Hansen J statistic indicates that we pass the overidentification test for instrument validity for the two models.

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[39] Recall that $\delta$ measures knowledge depreciation. These results can be found in Table 2.10 in Appendix 2.

[40] One would expect the F statistic to be above 20 for instruments not to be weak.

Our results indicate the central role played by learning opportunities and innovation in improving nuclear reactors' economic and safety performance, while at the same time highlighting the differences between economic and safety performance. To facilitate the discussion of the results, we will focus respectively on learning opportunities and incremental innovation.

**Table 2.4: Summary Statistics**

| VARIABLES | Mean | Std. Dev. | Min | Max |
|---|---|---|---|---|
| $UF$ | 21.75 | 19.00 | 0 | 100 |
| $PUF$ | 15.03 | 14.98 | 0 | 100 |
| $UUF$ | 6.72 | 13.00 | 0 | 100 |
| $AGE$ | 14.57 | 8.91 | 1 | 40 |
| $SHARE$ | 31.02 | 21.67 | 0.13 | 79.07 |
| $SIZE$ | 850.51 | 290.57 | 10 | 1,500 |
| $NATKNOW$ | 431.99 | 285.43 | 0 | 902.39 |
| $INTKNOW$ | 541.27 | 280.92 | 12.61 | 1,089.58 |
| $INTRASITE$ | 10.63 | 11.80 | 0 | 60.04 |
| $INTERSITE$ | 71.11 | 117.51 | 0 | 461.81 |
| $INTERFIRM$ | 283.76 | 296.79 | 0 | 892.18 |

Note that while variables in market structure considerations are mostly introduced as control variables, the results still provide insights into the effect of nuclear reactor size on performance. We find diseconomies of scale[41] for safety performance, and no significant impact of size on economic performance. This result is in line with the existing literature (Lester and McCable, 1993), where diseconomies of scale are found for the US and the French reactors. However, they highlight the fact that the size of nuclear reactors essentially impacts safety performance, which can be explained by greater complexity of operating larger reactors.

In addition, while our results show that reactor size has a negative impact on safety performance, one might expect that this effect could be stronger for future reactor technologies. For instance, it has been reported (Ingersoll, 2009) that third generation Small and Medium Reactors (SMRs) present many benefits in terms of core damage safety margins due, for instance, to simpler designs and faster heat removal decay.

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[41] Note that we also tested the regressions, by introducing a quadratic term for MWe, but rejected the null hypothesis that MWe should be introduced with a quadratic term.

**Table 2.5: Coefficients estimate for the Unavailability Factor regression**

| VARIABLES | (1)<br>$ln.UF$ | (2)<br>$ln.UF$ | (3)<br>$ln.UF$ | (4)<br>$ln.UF$ | (5)<br>$ln.UF$ | (6)<br>$ln.UF$ |
|---|---|---|---|---|---|---|
| $ln.SHARE_{c,t}$ | -.528*** | -.505*** | -.445*** | -.426*** | -.566*** | -.426*** |
|  | (.151) | (.111) | (.108) | (.111) | (.122) | (.112) |
| $ln.SIZE_{i,t}$ | .0714 | -.355 | -.345 | -.584 | -.561 | -.585 |
|  | (.319) | (.481) | (.483) | (.487) | (.486) | (.487) |
| $ln.AGE_{i,t}$ | -1.900*** | -1.917*** | -1.910*** | -1.773*** | -1.777*** | -1.790*** |
|  | (.216) | (.279) | (.279) | (.280) | (.282) | (.282) |
| $ln.AGE2_{i,t}$ | .610*** | .614*** | .612*** | .594*** | .598*** | .599*** |
|  | (.086) | (.107) | (.106) | (.106) | (.107) | (.107) |
| $ln.NATKNOW_{c,t-1}$ |  | -.236*** | -.195*** | -.180*** |  | -.150* |
|  |  | (.055) | (.059) | (.057) |  | (.091) |
| $ln.INTKNOW_{c,t-1}$ |  |  | -.352*** | -.375*** |  | -.378*** |
|  |  |  | (.121) | (.114) |  | (.112) |
| $ln.INTRASITE_{i,t-1}$ |  |  |  | -.166*** | -.165*** | -.166*** |
|  |  |  |  | (.031) | (.032) | (.031) |
| $ln.INTERSITE_{i,t-1}$ |  |  |  | -.0115 | -.0270 | -.0124 |
|  |  |  |  | (.028) | (.029) | (.028) |
| $ln.INTERFIRM_{i,t-1}$ |  |  |  | -.295* | -.337* | -.289* |
|  |  |  |  | (.165) | (.204) | (.165) |
| $ln.AGE_{i,t} * ln.NATKNOW_{c,t-1}$ |  |  |  |  |  | -.0161 |
|  |  |  |  |  |  | (.047) |
| $CONSTANT$ | 111.03*** | 84.82* | 98.01** | 48.63 | 35.20 | 51.59 |
|  | (48.31) | (49.01) | (48.85) | (56.27) | (6.47) | (56.05) |
| Control variables | Yes | Yes | Yes | Yes | Yes | Yes |
| Time FE | Yes | Yes | Yes | Yes | Yes | Yes |
| Trend * Country | Yes | Yes | Yes | Yes | Yes | Yes |
| Observations | 8,139 | 8,139 | 8,139 | 8,13 | 8,13 | 8,13 |
| Number of reactors | 349 | 343 | 343 | 343 | 343 | 343 |
| Adjusted R-squared | .179 | .185 | .186 | .189 | .185 | .189 |

Note: *** p<0.01, ** p<0.05, * p<0.1. Robust standard errors in brackets.

Table 2.6: Coefficients estimate for the Unplanned Unavailability Factor regression

| VARIABLES | (7)<br>$ln.UUF$ | (8)<br>$ln.UUF$ | (9)<br>$ln.UUF$ | (10)<br>$ln.UUF$ | (11)<br>$ln.UUF$ |
|---|---|---|---|---|---|
| $ln.SIZE_{i,t-1}$ | 1.398*** | 1.350** | 1.349** | 1.380** | 1.421*** |
| | (0.536) | (0.533) | (0.532) | (0.538) | (0.542) |
| $ln.PUF_{i,t}$ | 0.0622 | 0.0622 | 0.0627 | 0.0623 | 0.0621 |
| | (0.0466) | (0.0465) | (0.0465) | (0.0464) | (0.0465) |
| $ln.AGE_{i,t}$ | -1.328*** | -1.337*** | -1.344*** | -1.142** | -1.130** |
| | (0.498) | (0.496) | (0.496) | (0.501) | (0.502) |
| $ln.AGE2_{i,t}$ | 0.345** | 0.346** | 0.348** | 0.315* | 0.312* |
| | (0.168) | (0.168) | (0.168) | (0.168) | (0.169) |
| $ln.NATKNOW_{c,t-1}$ | | -0.243*** | -0.225*** | -0.238*** | |
| | | (0.0709) | (0.0718) | (0.0720) | |
| $ln.INTKNOW_{c,t-1}$ | | | -0.166 | -0.178 | |
| | | | (0.151) | (0.151) | |
| $ln.INTRASITE_{i,t-1}$ | | | | -0.114*** | -0.115*** |
| | | | | (0.0435) | (0.0436) |
| $ln.INTERSITE_{i,t-1}$ | | | | -0.0243 | -0.0352 |
| | | | | (0.0360) | (0.0363) |
| $ln.INTERFIRM_{i,t-1}$ | | | | 0.577*** | 0.511*** |
| | | | | (0.168) | (0.176) |
| $TMI$ | -0.342 | -0.304 | -0.342 | -0.760*** | -0.701** |
| | (0.248) | (0.248) | (0.250) | (0.287) | (0.287) |
| $CHERNO$ | -0.898 | -0.902 | -1.063* | -1.459** | -1.227** |
| | (0.583) | (0.582) | (0.595) | (0.619) | (0.607) |
| Instruments | $\Delta lnPUF_{i,t-1}$<br>$\Delta lnPUF_{i,t-2}$ | $\Delta lnPUF_{i,t-1}$<br>$\Delta lnPUF_{i,t-2}$ | $\Delta lnPUF_{i,t-1}$<br>$\Delta lnPUF_{i,t-2}$ | $\Delta lnPUF_{i,t-1}$<br>$\Delta lnPUF_{i,t-2}$ | $\Delta lnPUF_{i,t-1}$<br>$\Delta lnPUF_{i,t-2}$ |
| Hansen J P-value | 0.867 | 0.864 | 0.8615 | 0.884 | 0.888 |
| Size distortion | <10 % | <10 % | <10 % | <10 % | <10 % |
| Shea Part $R^2$ | .058 | .058 | .058 | .059 | .059 |
| F stat | 204.00 | 204.12 | 204.65 | 205.38 | 205.04 |
| Control variables, Time FE & country time trend | Yes | Yes | Yes | Yes | Yes |
| Observations | 7,431 | 7,431 | 7,431 | 7,428 | 7,428 |
| # of reactor | 335 | 335 | 335 | 335 | 335 |
| Adjusted R-squared | 0.040 | 0.042 | 0.042 | 0.045 | 0.043 |

Note: *** p<0.01, ** p<0.05, * p<0.1. Robust standard errors in brackets.

### Table 2.7: Coefficients estimate for the Planned Unavailability Factor regression

| VARIABLES | **(12)**<br>$ln.PUF$ | **(13)**<br>$ln.PUF$ | **(14)**<br>$ln.PUF$ | **(15)**<br>$ln.PUF$ | **(16)**<br>$ln.PUF$ |
|---|---|---|---|---|---|
| $ln.SIZE_{i,t-1}$ | -0.282 | -0.314 | -0.321 | -0.475 | -0.448 |
| | (0.623) | (0.620) | (0.618) | (0.624) | (0.627) |
| $ln.UUF_{i,t}$ | -0.487*** | -0.491*** | -0.490*** | -0.488*** | -0.484*** |
| | (0.126) | (0.126) | (0.126) | (0.127) | (0.127) |
| $ln.AGE_{i,t}$ | -2.588*** | -2.601*** | -2.621*** | -2.529*** | -2.505*** |
| | (0.598) | (0.599) | (0.599) | (0.596) | (0.595) |
| $ln.AGE2_{i,t}$ | 0.872*** | 0.874*** | 0.881*** | 0.863*** | 0.855*** |
| | (0.200) | (0.200) | (0.200) | (0.200) | (0.200) |
| $ln.NATKNOW_{c,t-1}$ | | -0.187** | -0.140* | -0.128* | |
| | | (0.0742) | (0.0743) | (0.0749) | |
| $ln.INTKNOW_{c,t-1}$ | | | -0.452*** | -0.409** | |
| | | | (0.164) | (0.165) | |
| $ln.INTRASITE_{i,t-1}$ | | | | -0.111** | -0.110** |
| | | | | (0.0523) | (0.0524) |
| $ln.INTERSITE_{i,t-1}$ | | | | -0.0678 | -0.0826** |
| | | | | (0.0414) | (0.0413) |
| $ln.INTERFIRM_{i,t-1}$ | | | | -0.343* | -0.404** |
| | | | | (0.179) | (0.183) |
| $TMI$ | -1.079*** | -1.051*** | -1.156*** | -0.801** | -0.678** |
| | (0.274) | (0.273) | (0.276) | (0.331) | (0.329) |
| $CHERNO$ | -3.115*** | -3.122*** | -3.563*** | -3.140*** | -2.686*** |
| | (0.684) | (0.685) | (0.700) | (0.737) | (0.718) |
| Instruments | $\Delta lnUUF_{i,t-1}$<br>$\Delta lnUUF_{i,t-2}$ | $\Delta lnUUF_{i,t-1}$<br>$\Delta lnUUF_{i,t-2}$ | $\Delta lnUUF_{i,t-1}$<br>$\Delta lnUUF_{i,t-2}$ | $\Delta lnUUF_{i,t-1}$<br>$\Delta lnUUF_{i,t-2}$ | $\Delta lnUUF_{i,t-1}$<br>$\Delta lnUUF_{i,t-2}$ |
| Hansen J p-value | 0,32 | 0.311 | 0.317 | 0.322 | 0.305 |
| Size distortion | <10 % | <10 % | <10 % | <10 % | <10 % |
| Shea Part $R^2$ | .014 | .0140 | .0140 | .0139 | .0140 |
| F stat | 35.76 | 35.43 | 35.49 | 35.10 | 35.46 |
| Control variables, Time FE & country time trend | Yes | Yes | Yes | Yes | Yes |
| Observations | 7,431 | 7,431 | 7,431 | 7,428 | 7,428 |
| # of reactor | 335 | 335 | 335 | 335 | 335 |
| Adjusted R-squared | -0.039 | -0.040 | -0.039 | -0.037 | -0.037 |

Note: *** p<0.01, ** p<0.05, * p<0.1. Robust standard errors in brackets.

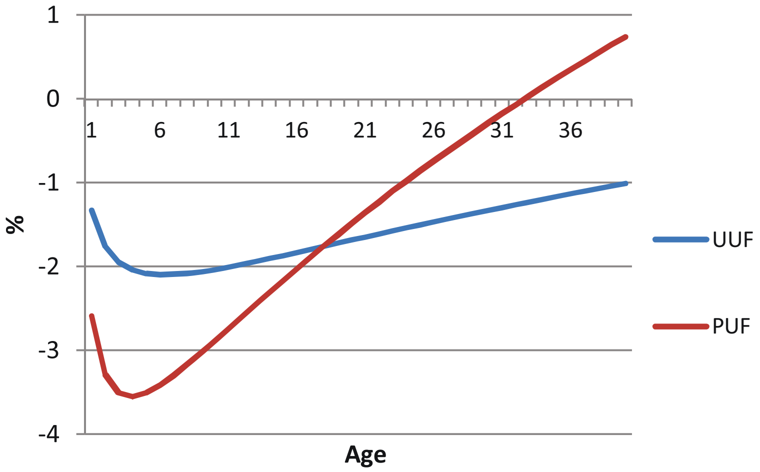
### 5.1. Learning opportunities

The results present robust evidence of the existence of learning by doing at the reactor level. While this result is consistent with the hypothesis tested in the existing literature (e.g. Lester and McCabe, 1993), this paper is the first to provide robust empirical evidence of this feature on reactors' performance. More importantly, we find that learning by doing is gradually outweighed by an aging effect which takes place at different stages of the nuclear reactors' life-span.

For illustrative purposes, Figure 2.6 (below) plots the cumulative learning by doing for economic and safety performance. The figure highlights that the magnitude of learning by doing is limited and concentrated in the first years of operation. We find that safety and economic performance peak after 7 and 5 years of operation, respectively. However, the impact of the aging effect also differs between economic and safety performance. Safety performance deteriorates at a much slower rate than economic performance, meaning that the cumulative learning remains positive up to 40 years of operation, which is the standard design lifetime of nuclear reactors.

Conversely, the cumulative learning of economic performance deteriorates more quickly, leading to the learning by doing cumulative gains being outweighed by the aging effect after approximately 30 years of operation. However, it is important to note that this result should not be interpreted as a decline in the competitiveness of these reactors. Rather, as nuclear reactors have finished paying back fixed costs, their competitiveness is likely to increase despite lower generation. In addition, one can hypothesize that plant operators might plan more for unplanned outages at this stage.

**Figure 2.6: Cumulative learning curves according to estimates from reg.10 and14**



In terms of learning spillovers, we find that learning spillovers are essentially concentrated at the site level and impact both economic and safety performance. Conversely, we find limited evidence of spillovers from reactors operated by the same operator but located on different sites. These two results stress the importance of the site management in improving performance. In addition, these results suggest that the benefit of a concentrated nuclear industry – such as France – is not due to operating a large number of reactors but to the location of multiple reactors on the same site.

Conversely, we find contrasting evidence for the existence of learning spillovers among firms. On the one hand, we find that economic performance benefits from inter firm spillovers, which reflects the existence of nuclear operators' associations (such as the INPO in the US) that play a role in sharing experience among plants' operators. On the other hand, we find that inter firm spillovers have a negative effect on safety performance. While this result may at first appear puzzling, it could capture the fact that the existence of several nuclear operators has an adverse effect on safety.

### 5.2. Stocks of incremental innovations

The results concerning the role of incremental innovation - measured in terms of the discounted stocks of patents – are the most important results of this study. We show that incremental innovations do not only play a role in reducing reactor construction cost (Jamasb, 2007), but also have an impact on both the economic and safety performance of existing reactors. In that respect, it highlights that the impact of innovation effort on existing reactors' economic and safety performance needs to be taken into account when assessing the social return of public R&D expenditures in the nuclear sector.

We find that national innovation has a positive and significant impact on both economic and safety performance. These estimates use a log-log transformation and can directly be read in terms of elasticities. For instance, according to regression (6) in Table 2.6, a 10% increase in the national stock of innovation is estimated to lead to a 1.5% reduction in the share of nuclear reactors' outages. It is also worth noting that the effect of the national stock of innovation is stable over both the economic and safety dimensions of reactors' outages. However, we do not find evidence of an interaction effect between learning by doing and the level of national innovation, or of an interaction effect between national and foreign innovations (not reported in the tables)

However, international technology transfers have a different impact on nuclear reactors as they are found to have a significant impact at the 5% confidence level on economic performance (i.e. planned outages), but not on safety performance (i.e. unplanned outages). In particular, we find that international technology transfers tend to have a stronger impact than national innovations with elasticities of -0.128 and -0.409, respectively, in regression (15) (Table 2.8). This result is important from a technology policy point of view, as it illustrates that nuclear reactors' economic performance is largely driven by these international technology transfers. This characteristic of the nuclear industry innovation system can be explained by the network effect associated with technology adoption in the nuclear industry (Cowan, 1990), where first movers (i.e. the US, then France, Germany and Japan) have incentives to transfer their technologies in order to benefit from increasing returns and, eventually, dominate the market for nuclear reactors and services.

The results also shed light on one of the potential limits of these international technologies transfers in the nuclear sector: we do not find evidence of a significant impact on nuclear reactors' safety. This result is equally important from a technology policy point of view, considering that incremental innovations are found to have a positive impact on safety in the country where they originate, but not when they are transferred to another country. Hence, one could consider that national incremental innovations do not only impact reactors' safety through the availability of new technologies, but also reflect the existence of national R&D capabilities which allow a better understanding of reactors' technical failures leading to unplanned outages. In other words, one may argue that this attribute of national innovations remains specific to the country where it originates and that there exists some limits to the development of nuclear power programs on, for example a turnkey basis, without the association of national R&D capabilities.

# 6. Conclusions

This paper studies the role of innovation and learning opportunities on nuclear reactors' economic and safety performance. It is important to recall that economic and safety performance are defined throughout this paper in terms of the duration of outages caused by planned (i.e. maintenance and refueling) and unplanned (i.e. technical failures) outages, respectively, and divided by the potential electricity generation during the year should one reactor operate at full capacity. In that respect, this measure remains a proxy for economic and safety performance. For instance, safety performance includes other dimensions, such as worker radiation exposure or environmental hazards risks, which are not studied and could follow different patterns.

Bearing these caveats in mind, our results do provide robust and significant evidence for the importance of the stock of innovation and learning spillovers. In particular, we show that both innovations from national and foreign innovators are important in improving nuclear reactors' economic performance, but that international technology transfers only have an impact on safety performance. At a time when funding for nuclear R&D is declining, this result shows that it may be in the interest of the nuclear industry to foster international technology transfers in order to maintain knowledge within the industry, and by extension nuclear reactors' economic performance.

However, national innovations remain necessary for safety performance, which can be explained by the fact that these innovations reflect the national knowledge capabilities of the country where a reactor is located. In that respect, our results stress the potential limit of international technology transfer programs on a turnkey basis, as these programs tend to be developed without the association of national R&D capabilities.

Our results provide the first comprehensive analysis of learning by doing since the development of commercial nuclear reactors as we study performance over the last 40 years in 12 countries. Overall, we show that cumulative learning by doing is limited in terms of magnitude and takes place in the first years of operation. Nuclear reactors' aging effect is essentially relevant for economic performance after 30 years of operation, but safety performance is impacted by this aging effect only after 40 years of experience. In addition, one may argue that reactors' life extension programs may at some point reverse this trend, as they will usually include the replacement of major components such as steam generators. In accordance with the existing literature (Lester and McCable, 1993), we also find that nuclear reactors benefit from spillovers effects, measured by reactor-years of operation of other reactors, essentially at the site level.

These results could be further explored and refined in a number of directions. Firstly, owing to data availability constraints, our aggregate measures of economic and safety performance do not permit the distinction between improvements in annual performance due to a reduction in outage duration or reduction in the number of outages. Secondly, the paper does not take into account the characteristic of reactor ownership, whereas the recent literature (Davis and Wolfram, 2012; Hausman, 2012) shows that nuclear reactors' divestiture is relevant in the US for both economic and safety performance. Thirdly, in parallel to nuclear reactor ownership considerations, nuclear reactors' management procedures may also play a role in performance (Rothwell, 1996). Fourthly, our study would benefit from a more refined measure of incremental innovations in order to distinguish between nuclear patents relevant for economic and safety performance. Key words search based on patent abstracts may be a way to address this issue.

Finally, our paper does not explicitly measure the role of nuclear reactors' standardization on economic and safety performance. A more continuous measure of standardization based on technical characteristics would provide a valuable case study on the economic and safety benefits of standardization.

# Chapter 3:

# Measuring the effect of persistent treatments: evidence from restructuring the US nuclear power sector.

## Abstract

The predominant empirical strategy when measuring the effect of endogenous government interventions is to represent the intervention by a dummy variable and to instrument it with either exogenous shocks directly, or predicted values from a probit model. These modelling strategies assume that if the net instrumental effect changes sign after the implementation of the intervention, then one would expect the post-intervention conditions to revert to their original state. In practice, market conditions are sometimes subject to persistence with the probability of reversal being close to 0 in the time periods following an intervention. We evaluate government interventions in the US nuclear power sector by creating instruments for interventions based on proportional hazard models. This procedure reduces the instrument variability to 0 following the intervention when the likelihood of reversed conditions is low. We find that divesture, with the vertical unbundling of utilities, reduces the unavailability factor substantially more than previously found. Contrary to previous studies, we find that wholesale market creation has no significant impact on outage level.

# Résumé

La stratégie empirique prédominante lors de la mesure de l'effet des interventions gouvernementales endogènes est de représenter l'intervention par une variable muette et de l'instrumenter avec des chocs exogènes, directement ou en utilisant les valeurs prédictives d’un modèle probit. Ces stratégies de modélisation supposent que si les variations nettes des effets instrumentaux changent de signe après la mise en œuvre de l'intervention, on pourrait s'attendre à revenir à l’état d'origine. En pratique, les conditions de marché sont parfois soumises à une forte inertie, et la probabilité d'inversion est proche de 0 à la suite d’une intervention. Nous évaluons les interventions gouvernementales dans le secteur de l'énergie nucléaire aux Etats Unis en créant des instruments basés sur des modèles de risque proportionnels. Cette procédure réduit la variabilité des instruments à 0 suite à l'intervention lorsque la probabilité de changement des conditions est faible. Nous constatons que la séparation verticale des activités de production et de distribution des électriciens nucléaires réduit le facteur d'indisponibilité beaucoup plus que précédemment trouvé. Contrairement aux précédentes études, nous constatons que la création de marchés de gros n'a pas d'impact significatif sur le niveau d'interruption des réacteurs.

# 1. Introduction

Governments frequently intervene in markets by adjusting legal or regulatory conditions. It is unsurprising that the effect(s) of such interventions are measured to facilitate continuing improvements in the affected market and to transfer adequate policy instruments to other markets. Many interventions can be thought of as a discrete shift in the market conditions and it is therefore common that they are approximated by dummy variables. Hence, measuring the effect of this type of intervention involves estimating an "average treatment effect".[42]

The primary empirical problem when establishing the effect of a 'treatment'/intervention is that it is endogenous – deteriorating market performance increases the risk of intervention. The predominant strategy used to overcome this problem has been to instrument the dummy variable with continuous exogenous shock(s) using linear models, or to use the predictions from probit models. However, these strategies assume that if the net instrumental effect changes sign following the implementation of the intervention, one should expect the post-intervention conditions to revert to their original states. That is not always realistic since it may take time to evaluate a policy change; even if the effect reveals itself quickly it might not be possible to (quickly) implement another change since market agents may lobby for the protection of sunk investments (Coate and Morris, 1999), and uncertainty about future gains and losses alters voters preferences in favour of the status quo (Fernandez and Rodrik, 1991). When policy changes are costly, as in Zhao and Kling's (2003) model, policies can be even more persistent.[43] Leading examples where policies are highly stable are the network sectors where capacity investments are large and last several decades.

The purpose of this paper is to measure the effect of policy interventions when market conditions persist over several periods. In addition to the general problem of endogeneity just described, such interventions also affect the desirable properties of instruments. Specifically, the ideal instrument is one that varies prior to the intervention but has substantially reduced, or even no, variability following the intervention. Searching for

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[42] The literature on average treatment effects, which has focused on the evaluation of labour and educational program participation, is reviewed by Wooldridge (2002) and Heckman (2010).

[43] A related explanation for policy persistence, and particularly why regulatory regimes may persist, is the obstruction of information regarding true market conditions as explained by Warren and Wilkening (2012).

instruments that naturally have those properties is one obvious option. If such instruments are unavailable, one can instead create an instrument where restrictions are imposed on the post-intervention variability. Wooldridge (2002, pp. 623-625) has suggested using the predictions from a probit model to instrument a treatment, but the immediate problem with the probit model is that there is no straightforward way of simultaneously incorporating low persistence prior to the intervention and high persistence following the intervention. Heckman and Navarro (2007) develop a structural methodology that involves persistent treatment but they do so at the cost of increased complexity. Other, reduced form models cited by them are also not always accessible to practitioners.

In this paper we suggest a simple alternative: the use of predicted values from a proportional hazard model (i.e. a survival model) as an instrument. In this model, the 'end' of the initial state is represented by the intervention and the final value, i.e. the predicted value in the period when the intervention occurs, can be extrapolated to all future time periods. Thus, an implicit assumption underlying this procedure is that of extreme persistence in the treatment. While in principle predicted values from a survival model are appropriate for use as an instrument for the type of interventions we are interested in, it is difficult to assess their statistical properties relative to probit predictions and other estimation strategies.

We implement our method on the US nuclear power sector where a number of states decided to introduce wholesale electricity markets and where some vertically integrated utilities were forced to divest their assets during the 1990s and 2000s. We use yearly data at the state and reactor level between 1994 and 2011 and investigate how the unavailability factor has been affected by these two market interventions.

Zhang (2007) identifies how incentives in the nuclear sector were affected by market reforms. She concludes that in states with wholesale markets, plants were no longer able to simply pass on the costs of repair and maintenance that were performed during outages. Plants therefore had much stronger incentives to reduce outages in restructured states. Zhang also reports anecdotal evidence in support of both reduced outage frequency and average outage time. Furthermore, Delmas and Tokat (2005) review the general literature on the expected outcome following vertical separation (i.e. divestiture). Their conclusion is that the outcome is ambiguous since, on the one hand, transaction costs can increase as a result of the technological interdependence and uncertain consumer demand in electricity markets, whereas on the other hand, the coordination cost can increase when units are integrated.

Previous empirical studies that have looked at the effects of market interventions in nuclear markets have focused on a single intervention. For example, Zhang (2007) studied the effects of the introduction of wholesale markets on outages, Pollitt (1996) looked at the response to privatisation of nuclear power plants in several countries and Davis and Wolfram (2012) investigated the effects of utility divestiture on outages.[44] The general conclusions based on these studies is that both the introduction of wholesale markets and divestiture have improved the economic performance of nuclear reactors and that this improvement has not been achieved to the detriment of safety. However, two potential problems can be observed while reviewing this literature. At the state level, the timing of different interventions tends to be correlated. This means that if only one intervention is included in the econometric model it is difficult to establish which specific intervention contributed to the estimated effect. Additionally, the previous literature, with the exception of Zhang (2007), does not fully address the endogeneity concerns.[45] Kwoka (2008) points out that this has blurred the understanding of how restructuring of the US electricity market has affected economic performance.

Foreshadowing our main results, we find that the introduction of wholesale markets had no significant effect on the nuclear unavailability factor. Divested assets, on the other hand, have reduced the unavailability factor and the reduction is both statistically and economically significant. When predictions based on both probit and survival models are used as instruments, they turn out to be substantially stronger than when individual instruments are inserted directly (i.e. not as predicted values) into a two-stage IV-model. The restrictive set of instruments used in previous studies is not strong enough to identify any significant effect from the interventions. Importantly, our initial hypothesis that survival-based instruments are more precise than instruments without restrictions on post-intervention variability is confirmed by the data.

The ensuing sections of this paper are organized as follows. Firstly, we review the policy changes in the US electricity market during the 1990s and 2000s and their possible

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[44] Other studies in the broader field of electricity market restructuring have looked at the impact on the electricity price (Fabrizi et al., 2007), the heat rate for fossil plants (Craig and Savage, 2013), and productive efficiency (Delmas and Tokat, 2005). Following the assumption that explanatory variables are strictly exogenous, frontier methods have also been applied (Hiebert, 2002; Knittel, 2002). Moreover, Hausman (2012) has looked at whether electricity market restructuring impacts safety performance and Verna et al. (1999) look at the economic and safety impacts of some performance-based incentive programs prior to deregulation.

[45] Other papers, such as Fabrizio et al. (2007) or Craig and Savage (2013), deal with other endogeneity problems related to electricity generation, such as entry and exit following policy change and the simultaneity between demand and input choice, which are not relevant to our analysis.

consequences for the restructuring of nuclear power generation. Section 3 presents our empirical strategy and the general conditions used to tackle endogeneity when endogenous variables are discrete and subject to inertia. Section 4 describes the data. Section 5 and 6 contains our main results and extensions on the existence of spillover and heterogeneous effects, respectively. Finally, Section 7 concludes.

# 2. Restructuring of the US electricity market

Over the past 35 years the US energy market has been fundamentally restructured. Detailed descriptions of this transformation process have been laid out elsewhere (e.g. Delmas and Tokat, 2005; Zhang, 2007; Davis and Wolfram, 2012), and thus we only provide a brief summary here. The restructuring began with the Public Utility Regulatory Policies Act in 1978 that opened up the market to independent power producers. This was followed by the Energy Policy Act in 1992, which allowed non-utilities to own power plants and requested utilities to allow third-parties to access their networks for the purpose of wholesale distribution. Deregulation that affected the end consumer, however, did not start until 1996 when utilities were also required to distribute energy from competitors.

To facilitate proper functioning of wholesale competition, several states have decided to create wholesale markets and to require vertically integrated utilities to divest their assets. Note, however, that if the final objective of these two market reforms was to promote competition between electricity generators and technologies, they also served somewhat specific objectives. In particular, the political economy of wholesale market creation has been stressed in the literature (Joskow, 1997), and an important driver of this reform was the difference in electricity prices between US states. However, divestiture – which in most cases followed wholesale market competition – was also a way of solving the stranded cost problem (Davis and Wolfram, 2012) accumulated by the then regulated utilities. The unbundling of vertically integrated assets further entails a gain in focus, in particular as divested nuclear reactors have been bought by nuclear operators which specialize in nuclear power[46]. Finally, the divestiture of the US nuclear power sector has provided the opportunity

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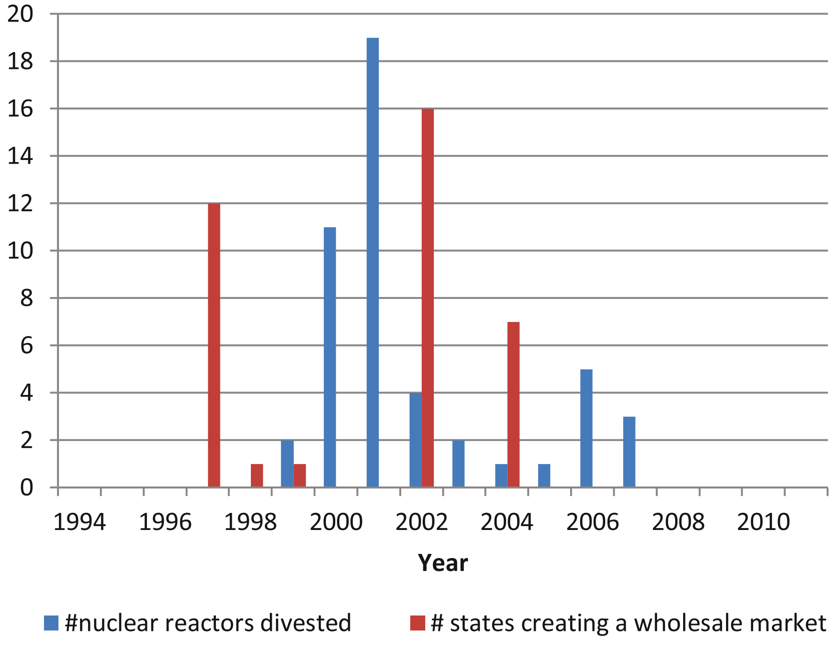
[46] Or, at least, by large non-utility generators such as Duke, Entergy or Exelon, with nuclear divisions specialized in nuclear power operations.

to consolidate the industry, and today the three largest nuclear operators control one-third of US nuclear capacity.

In 2011, about 75% of the 103 reactors sold their electricity on wholesale markets and approximately 50% had been divested. The number of wholesale markets and divested reactors are presented in Figure 3.1 for each year. While the creation of wholesale markets and the divestiture of reactors were more prone to occur in some years, it is clear that these reforms exhibit temporal variation. Table 3.1 provides further evidence of reform heterogeneity as it indicates that, while no reactor was exposed to any of the reforms in 1995, a majority had been reformed by the end of the sample period, and the reform variability was high when all four types of outcome (no reform, only divestiture, only wholesale market or both divestiture and wholesale market) were represented.

**Figure 3.1: Number of states creating a wholesale market and number of reactors divested by year**



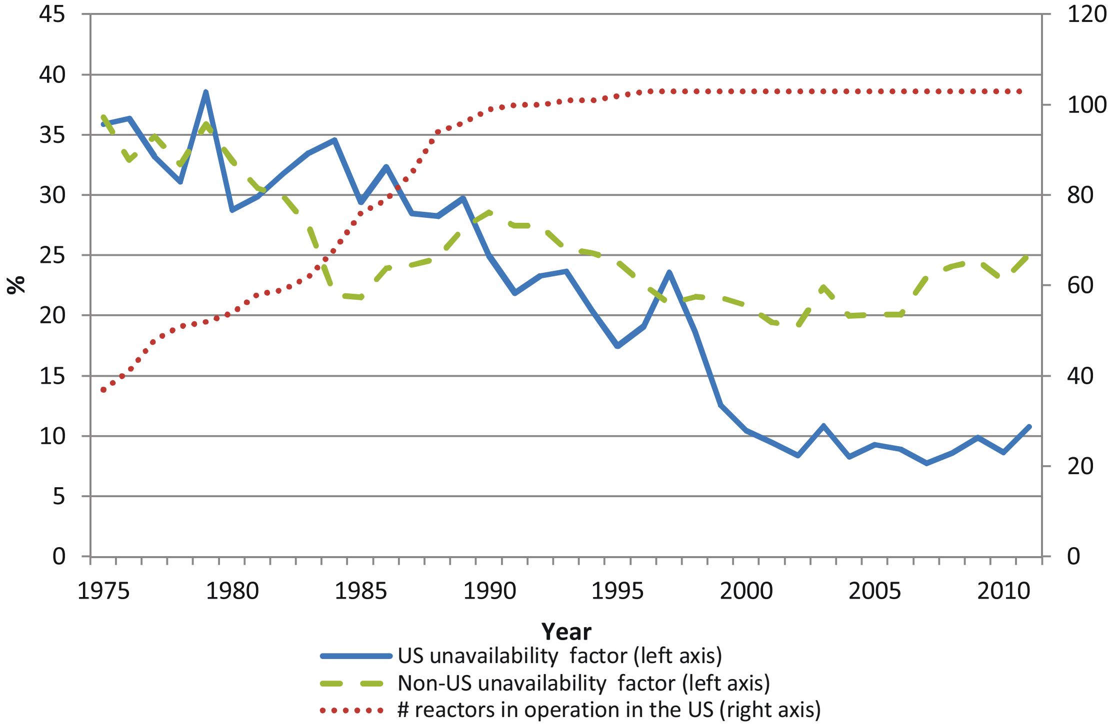
Source: Information on the date of nuclear reactors' divestiture comes from the Nuclear Energy Institute. Data on state level wholesale market creation comes from the US Energy Information Administration.

### Table 3.1: Deregulation and divestiture of nuclear reactors as of 2011

| | 1995 | | | 2011 | | |
|---|---|---|---|---|---|---|
| | **Regulated reactors** | **Deregulated reactors** | **Total** | **Regulated reactors** | **Deregulated reactors** | **Total** |
| **Non-divested reactors** | 103 | 0 | 103 | 18 | 37 | 55 |
| **Divested reactors** | 0 | 0 | 0 | 6 | 42 | 48 |
| **Total** | 103 | 0 | 103 | 24 | 79 | 103 |

The performance of existing reactors, measured as the unavailability factor (electricity generation losses resulting from planned and unplanned outages divided by total capacity), displays a clear negative trend over the last four decades. As displayed in Figure 3.2, US plants performed somewhat worse than plants in other countries during the 1980s, however they performed slightly better in the 1990s and since 1999-2000 they have clearly outperformed reactors in other countries.

### Figure 3.2: Trend in NPP performance in the US and internationally



Source: IAEA Power Reactor Information System (PRIS), available at http://www.iaea.org/pris/

The improved performance of the US nuclear power plants can be due to a number of factors related to changes in economic and safety regulatory conditions within the sector. With respect to changes in safety regulation, the Three Mile Island accident triggered two important reforms: (*i*) the creation of the Nuclear Regulatory Commission (NRC) and the development of performance-based safety standards in the early 1990s, and (*ii*) self-regulation, marked by the creation of the Institute for Nuclear Power Operation (INPO) that facilitates the exchange of good practices concerning both economic and safety performance.[47]

# 3. Econometric analysis

## 3.1. IV Approach with hysteresis of discrete endogenous variables

Our goal is to determine the average effect of an endogenous discrete treatment, i.e. a market intervention (for notational simplicity we restrict the general discussion here to one treatment). With subscript 0 denoting reactors that are not subject to treatment and subscript 1 denoting those that are treated, one can formulate the relevant model as:

$$y = \alpha w + \boldsymbol{X}\boldsymbol{\beta}_0 + u_o. \tag{3.1}$$

Here $\alpha$ is the average treatment effect and $u_0 \equiv v_0 - L(v_0|\boldsymbol{X},\boldsymbol{Z})$ where $L(v_0|\boldsymbol{X},\boldsymbol{Z})$ represents a linear projection of $v_0$ conditioned on a vector of explanatory exogenous variables $\boldsymbol{X}$ and a vector of instruments $\boldsymbol{Z}$. As $w$ is correlated with $u_0$, OLS is inconsistent. However, 2SLS is consistent under relatively weak assumptions, and it is also asymptotically efficient under somewhat more restrictive assumptions.

Specifically, consider the following assumptions:[48] (*i*) $v_1 = v_0$; (*ii*) $E(v_0 \mid \mathbf{X},\mathbf{Z}) = L(v_0 \mid \mathbf{X})$; (*iii*) $P(w=1 \mid \mathbf{X},\mathbf{Z}) \neq P(w=1 \mid \mathbf{X})$ and $P(w=1 \mid \mathbf{X},\mathbf{Z}) = G(\mathbf{X},\mathbf{Z};\boldsymbol{\pi})$ has a known parametric form; and (*iv*) $\mathrm{Var}(v_0 \mid \mathbf{X},\mathbf{Z}) = \sigma_0^2$. Assumption (*ii*) generally holds when $y$ is continuous. Assumption (*iii*) states that $\boldsymbol{Z}$ has predictive power and that the treatment function can be

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[47] All US nuclear power plant operators belong to INPO. Hence, in the econometric analysis developed in this paper, changes in the NRC and INPO regulation are captured by time fixed effects.

[48] This is based on Wooldridge (2002, pp. 621-625).

estimated under a parametric assumption. Assumption (*iv*) states that the error variance should be constant but heteroskedasticity robust standard errors relax this assumption. When these assumptions hold, Wooldridge (2002) suggests a three-stage procedure where, in the first stage, the treatment response function $P(w=1|\mathbf{X},\mathbf{Z})=G(\mathbf{X},\mathbf{Z};\boldsymbol{\pi})$ is estimated using a standard probit model. The estimated values from this estimation, $\hat{G}_i$, are then used as an instrument in a regular two-stage IV-model.

Our situation is characterised by a relatively low but variable probability for treatment, but once the unit is treated, the probability of the unity remaining treated in subsequent periods increases to a fixed value close to 1. A standard probit model cannot handle this inherent persistence in treatment, and a dynamic probit assumes that the persistence is fixed over the sampled time period, i.e. that the persistence is equally high prior to the treatment as it is following the initialisation of the treatment.[49] A conceptually more appealing instrument would start at a low $\hat{G}_i$, monotonically increase and once/if treated, remain at a high level with low variability. In other words, when a unit is treated at time t, (i.e. $w_t = 1$), it remains treated, (i.e. $w_l = 1, \forall\, l > t$). Compared to this idealised instrument the probit model suffers from lower efficiency and potentially from omitting a relevant variable. A potentially more appropriate approach is to approximate the $G(\mathbf{X},\mathbf{Z};\boldsymbol{\pi})$ function using a proportional hazard model. In this model, the hazard rate is formulated as $h(t)=\frac{f(t)}{S(t)}$, where the numerator is the density of the function representing the probability that the random variable *T* is less than some value *t*: $f(t)=\frac{dF(t)}{dt}=\frac{d[\Pr(T<t)]}{dt}$; and the denominator is the survival function defined as $S(t)=1-F(t)=\Pr(T\geq t)$. This allows us to write the probability of intervention in period *t*, given that no intervention was present in period *t*-1, as:

$$G(\boldsymbol{X},\boldsymbol{Z};\boldsymbol{\pi}) = h(t) = h_{base}(t)\exp(\boldsymbol{X},\boldsymbol{Z};\boldsymbol{\pi}) \tag{3.2}$$

$\hat{G}_i$ is fixed in all periods subsequent to the market intervention and set to the value predicted in the period where the intervention takes place.

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[49] Even a standard dynamic probit model, i.e. with fixed persistence, turns out to be problematic due to the limited variability in when interventions took place.

### 3.2. Models Specifications

When specifying equation (3.1) we use the reactor unavailability factor ($UF$) as a dependent variable. As explanatory variables we begin by including the two endogenous indicator variables that represent divestiture ($Divest$) and the introduction of an electricity wholesale market ($WholeSale$). As controls we include the age of the reactor in level ($Age$), and squared ($Age^2$). This allows us to write equation (3.1) as:

$$UF_{i,t} = \alpha_1 Divest_{i,t} + \alpha_2 WholeSale_{j,t} + \beta_1 Age_{i,t} + \beta_2 Age_{i,t}^2 + \boldsymbol{\eta}_i + \boldsymbol{\lambda}_t + u_{i,t} \tag{3.3}$$

where $i$ is reactor, $j$ is state, $t$ is year, $\boldsymbol{\eta}$ are year fixed effects, $\boldsymbol{\lambda}$ are reactor fixed effects and $u$ are the random errors. The estimation of equation (3.3) poses no complication apart from what has already been discussed.

Before specifying equation (3.2) we take a closer look at the previous literature. Two studies use data from the US electricity market to identify what factors influence energy market restructuring (Ando and Palmer, 1998; Damsgaard, 2003). Both implement survival models using actual or intended implementation of competition in the retail market as the dependent variable. While in this paper we do not investigate what caused the establishment of retail markets, we assume that the fundamental drivers for all deregulatory activities were similar. Ando and Palmer (1998) find that the strength of the dominating interest group is positively related to deregulation when the potential efficiency gains are large. High electricity prices and large price differences with neighbouring states also increased the likelihood of deregulation. Damsgaard (2003) largely supports these conclusions. In addition he finds some support for the idea that the share of independent power producers increases the likelihood of deregulation.

Zhang (2007), uses the share of industrial revenue ($ShInd$), the share of hydroelectricity ($ShHydro$) and the political majority at the state level ($Rep$) instruments for $Wholesale_t$. Delmas and Tokat (2005) suggest that the average price of electricity ($ElecP$) can be an additional instrument for general energy market restructuring as it can be interpreted as a measure of market performance. And as reported earlier, Ando and Palmer (1998) and Damsgaard (2003) claim that the difference in electricity price between neighbouring states ($ImportGap$) and the share of independent power producers ($ShIPP$) can explain the occurrence of reforms in the US electricity market.

However, in our benchmark specification of equation (3.2) we exclude explanatory variables that represent prices since unobserved demand variations can affect both outages and the price of electricity. We also exclude share of independent power producers as their entry was facilitated by market reforms (making them endogenous in equation (3.2)).

In addition to these insights, we hypothesise that the share of nuclear generation in the state electricity mix ($ShNuc$) may also influence the likelihood of interventions. We include a linear trend $t$ and squared trend $t^2$. This smooth trend function replaces the year dummies since separate year effects lead to serious over-fitting. The smooth time function can be regarded as capturing the general sector-specific willingness to liberalise markets that is driven by technological and/or ideological shocks. $Age$ and $Age^2$ are included as they are exogenous variables in equation (3.3).

A fundamental difference between divestitures and the introduction of wholesale markets is that divestiture takes place at the reactor level whereas wholesale markets are introduced at the state level. However, we assume that the same factors drive both reforms and that policy-makers in both cases decide to implement the reform in the year prior to the implementation. All explanatory variables are therefore lagged one period. Finally, we explored the inclusion of panel effects at different levels (reactor and state) but parameters were generally unrealistic or the estimations did not converge when they were included. All models are therefore estimated from the pooled sample. Hence, equation (3.2) is formulated as:

$$\begin{aligned} h(t) = h_{base}(t)\exp\big(&\pi_0 + \pi_1 ShInd_{i,t-1} + \pi_2 ShHydro_{i,t-1} + \pi_3 Rep_{i,t-1} \\ &+ \pi_4 ShNuc_{i,t-1} + \pi_5 t + \pi_6 t + \pi_7 Age_{i,t} + \pi_8 Age_{i,t}^2\big) + \varepsilon_{i,t} \end{aligned} \tag{3.4}$$

# 4. Data

Compared to previous studies that have evaluated the effects of the restructured US electricity market on the nuclear power sector, we use a data set that covers the period from 1994 to 2011 (with pre-sample data available to get predicted values from 1994 for the survival models as well as historical performance data since 1970 to study heterogeneous effects of policy reforms in Section 6.2.). In the context of endogeneity, a large data set is important since IV-estimators are consistent but not unbiased.

Data are collected from a range of different sources. We use annual data on nuclear reactors' outage duration from the IAEA PRIS database, these data are available from 1970 up to 2011 and we restrict our sample to the 1994-2011 period, giving us 1,851 observations. State level data used in the survival and probit models are available from 1990 up to 2012, giving us 2,266 observations, and the full sample is used in order not to use degrees of freedom. Data on nuclear reactor location and technical characteristics are collected using the same IAEA database. This includes the state where reactors are located, the year when reactors were first connected to the grid, and technical characteristics in terms of technology (PWR versus BWR), containment structure, and steam generator type[50]. Data on the year of divestiture and wholesale market creation decisions are collected from Davis and Wolfram (2012) and Craig and Savage (2013), respectively[51]. Finally, data on state level electricity sector characteristics (share of nuclear and hydropower, electricity prices and share of IPPs) are collected from the Energy Information Administration databases and data on state level political majority from the US census bureau. These state level data on the electricity sector are only available from 1990, which explains the restriction of our sample to the 1994- 2011 period.

Table 3.2 below presents descriptive statistics of the data as well as the level at which these data are collected and the definition of the dependent and independent variables. Descriptive statistics are displayed in Table 3.3 and a few observations can be noted. Firstly, the maximum value of $UF$ is 100, indicating no production during a whole year. A closer examination of the data reveals 20 such observations. In the subsequent estimations we either include a dummy variable to control for these observations or exclude them. It should also be emphasised that as the minimum value for Age is 1, no reactor has been introduced during the sample period.

The minimum value of $ShNuc$ is 0. This indicates that a state has no nuclear power at all. The inclusion of these states is still necessary in order to avoid selection bias when equation (3.4) is estimated with the introduction of wholesale markets as the dependent variable.

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[50] These data are used in Table 3.7 to study technological spillovers between reactors with similar technical characteristics.

[51] These data are further cross-checked using the Nuclear Energy Institute website for divestiture and the Energy Information Administration website for wholesale market creation. Summary tables with detailed data on the dates of wholesale market creation and reactor divestiture can be found in Appendix 3.

### Table 3.2: Descriptive statistics

| Variable | Level of aggregation | No. obs. | Mean | Std. Dev. | Min | Max |
|---|---|---|---|---|---|---|
| $UF$ | Reactor | 1,851 | 12.397 | 15.132 | 0 | 100 |
| $Divest$ | Reactor | 2,369 | 0.204 | 0.403 | 0 | 1 |
| $WholeSale$ | Reactor | 2,369 | 0.398 | 0.489 | 0 | 1 |
| $Age$ | Reactor | 1,851 | 23.733 | 8.299 | 1 | 43 |
| $IndCons$ | State | 2,266 | 21.770 | 7.707 | 4.974 | 48.250 |
| $ShNuc$ | State | 2,266 | 16.286 | 8.399 | 0 | 70 |
| $ShHydro$ | State | 2,266 | 2.671 | 4.975 | 0 | 79.659 |
| $ShIPP$ | State | 2,266 | 22.882 | 31.403 | 0 | 95.184 |
| $Rep$ | State | 2,266 | 0.299 | 0.458 | 0 | 1 |
| $ImportGap$ | State | 2,266 | 0.048 | 0.185 | 0 | 2.614 |
| $ElecP$ | State | 2,266 | 7.372 | 2.979 | 2.274 | 19.839 |

# 5. Results

Using survival models with exponential baseline hazard and probit models, we begin by estimating equation (3.4) to generate $\hat{G}_i$ [52]. This is replicated for both the reforms, where we denote the predicted values as $\hat{G}_i^D$ when generated for nuclear reactors' divestiture and as $\hat{G}_i^W$ when applied to wholesale market creation. For each type of reform, we generate $\hat{G}_i$ both when electricity price variables are excluded (according to equation (3.4)) and when they are included (denoted $\hat{G}_i^{excl}$ when price variables are excluded and as $\hat{G}_i^{incl}$ when they are included). Parameter estimates for these models are displayed in Table 3.3 using both parametric survival model and cross section probit model specifications.

While the directional impact from coefficients are fairly similar for the survival and probit models (when coefficients are below 1 in the survival model they are negative in the corresponding probit model), precision is consistently higher in the probit models. The outcomes are not directly comparable, though, as the survival models are restricted to the

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[52] Other distributional assumptions for the baseline hazard did not converge.

non-reform observations whereas the probit models use the entire sample. Coefficients indicate that the age of the reactors is negatively related to reforms and time has an inverted U-shape in its relationship to reform, which was also evident in Figure 3.1. Moreover, divestiture seems to be more likely as the share of nuclear power in states increases and less likely as the share of hydro power increases. Of the price variables, only average state level electricity price has a significant impact as it increases the likelihood of introducing wholesale markets.

Results for the estimation of equation (3.3) are reported in Tables 3.3 and 3.4 using a range of model specifications. Table 3.3 presents estimates with no treatment for endogeneity and with the explanatory variables of the survival and probit models introduced directly as instruments for the two endogenous policy variables. Table 3.4 presents the core results of our analysis, with both survival and probit models used to create instruments, using different model specifications for the predicted values of equation (3.3) used as instruments and IV-GMM estimator. The instruments used for each regression and a number of statistical tests are also reported in Tables 3.3 and 3.4, concerning overidentifying restriction (Hansen J P-value) and weak identification (first stage Shea Partial $R^2$, first stage F statistic and LIML size distortion[53]).

The main findings of our analysis can be summarized as follows: (*i*) divestiture has been the main driver behind the improvement of the US nuclear reactors' outage time reduction and wholesale market creation is not found to have had a significant impact; (*ii*) classical instrumental approaches, which do not control for the discrete nature of the studied policy reforms or for policy inertia, produce weak instruments. In this respect, not accounting for endogeneity does, for our analysis, produce less biased estimates compared to the former approach, but underestimates the effect of divestiture compared to the survival or probit first stage approaches; and (*iii*), using a first stage survival model to create instruments leads to stronger instruments and, consequently, more precise estimates compared to a probit first stage approach.

Table 3.4 provides robust evidence for the reduction of the US nuclear reactors' outage time following the reorganisation of the US electricity market. This result is consistent between model specifications using instruments based on a first stage probit model (regressions (7), (8) and (9)) and a survival model (regression (10), (11), (12)). In particular, we find that

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[53] Based on Kleibergen-Paap Wald F statistic and using Stock and Yogo's (2005) critical values. These statistics are directly available using the « xtivreg2» command on Stata.

improvements in performance originate from nuclear reactors' divestiture, $Divest_t$, whereas the creation of wholesale markets, $Wholesale_t$, has had no significant impact on performance. Estimates from regression (10), our preferred estimate, indicates that divestiture reduces annual outage duration by approximately 14%.

This provides striking evidence for the benefit of divestiture in improving the efficiency of the US nuclear power sector. The benefit of divestiture policy can be explained by organisational changes with the speciation of nuclear reactors' buyers on nuclear generation (through the creation of nuclear divisions within companies devoted to plants' operation) and, more generally, with the gain in focus associated with the separation of electricity generation and distribution activities. At the same time, the effect of divestiture may also embody the benefit of nuclear industry consolidation, as divested plants have been bought by a few large independent power producers[54]. However, results for the role of wholesale market creation do not support the hypothesis that this market reform has impacted the US nuclear reactors. This can be explained by the fact that nuclear operators, in some cases, may have entered long term contracts with large industrial consumers, or the fact that wholesale markets operators cannot pass on the cost of (potentially expensive) unplanned outages to final consumers, which would incentivise them to plan for unplanned outages[55].

Regressions from Table 3.4 need to be contrasted with those from Table 3.3 where estimations do not deal with endogeneity (regressions (1), (2) and (3)), or do so using independent variables of equation (3.4) directly as instruments (regressions (4), (5) and (6)). Starting with the simplest model specifications, regressions (2) and (3) include reactor fixed-effects and show that they are able to capture part of the endogeneity compared to OLS in regression (1), as the point estimate for $Divest_t$ decreases from -3.2 to -7.3. This model specification, which essentially replicates Davis and Wolfram's (2012) approach, underestimates the benefit of divestiture policy by a factor of between 1.5 and 2 compared to the survival and the probit approaches, respectively (reported in Table 3.4), where the point estimates of $Divest_t$ are between -10.3 and -14.8.

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[54] Note that one cannot attempt to distinguish between divestiture and consolidation as both occurred simultaneously and there are no appropriate candidates for instrumenting the latter. Furthermore, we also attempt to look at the interaction between divestiture and consolidation and find that our results do not change significantly with the introduction of the interaction variable, which is not significant.

[55] In addition, we cannot rule out the possibility that this result could originate from the close timing between wholesale market creation and divestiture. However, the heterogeneity of the data (Table 3.1), makes this hypothesis less likely.

If panel fixed-effect regressions underestimate the effect of divestiture policy, one can argue that this choice of model specification may be a preferred option compared to an IV approach where dependent variables of equation (3.4) are used directly as instruments. For instance, regression (4) in Table 3.3 uses the same IV specification as Zhang (2007), with $Rep_{t-1}$, $IndCons_{t-1}$ and $ShHydro_{t-1}$ used as instruments for the two endogenous variables $Divest_t$ and $Wholesale_t$. This IV approach leads to a weak instrument problem with, for instance, the Shea partial R$^2$ statistic below 0.001 and LIML size distortion above 25%. The weak instrument problem is particularly troublesome as the estimated coefficient for $Divest_t$, the main variable of interest, is no longer significant contrary to panel fixed-effect and the IV models in Table 3.4. Note that in regression (6), where electricity price variables ($ElecPrice_{t-2}$ and $ImportGap_{t-2}$) are introduced as instruments along with the share of IPP ($ShIPP_{t-2}$), $Divesture_t$ regains significance. However, the latter result may be obtained at the cost of further endogeneity concerns for these added instrument variables and statistical tests for the instruments strength still report weak instruments (e.g. LIML size distortion above 25%).

In parallel, the results also indicate, that the first stage survival model approach produces stronger instruments, leading to less biased estimates with lower standard errors. For instance, comparison between regressions (7) and (10) shows that the first stage Shea Partial R$^2$ statistic for $Divest_t$ increases from 0.07 to 0.2, the F statistic increases from 24.1 to 117.6 and, finally, the LIML size distortion is reduced from 20% to less than 10%. This reduction in the instruments' biases leads to more precise estimates and the standard error for $Divest_t$ is reduced from 4.2 to 2.2.

Table 3.3: Estimation output of equation (3.4)

| | **Parametric survival model** | | | | **Probit model** | | | |
|---|---|---|---|---|---|---|---|---|
| | **Dep. Var.** *Dereg* | **Dep. Var.** *Divest* | **Dep. Var.** *Dereg* | **Dep. Var.** *Divest* | **Dep. Var.** *Dereg* | **Dep. Var.** *Divest* | **Dep. Var.** *Dereg* | **Dep. Var.** *Divest* |
| **Variable** | **(1) Hazard Ratio (SE)** | **(2) Hazard Ratio (SE)** | **(3) Hazard Ratio (SE)** | **(4) Hazard Ratio (SE)** | **(5) Mean (SE)** | **(6) Mean (SE)** | **(7) Mean (SE)** | **(8) Mean (SE)** |
| $IndCons_{t-1}$ | 0.969 | 0.981 | 1.06 | 1.011 | -0.023*** | -0.017** | 0.039*** | -0.018** |
| | (0.029) | (0.027) | (0.038) | (0.035) | (0.009) | (0.006) | (0.013) | (0.007) |
| $ShNuc_{t-1}$ | 1.008 | 1.044** | 0.982 | 1.036** | 0.010*** | 0.033*** | -0.002 | 0.019*** |
| | (0.016) | (0.019) | (0.014) | (0.018) | (0.004) | (0.005) | (0.006) | (0.006) |
| $ShHydro_{t-1}$ | 0.990 | 0.858* | 0.984 | 0.861** | -0.022*** | -0.084*** | -0.019*** | -0.044*** |
| | (0.015) | (0.068) | (0.021) | (0.062) | (0.004) | (0.015) | (0.005) | (0.014) |
| $Rep_{t-1}$ | 0.905 | 0.532* | 0.826 | 0.598 | -0.554*** | -0.325*** | -0.413*** | -0.067 |
| | (0.015) | (0.172) | (0.338) | (0.191) | (0.156) | (0.084) | (0.160) | (0.089) |
| $Age_{t-1}$ | 0.596*** | 0.830* | 0.642* | 0.876 | -0.275*** | -0.106*** | -0.302*** | -0.102*** |
| | (0.106) | (0.083) | (0.160) | (0.095) | (0.054) | (0.028) | (0.070) | (0.026) |
| $Age^2_{t-1}$ | 1.010*** | 1.00* | 1.01* | 1.00 | 0.005*** | 0.002*** | 0.006*** | 0.002*** |
| | (0.003) | (0.002) | (0.005) | (0.002) | (0.001) | (0.001) | (0.001) | (0.001) |
| $Trend_t$ | 5.598*** | 17.484*** | 8.645*** | 13.305*** | 0.863*** | 0.994*** | 0.949*** | 0.620*** |
| | (1.734) | (7.839) | (5.095) | (6.535) | (0.096) | (0.084) | (0.132) | (0.073) |
| $Trend^2_t$ | 0.933*** | 0.905*** | 0.913*** | 0.912*** | -0.023*** | -0.026*** | -0.030*** | -0.015*** |
| | (0.012) | (0.015) | (0.021) | (0.017) | (0.003) | (0.002) | (0.004) | (0.002) |
| $ImportGap_{t-2}$ | | | 1.920 | 0.388 | | | -0.669*** | -0.517** |
| | | | (3.603) | (0.411) | | | (0.254) | (0.212) |
| $ElecP_{t-2}$ | | | 2.342*** | 1.074 | | | 0.481*** | -0.080*** |
| | | | (0.451) | (0.150) | | | (0.080) | (0.027) |
| $IndCons_{t-1} * ElecP_{t-2}$ | | | 1.10 | 1.062 | | | 0.068*** | -0.002 |
| | | | (0.310) | (0.091) | | | (0.017) | (0.004) |
| $ShIPP_{t-2}$ | | | 1.019 | 1.009 | | | 0.016*** | 0.016*** |
| | | | (0.014) | (0.006) | | | (0.004) | (0.001) |
| Log pseudo-likelihood | 114.171 | 193.982 | 122.887 | 196.738 | -242.437 | -770.021 | -190.593 | -702.859 |
| No. of subjects | 31 | 103 | 31 | 103 | na | na | na | na |
| No. of failures | 25 | 48 | 25 | 48 | na | na | na | na |
| No. obs. | 384 | 1720 | 353 | 1618 | 651 | 2157 | 620 | 2055 |

Notes: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. SEs are clustered over reactors (when *Divest* is dep. var.) and over states (when *Dereg* is dep. var.). $Age_{t-1}$ and $Age^2_{t-1}$ are computed at the reactor and state levels respectively for the *Divest* and *Dereg* regressions.

## Table 3.4: Estimation output of equation (3.3) with traditional models

| Variable | OLS | FE | | IV-FE | | |
|---|---|---|---|---|---|---|
| | (1) | (2) | (3) | (4) | (5) | (6) |
| | Mean (SE) | Mean (SE) | Mean (SE) | Mean (SE) | Mean (SE) | Mean (SE) |
| $Divest_t$ | -3.204*** | -7.361*** | -7.329*** | 12.486 | 1.982 | -9.380*** |
| | (0.527) | (1.552) | (1.516) | (27.591) | (14.099) | (3.094) |
| $WholeSale_t$ | 1.546** | 2.450* | 2.34* | -42.301 | -23.065 | -2.13 |
| | (0.660) | (1.380) | (1.346) | (46.581) | (21.473) | (5.385) |
| $Age_t$ | 0.552*** | 0.083 | 0.073 | 1.098 | 0.704 | 0.305 |
| | (0.178) | (0.218) | (0.214) | (0.988) | (0.460) | (0.260) |
| $Age_t^2$ | -0.009*** | -0.0108** | -0.0104** | -0.001 | -0.004 | -0.010** |
| | (0.003) | (0.004) | (0.004) | (0.012) | (0.006) | (0.003) |
| Year FE | Yes | Yes | Yes | Yes | Yes | Yes |
| Treatment of obs. where $UF$=100 | Dum. Var. | Excluded | Dum. Var. | Dum. Var. | Dum. Var. | Dum. Var. |
| Instruments | | | | $Rep_{t-1}$<br>$IndCons_{t-1}$<br>$ShHydro_{t-1}$ | $Rep_{t-1}$<br>$IndCons_{t-1}$<br>$ShHydro_{t-1}$<br>$ShNuc_{t-1}$ | $Rep_{t-1}$<br>$IndCons_{t-1}$<br>$ShHydro_{t-1}$<br>$ShNuc_{t-1}$<br>$ElecP_{t-2}$<br>$ImpGap_{t-2}$<br>$ShIPP_{t-2}$ |
| Max LIML size distortion | | | | >25% | >25% | >25% |
| Hansen J. P-value | | | | 0.593 | 0.465 | 0.629 |
| First stage Shea Partial R². $Divet_t$ | | | | 0.003 | 0.008 | 0.108 |
| First stage Shea Partial R². $Dereg_t$ | | | | 0.001 | 0.004 | 0.036 |
| First stage F statistic. $Divest_t$ | | | | 25.285 | 20.242 | 27.797 |
| First stage F statistic. $Dereg_t$ | | | | 8.453 | 7.257 | 8.626 |
| R² | 0.441 | 0.147 | 0.436 | 0.341 | 0.195 | 0.427 |
| No. obs. | 1851 | 1831 | 1851 | 1851 | 1851 | 1851 |

Notes: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. $UF$ represents total number of outage hours divided by potential generation and is the dependent variable. SE are robust to heteroskedasticity and autocorrelation with a Bartlett bandwidth = 2.

### Table 3.5: Estimation output of equation (3.3) with the probit-IV and survival-IV models

| Variable | Probit IV-FE | | | Survival IV-FE | | |
|---|---|---|---|---|---|---|
| | (7) | (8) | (9) | (10) | (11) | (12) |
| | Mean<br>(SE) | Mean<br>(SE) | Mean<br>(SE) | Mean<br>(SE) | Mean<br>(SE) | Mean<br>(SE) |
| $Divest_t$ | -11.055*** | -10.746*** | -10.365*** | -14.123*** | -11.970*** | -14.810*** |
| | (4.243) | (2.681) | (2.763) | (2.284) | (1.868) | (2.593) |
| $WholeSale_t$ | -7.949 | 0.426 | 4.052 | -1.917 | -3.200 | 1.886 |
| | (5.042) | (2.945) | (3.385) | (2.641) | (2.662) | (2.820) |
| $Age_t$ | 0.524** | 0.223 | 0.080 | 0.372 | 0.349 | 0.278 |
| | (0.263) | (0.232) | (0.223) | (0.236) | (0.233) | (0.229) |
| $Age_t^2$ | -0.008** | -0.009** | -0.010*** | -0.008** | -0.008** | -0.009** |
| | (0.004) | (0.003) | (0.003) | (0.003) | (0.003) | (0.004) |
| Year FE | Yes | Yes | Yes | Yes | Yes | Yes |
| Treatment of obs. where $UF$=100 | Dum. Var. | Dum. Var. | Dum. Var. | Dum. Var. | Dum. Var. | Dum. Var. |
| Instruments | $\hat{G}_t^{D,excl}$<br>$(\hat{G}_t^{D,excl})^2$<br>$\hat{G}_t^{W,excl}$<br>$(\hat{G}_t^{W,excl})^2$ | $\hat{G}_t^{D,excl*}$<br>$(\hat{G}_t^{D,excl*})^2$<br>$\hat{G}_t^{W,excl*}$<br>$(\hat{G}_t^{W,excl*})^2$ | $\hat{G}_t^{D,incl}$<br>$(\hat{G}_t^{D,incl})^2$<br>$\hat{G}_t^{W,incl}$<br>$(\hat{G}_t^{W,incl})^2$ | $\hat{G}_t^{D,excl}$<br>$(\hat{G}_t^{D,excl})^2$<br>$\hat{G}_t^{W,excl}$<br>$(\hat{G}_t^{W,excl})^2$ | $\hat{G}_t^{D,excl*}$<br>$(\hat{G}_t^{D,excl*})^2$<br>$\hat{G}_t^{W,excl*}$<br>$(\hat{G}_t^{W,excl*})^2$ | $\hat{G}_t^{D,incl}$<br>$(\hat{G}_t^{D,incl})^2$<br>$\hat{G}_t^{W,incl}$<br>$(\hat{G}_t^{W,incl})^2$ |
| Max. LIML size distortion | <20% | <10% | <10% | <10% | <10% | <10% |
| Hansen J. P-value | 0.0002 | 0.998 | 0.594 | 0.620 | 0.524 | 0.987 |
| First stage Shea Partial $R^2$. $Divet_t$ | 0.071 | 0.142 | 0.141 | 0.203 | 0.325 | 0.164 |
| First stage Shea Partial $R^2$. $Dereg_t$ | 0.035 | 0.121 | 0.091 | 0.128 | 0.128 | 0.162 |
| First stage F statistic. $Divest_t$ | 24.194 | 77.650 | 51.228 | 117.630 | 191.952 | 99.975 |
| First stage F statistic. $Dereg_t$ | 11.673 | 43.522 | 25.511 | 53.811 | 58.019 | 60.002 |
| $R^2$ | 0.392 | 0.431 | 0.433 | 0.413 | 0.417 | 0.417 |
| No. obs. | 1850 | 1850 | 1850 | 1850 | 1850 | 1850 |

Notes: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. $UF$ represents total number of outage hours divided by potential generation and is the dependent variable. SE are robust to heteroskedasticity and autocorrelation with a Bartlett bandwidth = 2. Models (8) and (11) correspond to the specifications of Models (7) and (10), but use a multivariable fractional polynomial model to create instruments $\hat{G}_t^{D,excl*}$ and $\hat{G}_t^{W,excl*}$ The latter significantly improves the models' predictions (in particular the time variables), resulting in lower standard errors.

# 6. Extensions: spillover and heterogeneity

Results in Section 5 rely on two assumptions: firstly, that untreated units are completely unaffected by the treatment of other units and secondly, that units respond homogeneously to treatments. In this section we perform some sensitivity tests to evaluate the reasonableness of these assumptions. Spillover effects, i.e. that untreated units are affected by those that are treated, can occur as information can flow across units directly as a result of joint stakeholders, and indirectly as a result of industry associations and labour movements. If spillovers are present we will under-estimate the effect of the treatment.[56] In this section, we will now base our analysis on our preferred estimate in Table 3.5 (Regression (10)), where we use $\hat{G}_t^{D,excl}$ and $\hat{G}_t^{W,excl}$ as instruments with these predicted values being generated by a survival model.

## 6.1. Spillover effects

Table 3.6 explores whether spillovers exist between divested and non-divested plants. As aforementioned, in Section 2, the possibility of spillovers is motivated by the existence of organisations in the US which play a role in fostering the exchange of knowledge and experience between nuclear operators (e.g. the Institute for Nuclear Power Operation). The existence of spillover effects is tested at three different levels: (*i*) for nuclear reactors operated by the same operators (Regression (13)), (*ii*) for nuclear reactors with similar technological characteristics[57] (Regression (14)), and (*iii*) for nuclear reactors located in the same state or in neighbour states (Regressions (15) and (16))[58].

While overlaps may take place between these three spillover channels, results from Table 3.6 highlight the existence of some spillover effects at the three different levels. The clearest evidence relates to spillovers at the geographical and operational levels, with point estimates indicating that these two spillover channels have led to a reduction of non-divested reactor unavailability of more than 4%. Regression (16), where geographical spillovers are computed with the inclusion of neighbour states, shows that spillovers might even be higher, with a 9.2%

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[56] We also studied the possibility of learning following policy reforms. However, our estimations do not support this hypothesis, indicating that the effect of divestiture can be considered as a level shift.

[57] We define reactor technology classes based on reactor containment type, steam system supplier and design type using data for the US Nuclear Regulatory Commission Information Digest 2012–2013. Available at: www.nrc.gov/reading-rm/doc-collections/nuregs/staff/sr1350/appa.xls

[58] Regression (15) only considers geographical spillovers within states and Regression (16) considers geographical spillovers within states and neighbour states.

reduction in plant unavailability for non-divested reactors. With respect to technological spillovers (Regression (15)), these appear to be less significant, with significance only at the 10% level. This might simply reflect the fact that nuclear reactors are complex systems and our definition of technology classes might not capture all the differences between reactors.

As spillovers have not been considered in the previous section, the existence of spillovers should imply that previous estimates – where we only look at the average treatment effect – have underestimated the effects of divestiture policy in improving the availability of nuclear reactors. This is confirmed in all the regressions of Table 3.6, where the point estimates of $Divest_t$ are higher than the estimates reported in Table 3.5. This result is particularly policy relevant as it implies that the total benefit of divestiture would also encompass improvement of performance for non-divested reactors.

### 6.2. Heterogeneous effects

The heterogeneous effect of the two policy reforms on unavailability reduction is also another policy relevant question in order to assess the effectiveness of these policies. In particular, in Table 3.7 we look at whether nuclear reactors have been more impacted by these policy reforms with respect to technology type (PWR versus BWR reactors) and taking into account past reactors' performance.

We first divide our sample into four quartiles based on past performance up to wholesale market creation (which is in most cases the first reform implemented). Past performance data are collected using historical performance data available in the IAEA PRIS database and going back to 1970, meaning that we do not have sample truncation for reactors built before that date. The 1st quartile refers to the top 25% for performance up to wholesale market creation and the 4th quartile to the bottom 25%. These estimates highlight that the 1st quartile of reactors have reduced outage time by approximately 6% following divestiture and this effect increases (although $Divest_t$ is not significant for the 2nd quartile) as we look at samples of reactors with worse performance track records. For instance, reactors of the 4th quartile have reduced unavailability by a factor of 6 compared to the 1st quartile. This demonstrates the heterogeneous effect of divestiture policy, as well as its effectiveness, to the extent that the impact of this policy is greater for reactors with the worst performance track record. Hence, one could argue that divestiture does not only improve performance, it also allows reactors with lower performance history to catch up with the best performing reactors.

While we do not find a significant difference for the effect of divestiture on BWR versus PWR reactors, we find that BWR might have benefited from wholesale market creation. However, this effect is not robust when we further divide the sample of BWR reactors between reactors above and below the median, as divesture loses significance and wholesale market creation is only significant at the 10% level for the reactors below the median. The latter result might be explained by the fact that the data sets (approximately 300 observations) are too small to overcome the inherent bias introduced when using IV estimators.

**Table 3.6: Estimation output of equation (3.3) and spillovers**

| | **Operational Spillovers** | **Technical Spillovers** | **Geographic Spillovers** | |
|---|---|---|---|---|
| **Variable** | **(13)** | **(14)** | **(15)** | **(16)** |
| | **Mean (SE)** | **Mean (SE)** | **Mean (SE)** | **Mean (SE)** |
| $Divest_t$ | -15.115*** | -16.324*** | -19.199*** | -24.670*** |
| | (2.466) | (3.101) | (4.461) | (6.483) |
| $WholeSale_t$ | -1.935 | -6.162 | -0.685 | 1.528 |
| | (4.107) | (5.343) | (2.841) | (2.924) |
| $Op. Spill. Divest_{t-1}$ | -4.622** | | | |
| | (1.843) | | | |
| $Op. Spill. Wholesale_{t-1}$ | -0.493 | | | |
| | (2.135) | | | |
| $Tech. Spill. Divest_{t-1}$ | | -2.676* | | |
| | | (1.574) | | |
| $Tech. Spill. Wholesale_{t-1}$ | | -6.026* | | |
| | | (3.613) | | |
| $Geo. Spill. Divest_{t-1}$ | | | -4.248*** | -9.282*** |
| | | | (1.525) | (3.043) |
| $Geo. Spill. Wholesale_{t-1}$ | | | -2.463 | -1.437 |
| | | | (1.997) | (1.883) |
| $Age_t$ | 0.426 | 0.702** | 0.628** | 0.920** |
| | (0.277) | (0.344) | (0.293) | (0.366) |
| $Age_t^2$ | -0.008** | -0.007* | -0.009** | -0.007* |
| | (0.004) | (0.004) | (0.004) | (0.004) |
| Year FE | Yes | Yes | Yes | Yes |
| Treatment of obs. where $UF$=100 | Dum. Var. | Dum. Var. | Dum. Var. | Dum. Var. |
| Max. LIML size distortion | <10% | <10% | <10% | <10% |
| Hansen J. P-value | 0.798 | 0.474 | 0.532 | 0.297 |
| First stage Shea Partial R$^2$. $Divet_t$ | .188 | .139 | .091 | .057 |
| First stage Shea Partial R$^2$. $Dereg_t$ | .074 | .062 | .119 | .116 |
| First stage F statistic. $Divest_t$ | 100.131 | 57.532 | 38.985 | 20.310 |
| First stage F statistic. $Dereg_t$ | 24.549 | 20.423 | 53.659 | 49.162 |
| R$^2$ | 0.410 | 0.398 | 0.397 | 0.375 |
| No. obs. | 1850 | 1850 | 1850 | 1850 |

Notes: Regression (15) limits divestiture geographical spillovers to divested nuclear reactors within states, and Regression (16) includes spillovers from divested reactors within states and neighbour states. Geographical spillovers from reactors operating within wholesale electricity markets are based on neighbour states. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. $UF$ represents total number of outage hours divided by potential generation and is the dependent variable. SE are robust to heteroskedasticity and autocorrelation with a Bartlett bandwidth = 2.

**Table 3.7: Estimation output of equation (3.3) and heterogeneous effects**

| **Variable** | | ***Divest***<br>**Mean**<br>**(SE)** | ***Wholesale***<br>**Mean**<br>**(SE)** | $\mathbf{R^2}$ |
|---|---|---|---|---|
| Reactors ranked based on past performance until wholesale market creation | 1st Quartile<br>(N=465) | -5.942***<br>(2.272) | 5.131<br>(3.328) | 0.086 |
| | 2nd Quartile<br>(N=467) | -4.729<br>(4.190) | -5.883<br>(6.791) | 0.072 |
| | 3rd Quartile<br>(N=468) | -18.105***<br>(4.068) | -7.231**<br>(3.550) | 0.430 |
| | 4th Quartile<br>(N=450) | -36.797***<br>(10.953) | 0.254<br>(9.234) | 0.461 |
| BWR vs. PWR | BWR<br>(N=611) | -12.394***<br>(3.956) | -8.332***<br>(2.962) | 0.470 |
| | PWR<br>(N=1,239) | -13.845***<br>(2.598) | 2.814<br>(3.923) | 0.405 |
| Past performance BWR | Top 50 %<br>(N= 305) | 0.342<br>(2.466) | 2.099<br>(3.039) | 0.389 |
| | Bottom 50 %<br>(N= 306) | -14.492<br>(9.624) | -12.651*<br>(6.999) | 0.564 |
| Past performance PWR | Top 50 %<br>(N= 627) | -6.887***<br>(2.252) | -1.924<br>(4.030) | 0.095 |
| | Bottom 50 %<br>(N=612) | -20.855***<br>(6.230) | 3.396<br>(8.388) | 0.506 |

Notes: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. The dependent variable *UF* represents total number of outage hours divided by potential generation. SEs are robust to heteroskedasticity and autocorrelation with a Bartlett bandwidth = 2.

## 7. Conclusions

A general claim made in this study is that instruments based on proportional hazard models are conceptually more appropriate when measuring the effect(s) of government interventions that persist over time, leading to substantially stronger instruments. As the treatment of endogeneity often represents a shortcoming of many empirical studies dealing with electricity market restructuring (Kwoka, 2008), we argue that this approach could be replicated in the context of many structural policy interventions where policy inertia substantially reduces the risk of reversal following reform, but also in the context of other economic decisions with the same properties (e.g. mergers, investment decisions).

Building on this approach, our findings show that the divestiture of nuclear reactors in the US has led to a substantial reduction in the unavailability factor of divested nuclear reactors in the US between 12 and 14%. In addition, the results highlight that divestiture has been particularly effective in improving the performance of nuclear reactors with the highest outage track record and has also led to some spillovers toward none-divested reactors through geographical, operation and technological channels.

Taking into account potential increase in operation and maintenance costs associated with divestiture, our back of the envelope estimate (based on Davis and Wolfram, 2012) would imply that divestiture has led to 57 TWh of extra generation and, at a wholesale market price of USD 60 MWh, USD 3.5 billion annual increase in revenues for the US nuclear sector. At the same time, descriptive insights from Davis and Wolfram indicate that during the period studied annual expenditures for divested reactors related to the nuclear fuel cycle and additional investments (e.g. generation capacity increases) have increased by USD 460 million[59] and USD 50 million, respectively. In addition, labour expenditures do not differ significantly between divested and non-divested reactors. This means that additional expenditures only account for about 14.5% of the additional revenues of divested reactors. In addition, considering the merit order of nuclear plants compared to fossil fuel plants in the US, this improvement in performance also has a significant impact on $CO_2$ emissions.

However, this study should not be considered as a cost benefit analysis of the restructuring of the US electricity markets. In particular, we only focus on nuclear power and generation activity. In that respect, one could hypothesise that vertical unbundling could have benefited generation to the detriment of electricity distribution. For instance, Triebs et al. (2010) shows that divestiture improves electricity generation efficiency but reduces the efficiency of distribution activity.

Finally, one needs to acknowledge that this study captures the average effect of vertical unbundling on nuclear power generation efficiency and that divestiture policy has also led to other changes in the US nuclear industry structures. Firstly, the sale of nuclear reactors has changed the ownership structure of nuclear reactors with an increase in private ownership.

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[59] Based on a nuclear fuel cost of USD 7 per MWh (MIT, 2009) and a fuel waste fee collected by the Department of Energy of USD 1 per MWh. Fuel consumption in nuclear reactors is proportionnal to generation.

Secondly, divestiture has also provided the opportunity to consolidate the US nuclear power sector and today three independent power producers own one-third of nuclear reactors. While we do not expect that not taking into account consolidation and ownership impacts our results[60], these two variables are also subject to endogeneity concerns as they happen simultaneously with divesture, and extra instruments variables (for which we do not have good candidates) would be needed to include them in our analysis.

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[60] For instance Davis and Wolfram (2012) find that consolidation has no significant impact on generation.

# Chapter 4:

# Nuclear reactor construction costs: the role of lead-time, standardization and technological progress.

## Abstract

This paper provides the first comparative analysis of nuclear reactor construction costs in France and the United States. Studying the cost of nuclear power has often been a challenge, owing to the lack of reliable data sources and heterogeneity between countries, as well as the long time horizon which requires controlling for input prices and structural changes. We build a simultaneous system of equations for overnight costs and construction time (lead-time) to control for endogeneity, using expected demand variation as an instrument. We argue that benefits from nuclear reactor program standardization can arise through short term coordination gains, when the diversity of nuclear reactors' technologies under construction is low, or through long term benefits from learning spillovers from past reactor construction experience, if those spillovers are limited to similar reactors. We find that overnight construction costs benefit directly from learning spillovers but that these spillovers are only significant for nuclear models built by the same Architect-Engineer (A-E). 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.

# Résumé

Cet article constitue la première analyse comparative des coûts de construction de réacteurs nucléaires en France et aux États-Unis. L'étude du coût de l'énergie nucléaire a souvent été un défi, en raison de l'absence de sources de données fiables et de l'hétérogénéité entre les pays, ainsi que de l'horizon de long terme qui nécessite de contrôler pour le prix des inputs et les changements structurels. Nous construisons un système d'équations pour les coûts et le temps de construction afin de contrôler leur endogénéité en utilisant la variation de la demande d'électricité comme instrument. Nous argumentons que les avantages de standardisation des programmes de réacteurs nucléaires peuvent survenir grâce à des gains de coordination à court terme, lorsque la diversité des modèles de réacteurs nucléaires en construction est faible, ou par des avantages à long terme, du fait des effets apprentissage qui sont limités aux réacteurs similaires. Nous montrons que les coûts de construction bénéficient directement des effets d'apprentissage, mais que ces effets ne sont significatifs que pour les modèles de réacteurs construits par le même architecte ensemblier. En outre, nous montrons que la standardisation des réacteurs nucléaires en construction a un effet indirect et positif sur les coûts de construction grâce à une réduction des délais de construction, ce dernier étant l'un des principaux facteurs des coûts de construction. A l'inverse, nous explorons aussi la possibilité d'apprendre par la recherche et constatons que, contrairement à d'autres technologies de l'énergie, l'innovation dans le nucléaire conduit à des coûts de construction croissants.

# 1. Introduction and literature review

Many countries have asserted their interest in building nuclear power plants either to ensure security of energy supply, meet $CO_2$ emission reduction targets, or both. This is the case for China, the Czech Republic, India, Poland, Turkey, the United Kingdom (UK) and the United States (US) (IAEA, 2012). Nevertheless, uncertainties surrounding construction costs of new nuclear reactors, along with risks associated with changes in the regulatory framework, have raised doubts about the competitiveness of this technology in both developed and developing countries and led to difficulties for the financing of nuclear new-build projects (Nuttall and Taylor, 2009).

The construction costs of nuclear reactors are particularly important for the competitiveness of nuclear power for two reasons. Firstly, nuclear power is a base-load electricity source with a construction time of, on average, 7.4 years in OECD countries (See Table 4.3 in Section 4.4). As such, construction costs can represent between 60 to 80% of the levelized cost of nuclear power (IEA, 2010). Secondly, there is still a sense of agreement that building the first reactor of a new design will come with specific fixed costs. In that respect, the rationale for building this first reactor – and sometimes the associated subsidies – is motivated by the assumption that construction costs will decrease as the industry benefits from learning effects.

These risks and uncertainties are reflected in recent construction experience in OECD countries. For instance, while the initial cost estimate made by the French nuclear utility *Electricité de France* (EDF) in 2009 for the EPR nuclear reactor in Flamanville (France) was close to € 3 billion (i.e. $€_{2010}$ 2,000/MWe), the latest announcement indicates that the costs may have nearly tripled, up to € 8.5 billion (i.e. $€_{2010}$ 5,100/MWe),[61] and similar costs are expected for the EPR construction in Finland. In turn, other countries such as the UK, which have been considering the adoption of this technology, are reluctant to do so precisely because the costs estimates have increased and there remain large uncertainties about the possibility for EDF to derive learning by doing benefits from its current reactor's construction for future projects.

Despite the significance of construction costs for nuclear power competitive margins, the economic literature has so far failed to provide clear empirical evidence of the determinants of these costs and the existence of learning effects, mainly due to the lack of comparable and reliable data. In particular, data on construction costs for the French nuclear program were only

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[61] EDF Press Release 12/03/2012 (last accessed 10 June 2013): http://press.edf.com/press-releases/all-press-releases/2012/flamanville-epr-costs-revised-still-on-schedule-93875.html

published in 2012 (Cour des Comptes, 2012). Before this date, existing estimates (Grubler, 2010), were based on extrapolations of annual investment expenditures of EDF.

Most of the existing econometric studies have used data on US construction costs and attribute the escalation in costs to the increase in complexity of new reactors. Many authors argue that the experience gained by nuclear vendors led to the design of bigger and more complex reactors that took longer lead-times to construct and required closer regulatory monitoring (Komanoff, 1981; Zimmerman, 1982; Rothwell, 1986; Cantor and Hewlett, 1988; and Cooper, 2010). In the case of the French nuclear program, Grubler (2010) argues in favour of a negative learning by doing effect, whereas Escobar and Lévêque (2012) find evidence of learning within specific reactor models.

It is also generally accepted that the heterogeneity in the nuclear fleet and the multiplicity of vendors and utilities did not create the gains of learning by doing. David and Rothwell (1996) argue that the lack of standardization in the nuclear US fleet entailed « *ballooning*» of construction costs, although some positive learning effects are found by Cantor and Hewlett (1988) and McCabe (1996) for construction projects managed by utilities.

In this paper, we propose the first empirical investigation of the role of standardization and learning opportunities on nuclear reactors' construction costs, using historical cost data from the US and France. This choice is motivated by the fact that these two countries have followed different paths in terms of industrial structure and technological diversity. For instance, while in the US several firms have acted as Architect-Engineer (A-E) and vendors of nuclear reactors, these roles have been the responsibility of the utility EDF and Areva (formerly Framatome) in France, respectively. Similarly, if the two countries have both built Pressurized Water Reactors (PWR), France has implemented fewer technological variations compared to the US. This means that by looking at French and US experience together one can benefit from more heterogeneity in the data in order to derive robust estimates.

Our empirical strategy follows those of Rothwell (1986) and Cantor and Hewlett (1988), where a simultaneous equation model is estimated for construction costs and lead-time using US data. However, our analysis tackles a number of other empirical shortcomings. Firstly, our study allows direct comparison of nuclear reactors' overnight construction costs in the two countries using the access to data[62] on engineering and other related expenditures for French reactors, which are not detailed in the Cour des Comptes' (2012) report. Secondly, we use an IV approach, using the expected demand as an instrument for lead-time (Cantor and Hewlett, 1988), and also test the hypothesis that some of the benefits of standardization may have an indirect impact on cost through a reduction in lead-time. Thirdly, we consider two potential benefits of nuclear programs standardization: (*i*) standardization can have short term benefits on costs reductions through reduced diversity of designs for reactors under construction, leading to coordination gains; and (*ii*) standardization may also allow long term benefits through learning by doing spillovers from similar units built previously. In order to capture these spillover effects we differentiate spillovers based on reactor models and A-E firms.

In addition, the literature and policy debate has so far essentially focused on the role of experience through the study of learning by doing effects, in nuclear construction cost reduction. However, considering the importance of public R&D expenditures on nuclear power, an equally important policy question would be the influence of learning by searching. For instance, for many energy technologies, learning by searching has been highlighted as an important driver of energy cost reduction.

In the nuclear power sector, evidence of a positive learning by searching effect has only been found using cost and innovation data from energy economics modelling tools (Jamsab, 2007). In that respect, to the best of our knowledge, there is no existing literature that has looked at this effect using existing cost data. Hence, our study is the first to bring together data on nuclear power overnight construction costs and knowledge capabilities data, using original data from nuclear reactors' costs in the US and in France, and a measure of the stock of knowledge based on patent data.

Our results suggest that standardization of nuclear reactors programs is one of the main factors in limiting costs escalation and takes place at two levels. Firstly, standardization benefits are found to originate from coordination gains induced by the diversity of reactors under construction. However, this effect impacts costs indirectly through a reduction in lead-time, which has a strong and significant impact on costs. This result is also confirmed in other OECD countries with different market structure and technological paths.

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[62] These data on overnight construction costs have been made available to the authors by EDF. As such they differ slightly from the data available in the Cour des Comptes' report where expenditure regarding engineering work, pre-operating expenses, etc. are presented at an aggregated level.

Secondly, we find that learning by doing spillovers also relate to some long term benefits of standardization, considering that these spillovers are limited to nuclear models built by the same A-E firm. This highlights the importance of reactor design standardization and the role played by the A-E firm in reducing construction costs increases.

On the other hand, we show that contrary to other energy technologies (Kobos et al., 2006) there is a negative effect of learning by searching on reactors' overnight construction costs. This can be explained by the fact that innovation in nuclear power technologies has been driven by nuclear safety considerations (Chapter 1), leading to safer (Chapter 2), but more expensive nuclear reactors.

These results suggest paths for future cost reductions through greater standardization of reactor technologies and more emphasis on the role of A-E firms in improving the competitiveness of nuclear power. In parallel, from a policy perspective one may argue that lead-time will play a more important role under a liberalized electricity market, where higher discount rates may apply, meaning that the competitiveness of nuclear power will be more conditional on the standardization of nuclear programs.

The ensuing sections of this paper are organised as follows: in Section 2 we present our research hypotheses along with stylized facts on the development and cost experience of nuclear power in the US and France; Section 3 describes our empirical strategy and the results; Section 4 further investigates international experiences with nuclear power construction using a larger dataset on nuclear power lead-time; and finally, Section 5 concludes.

# 2. Main hypotheses, data and stylized facts

## 2.1. Main hypotheses on the relation between construction costs and lead-time

The construction of nuclear reactors is a complex process and requires the coordination of several firms, subject to monitoring and regulation from a nuclear safety regulator prior to, during and after the construction stage. Typically, following or not a tender, an electricity generation firm (hereafter the utility) places an order for the construction of a nuclear reactor and selects a specific reactor design offered by a nuclear vendor. This construction is then managed by an A-E firm which supervises the construction and coordinates the multiple firms involved in the project. This includes the constructor, the Nuclear Steam Supply System (NSSS) manufacturer, the turbine manufacturer, as well as a number of subcontractors. The allocation of firms' responsibilities may differ between projects and, for instance, the utility may decide to also be the A-E (as it is the case in France and sometimes in the US).

One consequence of the involvement of multiple firms in the project is that the objective functions of these firms may differ (Rothwell, 1986). In particular, the A-E firm will minimize costs, whereas the utility will aim to maximize the net present value of the project. This means that the lead-time of the project becomes a decision variable for the utility as, for instance, it can decide to spend more on construction costs in order to reduce the construction period and derive revenue sooner.

From an empirical point of view, the construction cost will be determined by these two objective functions and will be jointly determined with lead-time, leading to a simultaneity problem and lead-time to enter into the cost equation. The inclusion of lead-time in the cost equation can be further motivated by the fact that there exists additional fixed costs associated with longer construction periods, for instance, as utilities are generally in charge of project financing and due to immobilized construction equipment and labour force.

Consequently, OLS estimators will be biased. One solution consists of using an instrument variable approach in order to regain consistency. Our empirical strategy follows this approach with national expected demand ($ElecDem$) of electricity in country $c$ as an instrument for lead-time (Cantor and Hewlett, 1988), considering that future demand impacts the net present value of the project but does not influence current construction costs

Our baseline model specification follows equations (4.1) and (4.2) where $X_i$ is a vector of independent variables which can impact both cost ($CT_i$) and lead-time ($LT_i$) and will be further presented in the following sub-section:

$$CT_i = \alpha_0 + \alpha_1 LT_i + \sum_{j=2}^{J} \alpha_j X_{i,j} + u_i \tag{4.1}$$

$$LT_i = \beta_0 + \beta_1 ElecDem_i + \sum_{j=2}^{J} \beta_j X_{i,j} + \varepsilon_i \tag{4.2}$$

## 2.2. Data and hypotheses regarding the effects of standardization and learning opportunities

Data have been collected from a variety of sources. As mentioned in the introduction, overnight construction costs are collected from the Cour des Comptes' (2012) report, and adjustments have been made to account for engineering costs using additional data from EDF. For the US, overnight construction costs data have been published in the online Appendix of Koomey and Hultman (2007)[63].

However, the US costs data are still more detailed as they take place at the reactor level, whereas the French data have been published for pairs of reactors. This can be explained by the fact that the French nuclear program has been organised with the joint construction of two reactors on the same site. We tackle this shortcoming of the data by treating each pair of French reactors as one reactor, with the average capacity of the two and the date when the latest reactor's construction is completed as corresponding variables.

In parallel, data on nuclear reactor technical characteristics are collected from the IAEA Power Reactor Information System (PRIS) database. This covers the size of the reactor in MWe ($Cap_i$), that can be used to test the existence of economies of scale, the year when the construction of the reactor starts and the year when the construction is completed[64]. We also collect information on nuclear reactor cooling systems and containment structures[65], in order to define different reactor models. Additional data on A-E firms and initial operators are collected for the US from the US Nuclear Regulatory Commission. For France, these data do not require any specific access as EDF has always acted as the A-E firm and is the sole utility to operate nuclear reactors.

Based on these reactor level data on technology characteristics and industrial structure, we consider three main channels through which the organisation of the nuclear industry can reduce cost and/or lead-time: *(i)* the standardization of reactor models under construction; *(ii)* learning by doing opportunities from past reactors' construction; and *(iii)* learning by searching based on the discounted stock of nuclear specific patents.

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[63] Available at (last accessed 10 June 2013): www.sciencedirect.com/science/MiamiMultiMediaURL/1-s2.0-S0301421507002558/1-s2.0-S0301421507002558-mmc1.pdf/271097/FULL/S0301421507002558/a0a731e015ab16acfe667568061b8314/mmc1.pdf

[64] We define the year where construction is completed as the year when the reactor is connected to the electricity grid.

[65] Data on nuclear reactor cooling systems and containment structures are detailed in Appendix 4.

**Hypotheses on the role of nuclear programs standardization**

A number of efficiency gains may be expected from the standardization of nuclear programs. One aspect of standardization explored in the literature (David and Rothwell, 1996) relates to a trade-off between the ability to learn from diversity in nuclear reactors versus learning from similar models[66]. This long term dimension of standardization will be covered by the learning opportunities hypotheses, where learning may be conditional on the level of standardization.

In parallel, one may also argue that standardization benefits can arise from the diversity of nuclear reactors under construction. We expect that a country with low diversity in models of nuclear reactors under construction could benefit from coordination gains during the construction period. This could be driven by the fact that similar high-tech components will be built during the same period, such as steam generators or turbines, leading to economies of scale. Similarly, a low diversity in reactors under construction also reduces technological uncertainty and, in particular, reduces the workload for the nuclear safety authority which monitors the construction of reactors. To measure this potential benefit of standardization during the construction period, we compute a Herfindahl Hirschman Index (HHI) based on the number of specific reactor models under construction when the construction of reactor $i$ starts.

This index is defined according to equation (4.3) below as the sum of the squares of the market shares of the $M$ reactor models under construction in country $c$ and year $t$. To capture this expected benefit of standardization, we also control for the number of reactors under construction ($NPP.UC_i$) as, for instance, a high HHI could either correspond to a situation where only one reactor is under construction or to a situation where multiple and similar reactors are being built.

$$HHI_{c,t} = \sum_{m=1}^{M} s_{m,t,c}^{2} \tag{4.3}$$

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[66] Note that though we formulate the same hypothesis as David and Rothwell (1996) our approach is different. David and Rothwell measure standardization based on an HHI index of reactor performance once these reactors have been built. One could argue that this approach might be subject to endogeneity concerns, for instance, if the utility decides to spend more on fixed costs in order to derive higher operating performance.

### Hypotheses on learning by doing opportunities

As nuclear reactors are complex units, the ability to derive learning effects may be conditional on the similarities between reactor models and the A-E firm which builds reactors. In that respect, we hypothesize that experience spillovers can take place through two main channels: nuclear reactors completed by the same A-E firm ($ExpArq_i$) and completed nuclear reactors of the same design ($ExpMo_i$).

Furthermore, spillovers might also be conditional on the A-E firm's experience with specific nuclear models ($ExpArqMo_i$). One could argue that this corresponds to the second potential benefit of standardization mentioned above, where the ability to derive learning by doing spillovers is conditional on the standardization path followed by the nuclear industry, and this could be interpreted as a long term benefit of reactor standardization.

This more restricted level of learning by doing opportunities is defined following the traditional definition used in the literature (Irwin and Klenow, 1994). For instance, in equation (4.4) below we consider that country level experience ($ExpC_i$) can be disentangled into four levels of learning spillovers: *(i)* the experience of the A-E firm with the reactor model ($ExpArqMo_i$), *(ii)* the experience of the A-E firm with other models ($ExpArqNoMo_i$), *(iii)* the experience of other A-E firms with the same model ($ExpNoArqMo_i$), and *(iv)* the experience of other A-E firms with other models ($ExpNoArqNoMo_i$).

$$ExpC_i = ExpArqMo_i + ExpArqNoMo_i + ExpNoArqMo_i + ExpNoArqNoMo_i \tag{4.4}$$

### Hypotheses on learning by searching

In parallel to the learning by doing hypothesis, one standard hypothesis made in the energy economics literature is that learning by doing might not be the only source of learning. In particular, learning by searching is often found in many empirical studies dealing with the energy sector (e.g. Klaassen et al. 2005; Kobos et al., 2006) to contribute to cost reduction. In the case of nuclear power, the impact of innovation activity on cost remains an empirical question. On the one hand, there exists evidence (Jamsab, 2007) that innovation may contribute to cost reduction, although this evidence is derived from energy modelling tools and is not based on actual costs data. On the other hand, innovation in nuclear power essentially deals with safety improvements owing to the role of safety regulation (Chapter 1). As such, innovation might lead to safer, but more complex and more expensive nuclear reactors.

As a proxy for nuclear innovation, we rely on a unique dataset on nuclear specific patents[67], using a discounted stock of priority patent applications. This discounted stock is set at the country level, reflecting the fact that innovation can originate both from R&D laboratories and nuclear vendors and can be understood to reflect national knowledge capabilities. We set the discount factor at 10%, a conservative parameter found in many studies on the dynamics of innovation (Perri, 2005).

**Control variables**

As aforementioned, we also use the expected demand of electricity as an instrument for lead-time, using the three year trend in future electricity consumption, and we control for the possibility of structural breaks following two major nuclear accidents: Three Mile Island (TMI) in 1979 and Chernobyl in 1986. Because, the TMI accident took place in the US, we also investigate for the possibility that this accident has had a heterogeneous effect in the two countries, with country specific TMI dummy variables.

Finally, we collect data on prices for two major inputs to the construction of nuclear reactors: cement and labour force. These data are collected from the French National Statistics Institute (INSEE) and the US Census Bureau respectively for the two countries.

All the data are summarized and further defined in Table 4.1 below.

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[67] See Chapter 1 for more details of nuclear patent data. These data are extracted from the Patstat database and cover nuclear fission patents, excluding fast breeding reactors. It should be stressed that we use priority patent applications in France and the US filed by national innovators. In addition, most of the nuclear patents in Europe go through national patent offices (and not the European Patent Office) due to national security considerations. More details on the use of patents as a proxy for innovation effort can be found in a recent OECD (2009) report.

Table 4.1: Summary statistics

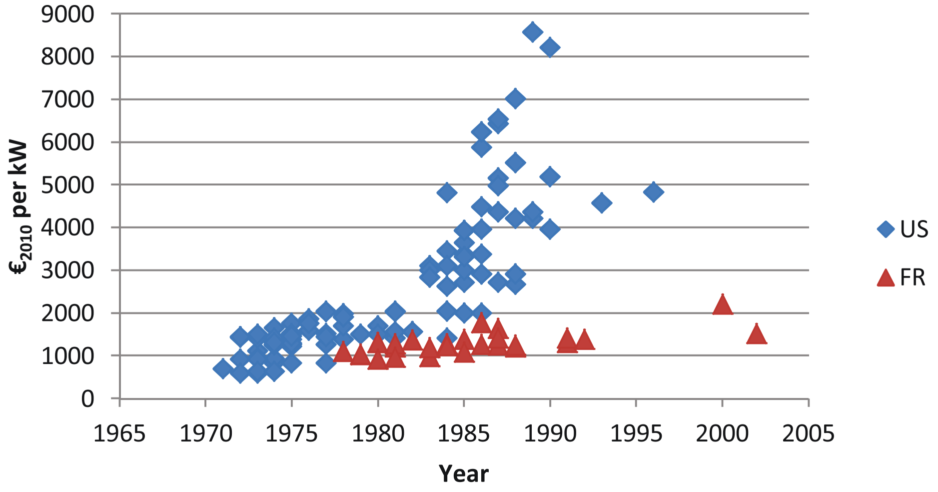
| Variable | Definition | Mean | Std. Dev. | Min | Max |
|---|---|---|---|---|---|
| $Cost$ | Cost in €$_{2010}$/MWe | 2282 | 1.639 | 599 | 8571 |
| $Leadtime$ | Construction time | 8.578 | 3.507 | 4.3 | 23.3 |
| $Cap$ | Size in MWe | 992.390 | 201.854 | 478 | 1472.5 |
| $HHI.Mo$ | Standardization of reactors under construction | 0.230 | 0.171 | 0.122 | 1 |
| $Know$ | Discounted stock of nuclear patents | 582.519 | 103.964 | 326.489 | 903.395 |
| $ExpArqMo$ | Experience A-E Model (# reactors) | 1.695 | 2.672 | 0 | 14 |
| $ExpArqNoMo$ | Experience A-E diff. model (# reactors) | 9.867 | 13.162 | 0 | 54 |
| $ExpNoArqMo$ | Experience diff. A-E model (# reactors) | 2.921 | 4.073 | 0 | 18 |
| $ExpNoArqNoMo$ | Experience diff. A-E diff. model (# reactors) | 27.414 | 25.731 | 0 | 87 |
| $Arq.Utility$ | Vertical integration A-E with utility | .382 | .487 | 0 | 1 |
| $Cement$ | Cement cost index | 88.019 | 31.571 | 36.8 | 186.556 |
| $Labour$ | Labour cost index | 247.568 | 168.027 | 87.439 | 921.968 |
| $DemElec$ | Future electricity demand (3 year trend) | 0.043 | 0.010 | 0.017 | 0.061 |
| $NPP.UC$ | #reactors under construction | 42.632 | 20.747 | 2 | 69 |

## 2.3. Stylized facts

Figure 4.1 below highlights the strong differences between the trend in overnight construction costs in France and in the US. In particular, we observe that over the entire time period the costs have more than doubled in France, from 921.1 €/Mwe in 1980 for the Tricastin 3 and 4 reactors up to 2209 €/MW in 2000 for the Chooz 1 and 2 reactors. In the US, this increase has been much more rapid with the cost almost increasing by a factor of 14 from 599 €/Mwe in 1972 for Turkey Point 3 up to 8571€/Mwe in 1989 for the Shoreham reactor.

One can also note that costs have been much more dispersed in the US. For instance, if we look at nuclear reactors completed in 1986 in the US, the costs range from 2000 €/Mwe for Catawba 2 and 6246 €/Mwe for the Hope Creek reactor. Since France and the US have experienced important differences in terms of industrial structure choices during this period, with more vertical integration and standardization of nuclear reactor designs for France, this figure provides initial suggestions that the French experience has been more successful in containing the escalation of construction costs. However, to explain the determinants behind construction costs and establish causality one has to develop a structural econometric framework, which we do in the next section.

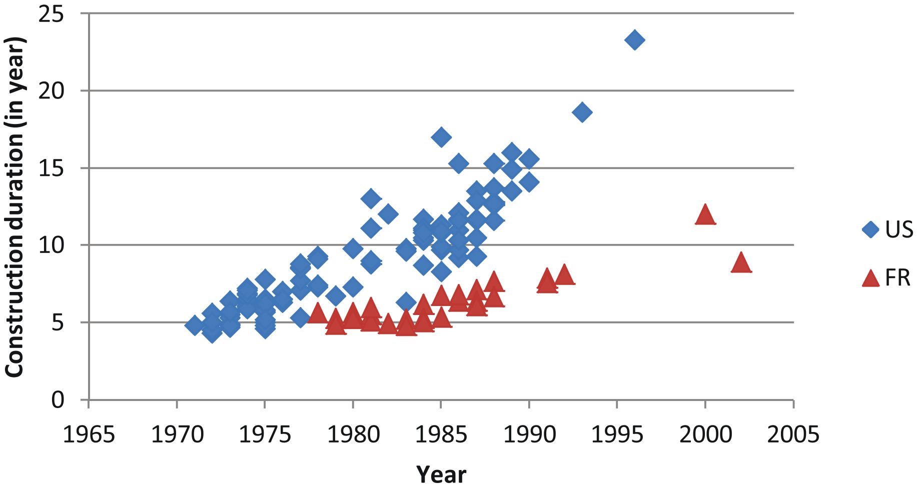
**Figure 4.1: Nuclear reactors' overnight construction costs in the US and France**



One of the most likely drivers of overnight construction costs is presented in Figure 4.2 below. In this figure we plot the construction time (in years) of nuclear reactors in the two countries. One can generally notice that we observe the same trend as in the previous figure presenting construction costs: construction time has increased more rapidly in the US than in France. This can be understood by the fact that long construction time will generate additional costs owing to immobilized equipment and labour force. This may also reflect complexity of nuclear design, leading both to more expensive reactors and longer construction times.

The increase in lead-time still appears to be of a lower magnitude than the increase in cost. For instance, lead-time in the US ranges from 5 years for the Vermont Yankee reactor, up to 23.3 years for the Watts Bar 1 reactor, which represents a 5-fold increase.

Figure 4.2: Nuclear reactors construction time in years



Finally, Figure 4.3 below presents the timing of nuclear reactors' construction (in MWe of newly installed capacity) in France and in the US. As we observe, the US nuclear program was initiated in the early 1960s about 10 years before the French program[68], and the last reactor was completed in 1996. The French nuclear program was initiated in the early 1970s in reaction to the first oil shock. About twice as many nuclear reactors have been built in the US compared to France (104 versus 58), and one would expect that if standardization of nuclear programs did not matter, the US would have experienced stronger cost reductions.

One may also notice that both programs have experienced some important variations over time. For instance, in the US the newly installed capacity dropped following the Three Mile Island (TMI) nuclear accident in 1979, which might be due to ensuing changes in safety regulation. Only two reactors have been completed in the US since 1990. Popular explanations for this change have been the counter oil shock of 1986, the liberalization of the US electricity market during the 1990s which shifted the allocation of construction risks from the consumers toward electricity producers, along with more stringent safety regulation.

In France, reactors were built essentially during the 1970s and the 1990s. Similarly to the case of the US, only two reactors have been completed since the early 1990s. However, the explanation for the lack of construction of new nuclear reactors might be somewhat different as the share of

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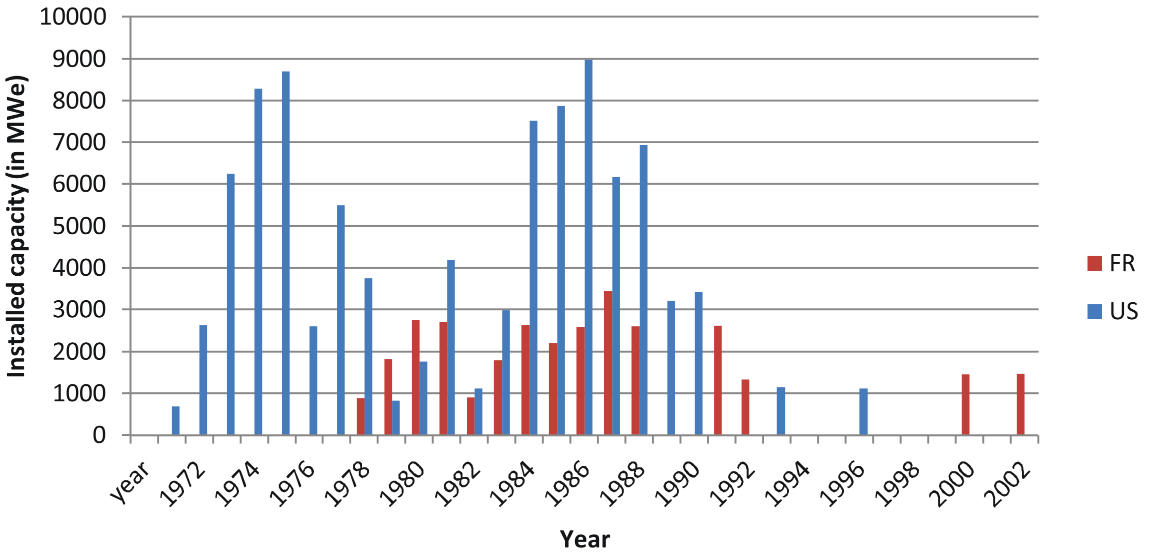
[68] Note that France initially started a nuclear program based on Graphite Gas Reactor (GGR) technology. However, the first oil shock in 1972 led the French government to decide to adopt the US PWR technology as it had already been built in the US. Only a few GGR were built in France and costs data on this reactor technology are not available.

nuclear power in the French electricity mix had reached 75% by 2000, leading to lower incentives to build new reactors.

Figure 4.3: Nuclear power installed capacity in MWe



# 3. Model specifications and results: France versus the US

## 3.1. Model specifications

The simultaneous system of equations used to study construction costs and lead-time follows a Cobb-Douglas functional form[69], taking into account the endogeneity of lead-time using expected demand of electricity as an instrument and controlling for the effects of capacity and input prices. A set of explanatory variables to identify learning effects are included, as well as the HHI index for short term standardization and dummy variables to differentiate projects managed or not by the utility, to capture the effect of structural breaks due to major nuclear accidents and to control for temporal and country fixed-effects.

Based on equations (4.1) and (4.2), the equations for the baseline model specification are as follows:

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[69] This functional form that has been extensively used in the literature on nuclear construction costs (e.g. Komanoff, 1981; Cantor and Hewlett, 1988; McCabe, 1996).

$$\begin{aligned}\ln(CTt)_i = {} & \beta_0 + \beta_1 \ln(Cap)_i + \beta_2 \ln(Cement)_i + \beta_3 \ln(Labour)_i + \beta_4 \ln(LT)_i \\ & + \beta_5 ArchUtility_i + \beta_6 \ln(ExpArqMo_i) + \beta_7 \ln(ExpArqNoMo_i) \\ & + \beta_8 \ln(ExpNoArqMo_i) + \beta_9 \ln(ExpNoArqNoMo_i) + \beta_{10} HHi.Mo_i \\ & + \beta_{11} \ln(NPP.UC\_i\ ) + \beta_{12} TMIUS + \beta_{13} TMIFR + \beta_{14} Country + \beta_{15} Trend \\ & + \varepsilon_i \end{aligned} \tag{4.5}$$

$$\begin{aligned}\ln(LT_i) = {} & \gamma_0 + \gamma_1 \ln(Cap)_i + \gamma_2 ArchUtility_i + \gamma_3 \ln(ExpArqMo_i) + \gamma_4 \ln(ExpArqNoMo_i) \\ & + \gamma_5 \ln(ExpNoArqMo_i) + \gamma_6 \ln(ExpNoArqNoMo_i) + \gamma_7 HHi.Mo_i \\ & + \gamma_8 \ln(ElecDem) + \gamma_9 \ln(NPP.UC_i) + \gamma_{10} TMIUS + \gamma_{11} TMIFR \\ & + +\gamma_{12} Country + \gamma_{13} Trend + u_i \end{aligned} \tag{4.6}$$

As aforementioned, our empirical strategy follows Rothwell's (1986) structural model which justifies the inclusion of lead-time in the cost equation as an endogenous variable. In his model, the utility chooses the construction lead-time to maximize the net present value of the plant and then the constructor minimizes the costs within this constraint. Moreover, Cantor and Hewlett (1988) argue that there are unobserved factors captured in the lead-times that are likely to affect the costs, such as the risks of changes in safety regulations during construction, or potential rise of hiring expenses due to long delays.

Recall that the $HHi.Mo$ measures the technological diversity in each country at the moment at which the construction of each reactor began. If this index is close to one, it means that in that year only one type of reactor was being built.

### 3.2. Results

The estimated output for equations (4.5) and (4.6) are presented in Tables 4.2 and 4.3 below, using four different model specifications. Estimation output of the cost and lead-time equations in Model 1 represents our baseline estimate. In this model, we make the hypothesis that learning by doing exists at the A-E firm level and for specific nuclear models. In Model 2, we consider the possibility of learning by searching in addition to standardization and learning by doing. Model 3 focuses on the learning effects at the A-E firm level, and we aggregate the experience of the A-E firm regardless of the reactor model. Finally, Model 4 considers the experience at the reactor model level, regardless of the A-E firm.

The first result of our analysis refers to the importance of model specification in identifying significant learning effects in the construction of nuclear power plants. Previous studies account for the experience at the firm level as in Model 3 or at the technological level as in Model 4. However as we can see in Tables 4.2 and 4.3, the learning effects are positive and significant only when we take into account solely the experience of A-E firms with specific models of reactor ($ExpArqMo_i$). After taking into account the effect of $ExpArqMo_i$ on lead-time, the point estimate of our baseline model (1) indicates that when this specific experience increases by 1%, costs are reduced by -0.142 + 1.933 * 0.009 = 0.124%.

In other words we find that, everything being equal, one can expect on average a 12.4% reduction in construction costs for the second unit of a reactor model built by the same A-E firm.

This result is in line with what is expected from the economic literature on learning effects and recent evidence (Escobar and Lévêque, 2013) on the French nuclear fleet and or confirmed using different model specifications as shown in Appendix 4[70]. From a policy perspective, it is important to highlight that the benefits that a firm can derive from standardization in terms of reduction in construction costs, after building the first reactor of a series, requires long term commitment precisely because the construction of a nuclear power plant is a lengthy project.

Regarding the learning effects in the lead-time equation, we find that experience in the construction of other models, either of the same firm ($ExpArqNoMo_i$) or of others ($ExpNoArqNoMo_i$), has a negative impact on the construction periods which translates into an increase in the construction costs. This result shows that, due to the complexity of a nuclear reactor and the importance of A-E firms in construction projects, it is not possible to directly transfer previous knowledge and experience gained on the construction of any type of reactor to the new projects.

This detrimental effect of model diversity also leads to short term benefits of standardization. The estimate for the $HHI.Mo_i$ index suggests that an increase in the diversity of models under construction in a given year (i.e. HHI smaller than 1), increases construction costs indirectly through lead-time, considering that lead-time is found to have a strong and significant impact on costs.

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[70] For robustness tests we consider, in Appendix 4, country specific time trends (with a quadratic term) in order to control, for instance, for time variant changes in safety regulation in France and the US. We also define the learning by doing variables as $1/(1+X)$ instead of $ln(X)$ as both model specifications have been used in the literature (Joskow and Rose, 1985). Our results remain unchanged.

This result can be explained by the fact that when the diversity of nuclear reactors is high, the nuclear safety authority has to assess the potential risks of different models of reactors which prevents rapid monitoring and licensing procedures, due to the heterogeneity in demand which could lead to supply chain constraints and construction delays. As such, it is rational to find that this short term effect impacts primarily the lead-time equation.

Given the nature of these three results, one may argue that the lack of standardization harms the competitiveness of nuclear power in two ways. Firstly, it reduces the potential gains in terms of costs savings in the long term, through learning by doing at the firm level. Secondly, it tends to increase the construction lead-times and therefore the construction costs in the short term.

In addition, the results highlight positive and significant economies of scale. Indeed, we find that larger nuclear reactors take longer to build but are also cheaper per MWe. The net effect on cost can be derived from offsetting the direct effect on cost with the indirect effect on lead-time. For instance, Model 1 indicates a net impact of -0.769 + (1.933 * 0.125) = -0.527. This coefficient can be interpreted as an elasticity, meaning that a 10% increase in size reduces construction costs by 5.27%.

With respect to the role of A-E firms, we also show that when a utility takes the A-E firm responsibility, construction costs are lower than when a project is managed by another firm. This result has been identified in previous studies (e.g. Cantor and Hewlett, 1986 and McCabe, 1996) and it can be understood by the fact that a vertically integrated utility reduces potential asymmetric information problems between the utility and the firms involved in the construction of nuclear reactors, leading to cost reductions.

In Table 4.2 we also present the results for Model 2, which in addition to the variables in Model 1 includes the discounted stock of priority patent applications ($Know_i$) in order to capture the effect of innovation on construction costs. The positive estimate found is contradictory to the pattern observed in many energy technologies, such as other renewable energy sources (Kobos et al., 2006). This can be explained by the fact that innovation has been driven by the requirements of nuclear safety authorities (Chapter 1), leading to improvements in the safety performance of existing reactors (Chapter 2).

In other words, this highlights the long term trade-off faced by the nuclear power sector: on the one hand innovation is needed to reduce the externalities associated with nuclear accident risks;

on the other hand this innovation hampers the competitiveness of nuclear power through an increase in construction costs.

One can also note that this result is contrary to the initial findings of Jamsab (2007) who relies on data extracted from energy modelling tools. Hence, from a methodological perspective this result stresses the necessity of looking at real cost data before drawing policy conclusions on energy technologies costs trajectories.

Finally, it is important to analyse the effect of the major nuclear accidents in our system of equations. As we can see in Table 4.3, the impact on the construction costs both in the US and in France due to TMI and Chernobyl came indirectly from an increase in lead-time. Logically, TMI primarily impacted the US where this reactor was located and had no significant impact on France. Chernobyl, which took place in the Ukraine, had a positive and significant impact, albeit at the 10% level, on lead-time in the two countries. This result suggests that closer monitoring from nuclear safety authorities following these accidents resulted in delays in the construction of the reactors installed afterwards.

### Table 4.2: Estimation output of equations (4.5) and (4.6)

| | Model 1 | | Model 2 | |
|---|---|---|---|---|
| | Cost | Leadtime | Cost | Leadtime |
| $ln.Cap$ | -0.769*** | 0.125** | -0.624*** | 0.125** |
| | (0.192) | (0.053) | (0.182) | (0.0531) |
| $ln.Cement$ | 0.126 | | 0.0882 | |
| | (0.469) | | (0.424) | |
| $ln.Labour$ | -1.375 | | -0.771 | |
| | (0.852) | | (0.806) | |
| $ln.Leadtime$ | 1.933*** | | 1.064* | |
| | (0.580) | | (0.622) | |
| $ln.ExpArqMo$ | -0.142*** | 0.009 | -0.149*** | 0.009 |
| | (0.038) | (0.011) | (0.034) | (0.011) |
| $ln.ExpArqNoMo$ | 0.025 | 0.026*** | 0.029 | 0.026*** |
| | (0.034) | (0.009) | (0.031) | (0.009) |
| $ln.ExpNoArqMo$ | 0.046 | 0.010 | 0.038 | 0.010 |
| | (0.039) | (0.012) | (0.035) | (0.012) |
| $ln.ExpNoArqNoM$ | -0.068 | 0.141*** | -0.039 | 0.141*** |
| | (0.096) | (0.017) | (0.087) | (0.017) |
| $ln.Know$ | | | 1.416*** | |
| | | | (0.522) | |
| $HHI.Mo$ | 0.454 | -0.566*** | 0.374 | -0.566*** |
| | (0.537) | (0.160) | (0.485) | (0.160) |
| $ln.NPP.UC$ | 0.313*** | -0.071** | 0.324*** | -0.071** |
| | (0.117) | (0.034) | (0.105) | (0.034) |
| $Arq.Utility$ | -0.256*** | 0.009 | -0.285*** | 0.009 |
| | (0.093) | (0.028) | (0.085) | (0.028) |
| $ln.Demand$ | | -1.235*** | | -1.235*** |
| | | (0.113) | | (0.113) |
| $TMI.US$ | -0.058 | 0.272*** | 0.115 | 0.272*** |
| | (0.184) | (0.0431) | (0.179) | (0.043) |
| $TMI.FR$ | -0.015 | -0.028 | -0.064 | -0.028 |
| | (0.246) | (0.074) | (0.223) | (0.074) |
| $Cherno$ | -0.077 | 0.058* | -0.030 | 0.058* |
| | (0.123) | (0.031) | (0.113) | (0.031) |
| $Constant$ | 6.420** | -2.347*** | -4.182 | -2.347*** |
| | (2.915) | (0.448) | (4.767) | (0.448) |
| Country FE | Yes | Yes | Yes | Yes |
| Trend + trend$^2$ | Yes | Yes | Yes | Yes |
| Obs. | 128 | 128 | 128 | 128 |
| Adj. R$^2$ | 0.833 | 0.955 | 0.866 | 0.955 |

Note: Standard errors in brackets. *** p<0.01, ** p<0.05,* p<0.1

Table 4.3: Estimation output of equations (4.5) and (4.6)

| | **Model 3** | | **Model 4** | |
|---|---|---|---|---|
| | **Cost** | **Leadtime** | **Cost** | **Leadtime** |
| $ln.Cap$ | -0.680*** | 0.121** | -0.716*** | 0.102** |
| | (0.196) | (0.052) | (0.191) | (0.048) |
| $ln.Cement$ | 0.038 | | 0.070 | |
| | (0.480) | | (0.457) | |
| $ln.Labour$ | -1.183 | | -1.071 | |
| | (0.883) | | (0.722) | |
| $ln.Leadtime$ | 1.910*** | | 1.808*** | |
| | (0.605) | | (0.499) | |
| $ln.ExpArq$ | -0.049 | 0.030*** | | |
| | (0.037) | (0.010) | | |
| $ln.ExpNoArq$ | -0.068 | 0.139*** | | |
| | (0.098) | (0.016) | | |
| $ln.ExpMo$ | | | -0.055 | 0.018** |
| | | | (0.034) | (0.008) |
| $ln.ExpNoMo$ | | | -0.061 | 0.164*** |
| | | | (0.093) | (0.016) |
| $HHI.Mo$ | 0.599 | -0.575*** | 0.619 | -0.231* |
| | (0.556) | (0.158) | (0.560) | (0.139) |
| $ln.NPP.UC$ | 0.332*** | -0.0751** | 0.337*** | -0.076** |
| | (0.123) | (0.033) | (0.114) | (0.030) |
| $Arq.Utility$ | -0.319*** | 0.012 | -0.253*** | -0.010 |
| | (0.095) | (0.027) | (0.082) | (0.022) |
| $ln.Demand$ | | -1.228*** | | -1.228*** |
| | | (0.111) | | (0.100) |
| $TMI.US$ | -0.102 | 0.285*** | -0.116 | 0.293*** |
| | (0.193) | (0.041) | (0.198) | (0.038) |
| $TMI.FR$ | 0.051 | -0.020 | 0.085 | -0.228*** |
| | (0.255) | (0.073) | (0.276) | (0.069) |
| $Cherno$ | -0.060 | 0.065** | 0.004 | 0.046* |
| | (0.129) | (0.030) | (0.124) | (0.027) |
| $Constant$ | 5.281* | -2.295*** | 5.067* | -2.313*** |
| | (3.015) | (0.443) | (2.799) | (0.396) |
| Country FE | Yes | Yes | Yes | Yes |
| Trend + trend$^2$ | Yes | Yes | Yes | Yes |
| Obs. | 128 | 128 | 128 | 128 |
| Adj. R$^2$ | 0.815 | 0.955 | 0.820 | 0.962 |

Note: Standard errors in brackets. *** p<0.01, ** p<0.05,* p<0.1

# 4. Nuclear reactors lead-time: insights from other OECD countries

Given the close relationship between the construction costs and lead-time and the importance of the latter in nuclear power future deployment, in this section we further investigate the impact of capacity, experience and standardization on lead-time using a larger dataset on nuclear reactors from 6 OECD countries. Our aim is to gain some insights into the construction of other nuclear fleets for which cost information is not available, and to identify if the results from the US and the French experience also apply to other OECD countries which have followed different paths in terms of technological choices and industrial structure.

## 4.1. The role of lead-time in liberalized electricity markets

As shown in the previous section, the increase in construction lead-times has been one of the main drivers of the capital costs escalation in nuclear power both in the US and France. However, in addition to the effect on construction costs, an increase in lead-times also means a delay in revenues for the investors and an increase in the interim interest rates. This gives lead-time a stronger role in the competitiveness of nuclear power in liberalized electricity markets where revenues for nuclear reactors' operators are derived from wholesale markets and not from rates of return regulation.

In addition, from a microeconomic perspective, private investors tend to employ higher discount rates than those used for public infrastructure. This implies that one might prefer to build a CCGT gas plant that can be planned and built in 2 years and be willing to face the fossil fuel and carbon price risk, instead of waiting more than 7 years (in the best case scenario) to start recovering their investments (MacKerron, 2004). In addition, the uncertainty of longer construction periods increases the difficulty of financing new nuclear capacity in liberalised electricity market (Nuttall and Taylor, 2009; Kessides, 2010) due to possible cost overruns.

Furthermore, in liberalized electricity markets the private option value that carbon-free nuclear power generation could bring, as a hedge against changes in gas or $CO_2$ emissions, will most likely disappear because of the strong correlation between electricity, gas and carbon prices (Roques et al., 2006).

Nuclear reactors lead-time can also have some macroeconomic implications, in particular if one also considers the pre-construction period necessary to receive the authorisation to build a reactor, which means that a nuclear project can take between 10 to 15 years between the start of the planning process and the end of construction. In this sense, the risk of delays in the construction process might encourage a wait-and-see policy, as by the time the new nuclear power plant starts generating electricity it would be reasonable to expect alternative technologies to have reduced their costs and become more competitive.

## 4.2. Data and Model

The data used are also extracted from the Power Reactor Information System (PRIS) database developed by the IAEA[71]. Similarly to the previous section, lead-time is computed as the difference in years between the construction and grid dates, and commercial reactors in 6 OECD countries are considered: the US, France, Canada, South Korea, Japan and the UK. Note that contrary to the previous section, we can make full use of the French data as, contrary to costs data, lead-time is available at the reactor level.

Figure 4.4 and Table 4.4 below highlight that the heterogeneity across our sample is substantial. This feature is understandable given the differences between countries and across years, in terms of labour productivity, regulatory licencing process, stage of development of construction techniques, etc. To capture these effects, we have included in our model a fixed effect for each country as well as a time trend and a quadratic term for the time trend.

Table 4.4 presents the average of the explanatory variable used in the regression. Differences in the lead-time average between Western and Asian countries are substantial. For Japan and South Korea the construction of a new reactor took only approximately 4 years, whereas in the US or in the UK it took more than twice as long, even when the average size of the reactors was similar. Important heterogeneity can also be observed for short term ($HHI.Mo_i$) and long term ($ExpArqMo_i$) average level of standardization.

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[71] International Atomic Energy Agency

Figure 4.4: Construction lead-times for the reactors in our sample

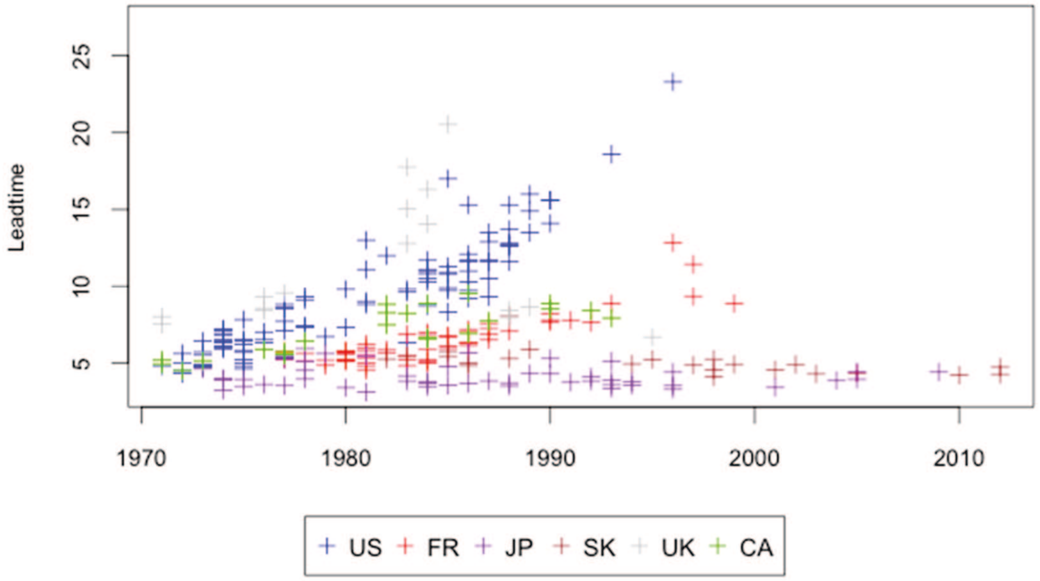

Table 4.4: Summary Statistics

| | Obs. | Mean lead-time (in year) | Mean *ExpArqMo* (#reactors) | Mean *HHI.Mo* (index) | Mean Capacity (in MWe) |
|---|---|---|---|---|---|
| France | 58 | 6.45 | 9.13 | 0.472 | 1083 |
| Canada | 22 | 7.07 | 2.29 | 0.361 | 687 |
| South Korea | 23 | 4.90 | 4.04 | 0.672 | 895.3 |
| Japan | 50 | 4.10 | 3 | 0.341 | 919.1 |
| UK | 17 | 8.63 | 4.80 | 0.861 | 645.1 |
| US | 98 | 9.27 | 2.10 | 0.152 | 972.4 |
| **Average** | 291 | 7.41 | 4.12 | 0.378 | 934.4 |

In Table 4.5 below we present the estimates similar to equation (4.6) in Section 3. We have also included nameplate capacity, electricity demand and the structural break dummies as controls. Three model specifications are considered. Model 1 shows the importance of controlling for structural breaks as, without the TMI and Chernobyl dummies, *HHI.Mo* is not significant in this model. On the other hand, significance at the 5% confidence level is regained in Models 2 and 3 where we control for these events. For robustness, Model 3 introduces time fixed effects and other robustness tests can also be found in Appendix 4[72].

These estimates show that increasing the size of the reactor has a positive and significant effect on lead-time. On average we have found an increase of 3% when scaling up by 10%. This result confirms the importance of offsetting the scale effects in the cost equation, as although increasing the size of the reactor means lower costs per MWe, the net effect should take into account the increase in the lead-time.

This model also confirms the insights from the previous section in terms of our HHI diversity index. Recall that high values of this index mean more market concentration, which in our case corresponds to a more standardized nuclear fleet. On the basis of the analysis using the lead-time, there is strong and significant evidence that reducing the diversity of the nuclear fleet is one of the major differences between countries with longer lead-times and those with shorter construction periods.

One can also notice the negative effect of the two major nuclear accidents on the construction lead-time. Both TMI and Chernobyl were found to be significant structural breaks, showing that these events have an influence beyond borders. As expected, the effect of TMI is stronger on the US compared to other countries.

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[72] In Appendix 4 we consider the four learning spillovers channels used in Section 3 and also define them both as $1/(1+X)$ and $ln(X)$. The results remain unchanged.

### Table 4.5: Regression results for lead-time with learning spillovers and the HHI index

| **Variables** | **(1)**<br>**ln.Leadtime** | **(2)**<br>**ln.Leadtime** | **(3)**<br>**ln.Leadtime** |
|---|---|---|---|
| $HHI.Mo$ | -0.0470 | -0.291** | -0.472** |
| | (0.157) | (0.135) | (0.182) |
| $ln.Cap$ | 0.324*** | 0.395*** | 0.254*** |
| | (0.0600) | (0.0528) | (0.0527) |
| $ln.Exparqmo$ | 0.0109 | 0.0198 | -0.00849 |
| | (0.0342) | (0.0322) | (0.0297) |
| $ln.demand$ | -29.77*** | -16.97*** | -21.21*** |
| | (3.108) | (2.866) | (3.265) |
| $ln.NPP.UC$ | 0.0759** | -0.0203 | -0.0547 |
| | (0.0322) | (0.0335) | (0.0478) |
| $TMI.US$ | | 0.432*** | 0.439*** |
| | | (0.0449) | (0.0628) |
| $TMI.Abroad$ | | 0.139** | 0.142** |
| | | (0.0542) | (0.0613) |
| $herno$ | | 0.188*** | 0.214*** |
| | | (0.0296) | (0.0271) |
| $Constant$ | 2.041*** | 1.105*** | 1.977*** |
| | (0.484) | (0.402) | (0.440) |
| Country FE | Yes | Yes | Ye |
| Time FE | No | No | Yes |
| Trend + Trend$^2$ | Yes | Yes | No |
| Obs. | 286 | 286 | 286 |
| Adj. R$^2$ | 0.775 | 0.840 | 0.870 |

Note: Robust standard errors in brackets. *** p<0.01, ** p<0.05, * p<0.1

# 5. Conclusions

In this paper we study the short and long term benefits of nuclear reactor standardization on the construction costs of nuclear reactors in the US and France between 1966 and 2002 using overnight construction costs data. Short term benefits are defined as the gains based on the diversity of nuclear reactors under construction, whereas long term benefits represent learning by doing spillovers from similar reactors. We build a system of equations to control for endogeneity between costs and lead-time, using the expected demand of electricity as an instrument for lead-time and control for input prices and the possibility of structural breaks following major nuclear accidents.

We show that short term gains from standardization have a positive impact on construction costs through a reduction in lead-time, the latter being one of the main drivers of construction costs in France and the US. This result is also confirmed for a range of other OECD countries with heterogeneous nuclear programs, and can be explained by the fact that the diversity of nuclear reactor models can lead to delays owing to supply line constraints or delays due to increased workload for the nuclear safety regulator. From a policy perspective, as liberalised electricity markets will tend to apply higher discount rates to nuclear new-build projects appraisal, we further argue that standardization of nuclear reactors will be a key criterion for the economic competitiveness of merchant nuclear reactors.

At the same time, we demonstrate that learning by doing spillovers are also conditional on the standardization of nuclear programs, considering that learning by doing spillovers only take place through reactors of the same model built by the same Architect-Engineer (A-E) firm. Regarding the role of the A-E firm, we also show that vertical integration of the utility and the A-E firm reduces construction costs, which can be explained by a reduction in the asymmetric information of the utility regarding costs.

Conversely, if we stress that lead-time contributes to construction costs reduction and has a stronger impact under liberalised electricity markets, this result may change for other determinants of construction costs. For example, we find evidence of economies of scale for construction costs, whereas from an investment perspective Gollier et al. (2005) show that Small and Medium Reactors (SMRs) will generate a significant option value when electricity prices are uncertain. In other words, investors may have to trade-off the economic gains associated with economies of scale for large reactors with the option value of SMRs. This calls for more research on the optimal size of nuclear reactors.

In parallel, we also find that the discounted stock of patents in the nuclear industry increases construction costs, reflecting the fact that innovation increases the complexity of nuclear reactors. This result is in direct contrast to the pattern in other energy technologies where technical progress contributes to costs reductions, and can be explained by the importance of safety regulation in the nuclear power sector which improves safety performance (Chapter 2), at the expense of increases in construction costs. This result is not without implications for the design of energy economics modelling tools, as the existing literature has shown that certain models' calibration (Jamsab, 2007) implicitly assumes that nuclear construction costs benefit from innovation effort. This result highlights the importance of building these models on evidence based on actual cost data.

However, even if our results highlight the benefit of nuclear programs standardization and suggest that innovation effort contributes to costs increases, they do not answer the question of the optimal pace of technological change in nuclear power technologies. In other words, there exists a trade-off between reductions in costs permitted by standardization and potential gains from adopting new technologies with better operating and safety performance. In addition, using patent data as a measure of innovation captures incremental innovation but fails to consider the possibility of radical technological change. In that respect, nuclear power has been characterised by incremental innovations from initial reactor designs in the 1950s. Radical innovations such as 4th generation of nuclear reactors could, on the other hand, contribute to costs reductions.

It is also important to note that safety regulation can impact construction costs and lead-time through dimensions other than technological change. In particular, the scope of standardization partly depends on the evolution of the safety rules in each country. This is reported to be the case in the US where, according to Cooper (2012), the increase in safety regulations issued by the NRC grew substantially following TMI (e.g. from three safety guidelines in 1970 to 143 by 1978), limiting the ability of nuclear vendors to standardize nuclear reactors as they had to comply with changes in safety rules.

Hence, the US experience shows that safety regulation can have important consequences on the economic competitiveness of nuclear reactors. In that respect, standardization and safety regulation do not have to be *per*-se incompatible and one could argue that for a given level of safety effort, nuclear safety regulation should be designed in order to allow nuclear reactors to benefit more from standardization gains.

This would necessitate institutional reforms. One possibility would be to reinforce nuclear reactor certification procedures through cooperation between national nuclear authorities, meaning that a nuclear reactor design can be certified jointly in several countries. This would represent a change from the current regulatory framework where each national safety authority issues design certification with its own specification requests and different timeframes.

# General conclusions

This PhD thesis follows a quantitative empirical approach to analyse how innovation and industrial structure settings of the nuclear power sector impact the economic and safety performance of this energy technology. As such, this thesis provides a number of results on, for instance, the role of standardization, market regulation or technological paths, which highlight how these factors can favour the economic competitiveness and safety performance of nuclear reactors.

These results are important from a policy perspective, considering that several countries (e.g. Vietnam, Turkey or the United Arab Emirates (UAE)), with little industrial base or national knowledge capabilities, are currently considering nuclear power. In addition, several mature nuclear countries, which stopped building nuclear reactors decades ago (e.g. the UK and the US), are also considering nuclear new-build and will need to make decisions in terms of industrial structure and technological paths. For example, should the UK select several nuclear vendors in order to foster competition or only one to benefit from standardization gains? Can a new entrant without national knowledge capabilities achieve the same level of safety performance compared to technologically advanced countries? How does electricity market regulation impact the incentives to improve the competitiveness of nuclear power during the construction and operating stages? These are some of the ongoing policy challenges that this PhD thesis addresses.

From a methodological perspective, this thesis relies on the collection of data from a variety of sources and econometric models. While these data do not allow for an exhaustive study of the nuclear power sector, they enable international comparisons of national nuclear development strategies over a fairly long time period using mostly original data sources. For instance, Chapter 4 is the first to analyse nuclear construction costs in France and the US using historical costs data. More generally, to the best of our knowledge, this thesis is the first quantitative analysis on innovation in nuclear power technologies.

The four Chapters are further organised around three research axes: (*i*) the determinants of innovation in nuclear power technologies (Chapter 1); the role of innovation and industrial structure on (*ii*) operating performances (Chapters 2 and 3) and (*iii*) construction costs (Chapter 4). Rather than summarizing the conclusions of each Chapter, which we do in the Introduction and in the respective Conlusions of each Chapter, we will organise this general conclusion around a policy discussion on the different findings of this thesis and on the paths for future research.

# 1. Policy implications

## 1.1. On the interactions between innovation, safety and economic performance

Chapters 1, 2 and 4 study the impacts of innovation on the nuclear power sector and have highlighted the interactions between innovation activity, nuclear reactor economic performance (both in terms of construction costs and outage level) and safety.

Chapter 1 highlights how government-led incentives (such as public R&D expenditures and nuclear reactor construction programs) and nuclear safety regulation foster innovation as well as the quality of innovation. We show that different actions from the nuclear safety authority (in particular, monitoring activity and corrective actions) have contrasting impacts on innovation and, in particular, that monitoring effort increases the incentives to innovate. At the same time, in Chapter 2 we show that the stock of national innovation improves both economic and safety performance. By further differentiating between national stocks of knowledge and international technology transfers we show that the former impacts both economic and safety performance of existing reactors, whereas the latter impacts only economic performance. This result is particularly policy relevant as it highlights that there exists a drawback in terms of safety performance of national nuclear programs based solely on international technology transfers. Furthermore, Chapter 4 shows that the stock of national innovation contributes to construction costs reduction.

These different results reveal the central role played by innovation in the nuclear power sector. Together, these results show that there exists a trade-off between improvements in safety performance enabled by innovation and the loss of economic competitiveness resulting from the increase in construction costs. In other words, innovation in nuclear contributes to safety performance improvements at the expense of a rise in construction costs.

However, the interactions between innovation, safety and economic performance remain difficult to capture. For instance, on the one hand we show that major nuclear accidents have led to an improvement in safety performance and have contributed to the rise in construction costs owing to construction time delays. On the other hand, major nuclear accidents also reduce incentives to innovate in nuclear owing to reduced government support for nuclear development, leading, as previously mentioned, to a negative impact on safety performance and rises in construction costs. As such, these results shed light on the importance of taking into account innovation before drawing policy conclusions on the impact of nuclear safety accidents on economic and safety performance.

For instance, when looking at the Fukushima-Daïchi nuclear accident, one should acknowledge that its long term impact on the risk of a nuclear accident remains ambiguous. In the short run, more compliance with safety regulation, combined with specific learning by accident, mean that safety performance should improve. In the longer run, the reduction in government-led support for nuclear development means that the resources available for technological progress are reduced, leading to less innovation compared to an alternative situation in which this accident did not have happened, and thus reduced safety improvement.

### 1.2. On the importance of industrial structure and economic regulation

Our results also shed light on the importance of concentrated industrial structure in the development of nuclear programs. Our results suggest that concentrated and government-led nuclear construction programs, such as in France, have been the most successful in limiting the rise in construction costs due to short and long term standardization gains. These short and long term standardization gains arise from lower diversity of reactor models under construction and learning by doing from specific reactor models built by the same Architect-Engineer (A-E) firm. In addition, vertical integration between the A-E firm and the utility also contributes to costs reductions.

Conversely, electricity markets liberalization leads to less centralized planning for construction programs and has a negative impact on the competitiveness of nuclear reactors owing to typically higher discount rates used for merchant plants. At the same time, we show that electricity markets liberalization with the vertical unbundling of generation and distribution activities, yields substantial improvements in the availability of nuclear reactors and the competitiveness of these divested nuclear reactors.

In that respect, our PhD thesis pinpoints a fundamental dilemma that nuclear projects face. On the one hand electricity markets hamper the development of nuclear new-build projects, whereas on the other hand, market mechanisms improve the competitiveness of these plants once they have been built. Several countries with liberalised electricity markets which are considering the nuclear new-build – such as the UK and the US – face this dilemma and have been trying to mitigate this problem through long term contracts and/or loan guarantees. However, one might argue that such arrangements also create challenges for the acceptability of nuclear projects as they imply that governments carry some financial risks while firms receive the potential benefits of these projects.

Finally, it is important to note that the findings of this thesis invalidate part of Cowan's (1990) claim on the technological lock-in of the US nuclear power sector. In particular, we show that substantial efficiency gains can be achieved during the lifetime of nuclear reactors through the restructuring of the nuclear sector with the divestiture of nuclear reactors in the US. However, one should be cautious in deriving policy implications on the opportunities for other countries to restructure their nuclear assets. In particular, the UK experience (Taylor, 2007) shows that transition costs towards electricity market reform could be significant when electricity generation is performed by a monopolistic public utility. One could argue that high transition costs would also apply to a country like France.

# 2. Paths for Future Research

In this last section, we suggest a number of directions for future research based on the findings of this PhD thesis. These directions can be organised around two research axes: (*i*) the interaction between economic and safety regulation and (*ii*) the channel for technology transfers and the optimal level of standardization of nuclear programs in light of the long term opportunities offered by radical innovation in future nuclear technologies.

## 2.1. On the interactions between economic and safety regulation

### *Economic regulation and safety performance*

Most of the policy debate surrounding nuclear power considers economic and safety regulation separately. However, as several dimensions of nuclear safety tend to be strongly correlated with economic performance (Hausman, 2012), certain economic market reforms (such as nuclear reactor divestiture) could be of benefit to nuclear safety. Due to this correlation between safety and economic performance, the findings of Hausman (2012) of a small safety improvement for divested nuclear reactors in the US might also be subject to an endogeneity bias. Hence, this empirical question should be studied using the same framework developed in Chapter 3 where we use the predicted value of a survival model as an instrument for the endogenous policy variables.

Similarly, divestiture is only one specific electricity market reform and incentive regulation has used a large variety of instruments. For instance, the recent French electricity market reform law (NOME) offers EDF's competitors access to nuclear generation from existing reactors at a regulated cost-plus tariff subject to uncertainty owing to strong political bargaining. To what extent does the NOME law impact nuclear safety? While this remains an empirical question, one might argue that the transfer of EDF revenues to its competitors might not be without consequences on nuclear safety as its reduces the incentives for EDF to minimize planned and unplanned outages.

### *Nuclear safety regulation and economic performance*

One should acknowledge that safety regulation can have consequences on the competitiveness of nuclear power and that institutional reforms of nuclear safety regulation could limit these effects without jeopardizing safety. For instance, an example of such institutional reform can be found with the reform of the licencing procedure for nuclear sites and reactor designs in the US, where a joint licence is now delivered, reducing uncertainty on regulatory decisions for investment decisions in nuclear new-build.

Other institutional reforms could be considered. In Chapter 4, we highlight that changes in safety regulation prevented the US nuclear sector from standardizing its nuclear program in the 1970s and 1980s and argue that for a given level of safety margin nuclear safety regulation should allow these standardization gains. This observation will certainly require more work on the institutional design of nuclear safety regulation.

### *Measuring nuclear safety*

Empirical work on nuclear safety suffers from the lack of available data sources on nuclear safety performance and regulation. For example, the measure of nuclear safety in Chapter 2 is based on a proxy for nuclear safety performance. More outage level data are available in the PRIS database at a more detailed level, but are not accessible for academic research for reasons unknown to us. Similarly, the IAEA does not make available historical data on INES scale events[73] based on the argument that these data are not comparable between countries. Simple econometric methods such as country specific time fixed effects would easily control for this and one could argue that nuclear safety research could benefit from the insights of these econometric tools.

## 2.2. On innovation and standardization

### *Measuring technology transfer: the role of "know how"*

This thesis is based on the extensive use of patent data as a measure of both innovation and technology transfers. In that respect, patent data are not without drawbacks and one could take our research further by looking at other mechanisms which support the diffusion of innovation. In particular, the construction and operation of nuclear reactors require what is often called *"know-how"* on nuclear technologies. For instance, a number of international turn-key nuclear programs (e.g. in the UAE, all the project management and construction work will be done by Korean firms with a fixed-price contract) have been associated with the transfer of this *"know-how"*. While this dimension of international technology transfers remains difficult to measure, one could argue that in light of the number of countries considering nuclear power plants without national knowledge capabilities, more work is needed on how to effectively transfer this knowledge within the nuclear sector.

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[73] The International Nuclear and Radiological Event Scale. See: http://www-ns.iaea.org/tech-areas/emergency/ines.asp

### *Radical innovation and optimal standardization of nuclear programs*

Although patent citations enable us to control for the quality of innovation, another limit of using patents is that they generally fail to capture radical innovations. This might not be *per-se* a shortcoming of our analyses, precisely because over the last 50 years innovation in nuclear power technologies has been characterised by incremental innovations from initial light water reactor technologies in the late 1950s. For example, the Evolutionary Power Reactor (EPR) under construction in China, Finland and France represents – as its name states – an incremental technological change from the French *N4* and the German *Konvoi* nuclear reactor models.

Conversely, the mid to long term outlook for nuclear technology developments offers a number of proposals for radical innovations with new Fast Breeding Reactors (FBRs) or thermal reactors technologies. These 4th generation (GenIV) nuclear reactors require more scrutiny as they could lead to radical changes in the competitiveness and safety of nuclear power. For instance, if findings from Chapter 4 show that innovation has up to now led to construction costs increases, this relationship might probably change with these future technologies.

# References

Ando, A.W. and Palmer, K. (1998), Getting on the map: the political economy of state-level electricity restructuring, *Resources For the Future Discussion Papers*, DP-98-19-rev.

Arrow, K. (1962), The economic implications of learning by doing, *Review of Economic Studies,* 29 (80): 155-173.

Berthélemy, M. and Lévêque, F. (2011), Harmonising nuclear safety regulation in the EU: which priority? *Intereconomics – Review of European Economic Policy*, 46 (3): 132-137.

Bier, V., Joosten, J., Glyer, D., Tracey, J. and Walsh. M. (2001), Deregulation and nuclear power safety: What can we learn from other industries?, *The Electricity Journal*, 14 (4): 49-60.

Bohi, D. and Palmer, K. (1996), The efficiency of wholesale vs. retail competition in electricity, *The Electricity Journal*, 9 (8): 12-20.

Brunnermeier, S.B. and Cohen, M.A. (2003), Determinants of environmental innovation in US manufacturing industries, *Journal of Environmental Economics and Management*, 45 (2): 278-293.

Cameron, A.C., Trivedi, P.K. (2010), *Microeconometrics using Stata*, *Revised Edition*, Stata Press, Texas.

Cantor, R. and Hewlett, J. (1988), The economics of nuclear power: Further evidence on learning, economies of scale and regulatory effects, *The Bell Journal of Economics,* 13: 297–310.

Carlisle, C.S., Hunter, J.R. and Waltar, Alan E. (2008), Nuclear knowledge management: a crucial bridge to the global nuclear renaissance, *International Journal of Global Energy Issues*, 30 (1-4): 360-375.

Coate, S. and Morris, S. (1999), Policy persistence, *American Economic Review*, 89: 1327-1336.

Cohen, L. (1979), Innovation and atomic energy: Nuclear power regulation, 1966-present, *Law and Contemporary Problems*, 43 (1): 67-97.

Cooper, M. (2010), Policy challenges of nuclear reactor construction, cost escalation and crowding out alternatives, *Unpublished manuscript*.

Cooper, M. (2012), Nuclear safety and nuclear economics, *Unpublished manuscript*.

Corderi, D. and Lin, C.Y. (2011), Measuring the social rate of return to r&d in coal, petroleum and nuclear manufacturing: A study of the OECD countries, *Energy Policy* 39 (5): 2780 – 2785.

Cour des Comptes (2012), Les coûts de la filière électronucléaire, *Rapport public thématique.*

Cowan, R. (1990), Nuclear power reactors: a study in technological lock-in, *Journal of Economic History*, 50 (3): 541-567.

Craig, J.D. and Savage S.J. (2013), Market restructuring, competition and the efficiency of electricity generation: Plant-level evidence from the United States 1996 to 2006, *The Energy Journal*, 34 (1): 1-30.

Damsgaard, N. (2003), Why deregulation? Economics and politics in retail electricity markets, *Working Paper*.

David, P.A. and Rothwell, G. (1996), Standardization, diversity and learning: Strategies for the coevolution of technology and industrial capacity*, International Journal of Industrial Organization,* 14: 181–201.

David, P.A., Maude-Griffin, R. and Rothwell, G. (1996), Learning by Accident? Reductions in the risk of unplanned outages in the US nuclear power plants after Three Miles Island, *Journal of Risk and Uncertainty*, 13: 175-198.

Davis, L. and Wolfram, C. (2012), Deregulation, consolidation, and efficiency: Evidence from US nuclear power, *American Economic Journal: Applied Economics*, 4 (4): 194–225.

Dechezleprêtre, A. and Glachant, M. (2013), Does foreign environmental policy influence domestic innovation? Evidence from the wind industry, *Environment and Resource Economics,* (forthcoming).

Dechezleprêtre, A., Glachant, M., Hascic, I., Johnstone, N. and Ménière, Y. (2011), Innovation and transfer of climate-mitigation technologies: A global analysis, *Review of Environmental Economics and Policy*, 5 (1): 109-130.

DeLeon, P. (1979), *Development and Diffusion of Nuclear Power Reactor: A Comparative Analysis,* The Rand Corporation, New-York.

Delmas, M. and Heiman, B. (2001), Government credible commitment to the French and American nuclear power industries. *Journal of Political Analysis and Management*, 20 (3): 433-456.

Eide, S., Rasmuson, D. and Atwood, C. (2005), Integrated initiating event performance indicator, *Idaho National Laboratory.*

Escobar, L. and Lévêque, F. (2012), Revisiting the cost escalation curse of nuclear power: New lessons from the French experience, *I3 Working Paper*.

Fabrizio, K.R., Rose,N.L and Wolfram C.D. (2007), Do markets reduce costs? Assessing the impact of regulatory restructuring on US electric generation efficiency, *American Economic Review*, 97 (4): 1250-1277.

Feinstein, J.S. (1989), The safety regulation of U.S. nuclear power plants: violations, inspections, and abnormal occurrences*. Journal of Political Economy*, 97 (1): 115-154.

Fernandez, R. and Rodrik, D. (1991), Policy persistence and rent extraction: status quo bias in the persistence of individual-specific uncertainty, *American Economic Review*, 81: 1146-1155.

Goldschmitd, S. (1980), *Le Complexe Atomique,* Fayard Press, Paris.

Gollier, C., Proult, D., Thais, F., Walgenwitz, G. (2005), Choice of nuclear power investments under price uncertainty: valuing modularity, *Energy Economics*, 27 : 667–685.

Grubler, A. (2010), The cost of the French nuclear scale-up: A case of negative learning by doing, *Energy Policy*, 38: 5174–5188.

Hamann, H.F. (1962), An appraisal of the atomic energy field after 20 years of the patent title policy. Patent, Trademark and Copyright, *Journal of Research and Education*, 6 (3): 378-409.

Hausman, C. (2012), Corporate incentives and nuclear safety, *Energy Institute at Hass Working Paper.*

Heckman, J.J. and Navarro, S. (2007), Dynamic discrete choice and dynamic treatment effects, *Journal of Econometrics*, 136: 341-396.

Heckman, J.J. (2010), Building bridges between structural and program evaluation approaches to evaluating policy, *Journal of Economic Literature*, 48 (2): 356-389.

Heo, E. and Shin, S.Y. (1998), Estimating learning effects on nuclear power plants: A count data model with a varying time interval as a duration variable, *Applied Economics Letters*, 6: 655-658.

Hiebert, L.D. (2002), The determinants of the cost efficiency of electric generating plants: A stochastic frontier approach, *Southern Economic Journal*, 68 (4): 935-946.

Hirsch, W. (1952), Manufacturing progress functions, *Review of Economics and Statistics,* 34 (2): 134-155.

Horbach, J. (2008), Determinants of environmental innovation: new evidence from German panel data sources. Research Policy, 37 (1): 163-173.

IAEA (1999), Modern Instrumentation and Control for Nuclear Power Plants: A Guidebook, *IAEA Technical Reports Series No. 387*.

IAEA (2005), The Power Reactor Information System (PRIS) and its extension to non-electrical applications, decommissioning and delayed projects information, *IAEA Technical Reports Series No. 428.*

IAEA (2012), Country Nuclear Power Profiles - 2012 Edition, *IAEA.*

IEA (2010a), *Projected Costs of Generating Electricity: 2010 Edition*, OECD/IEA, Paris.

IEA (2010b), *Energy Technology Perspectives 2010,* OECD/IEA, Paris.

IEA (2012), *World Energy Outlook 2012*, OECD/IEA, Paris.

Ingersoll, D.T. (2009), Deliberately small reactors and the second nuclear era, *Progress in Nuclear Energy*, 51 (4–5): 589-603.

Irwin, D.A. and Klenow, P.J. (1994), Learning by doing spillovers in the semiconductor industry, *Journal of Political Economy*, 102 (6): 1200-1227.

Jaffe, A.B. and Palmer K. (1997), Environmental regulation and innovation: a panel data study, *Review of Economics and Statistics*, 79 (4): 610-619.

.

Jamsab, T. (2007), Technical change theory and learning curves: Patterns of progress in electricity generation technologies, *The Energy Journal*, 28 (3): 51-71.

Johnstone, N., Hascic, I. and Popp , D. (2008), Renewable energy policies and technology innovation: evidence based on patent counts, *Environmental and Resource Economics*, 45 (1): 133-155.

Joint Congressional Committee on Atomic Energy (1952), *Atomic Power and Private Enterprise*, United States Congress, Washington DC.

Joint Congressional Committee on Atomic Energy (1959), *Atomic Energy Patents*, United States Congress, Washington DC.

Joskow, P.L. (1997), Restructuring, competition and regulatory reform in the US electricity sector, *Journal of Economic Perspectives*, 11 (3): 119–138.

Joskow, P.L. and Rose N. L. (1985), The effects of technological change, experience and environmental regulation on the construction cost of coal-burning generation units, *RAND Journal of Economics*, 16 (1): 1-27.

Joskow, P.L. and Rozanlski, A. (1979), The effects of learning by doing on nuclear power plants reliability, *Review of Economics and Statistics*, 61 (2): 161-168.

Kessides, I.N. (2010), Nuclear power: Understanding the economic risks and uncertainties, *Energy Policy*, 38 (8): 3849–3864.

Klaassen, G., Miketa, A., Larsen, K. and Sundqvist, T. (2005), The impact of R&D on innovation for wind energy in Denmark, Germany and the United Kingdom, *Ecological Economics,*. 54: 227–24.

Knittel, C.R. (2002), Alternative regulatory methods and firm efficiency: Stochastic frontier evidence from the US electricity industry, *Review of Economics and Statistics*, 84 (3): 530–540.

Kobos, P.H., Erickson, J.D., and Drennen, T.E (2006), Technological learning and renewable energy costs: implications for US renewable energy policy, *Energy Policy*, 34: 1645-1658.

Komanoff, C. (1981), Power Plant Cost Escalation Nuclear and Coal Cost, Regulation and Economics, *Van Nostrand Reinhold Publishing*.

Koomey, J. and Hultman, N.E. (2006), A reactor-level analysis of busbar costs for US nuclear plants, 1970–2005, *Energy Policy*, 35 (11): 5630–5642.

Krautmann, A.C. and Solow, J.L. (1988), Economies of scale in nuclear power generation, *Southern Journal of Economics*, 55 (1): 70-85.

Kwoka, J. (2008), Restructuring the U.S. electric power sector: a review of recent studies, *Review of Industrial Organization*, 32 (3-4):165–196.

Lester, R.K. and McCabe, M.J. (1993), The effect of industrial structure on learning by doing in nuclear power plant operation, *RAND Journal of Economics*, 24 (3): 418-438.

Llor, A. (2007), Delay from patent filing to technology transfer: a statistical study at a major public research organization. *Technovation*, 27 (8): 446-460.

Lowen, R.S. (1987), Entering the atomic power race: science, industry and government. *Political Sciences Quarterly*, 102 (3): 459-479.

MacKerron, G. (2004), Nuclear power and the characteristics of 'ordinariness' - the case of UK energy policy, *Energy Policy*, 32 (17): 1957–1965.

McCabe, M.J. (1996), Principals, Agents, and the learning curve: the case of steam-electric power plants design and construction, *Journal of Industrial Economics*, 165 (4): 357-375.

Muehlenbachs, L., Cohen, M.A. and Gerarden, T. (2011) Preliminary empirical assessment of offshore production platforms in the Gulf of Mexico, *Resources For the Future, Discussion Paper 10-66.*

Massachusetts Institute of Technology (2009), *Update of the MIT 2003: The Future of Nuclear Power*, MIT Energy Initiative, Cambridge, MA.

Newbery, D.M. and Pollitt, M.G. (1997), The restructuring and privatization of Britain's CEGB – Was it worth it? *Journal of Industrial Economics*, 45 (3): 269-303.

Newell, R.G., Jaffe, A.B. and Stavins, R.N. (1999), The induced innovation hypothesis and energy-saving technological change, *Quarterly Journal of Economics*, 114 (3): 941-975.

Newman, J.R. and Miller, B.S. (1947), Patent and atomic energy, *Law and Contemporary Problems*, 12 (4): 746-764.

Nuttall, W.J. (2005), *Nuclear renaissance: Technologies and policies for the future of nuclear power*, Taylor & Francis, New York and London.

Nuttall W.J. and Taylor S. (2009), Financing the Nuclear Renaissance?, *European Review of Energy Markets*, 3 (2): 187-202.

OECD (2009), *OECD Patent Statistics Manual,* OECD, Paris.

OECD/NEA (2007), *Innovation in Nuclear Energy Technology*, OECD, Paris.

OECD/NEA (2008), *The Regulatory Goal of Assuring Nuclear Safety*, OECD, Paris.

Perri, G. (2005), Determinants of knowledge flows and their effect on innovation, *Review of Economics and Statistics*, 87. (2): 308-322.

Peters, M., Schneider, M., Griesshaber, T. and Hoffmann, V.H. (2012), The impact of technology-push and demand-pull policies on technical change – Does the locus of policies matter?, *Research Policy*, 41 (8): 1296-1308.

Pollitt, M. (1995), *Ownership and performance in electric utilities: The international evidence on privatization and efficiency*, Oxford University Press, Oxford.

Pollitt, M. (1996), Ownership and efficiency in nuclear power production, *Oxford Economic Papers*, 48 (2): 342-360.

Popp, D. (2002), Induced innovation and energy prices, *American Economic Review*, 92 (1): 160-180.

Popp, D., Newell., R.G. and Jaffe, A.B. (2009), Energy, the environment, and technological change, *NBER Working Paper No. 14832.*

Porter, M.E. and Van der Linde, C. (1995), Toward a new conception of the environment-competitiveness relationship, *Journal of Economic Perspectives*, 9 (4): 97-118

Romer, P. (1990), Endogenous technological change, *Journal of Political Economy*, 98 (5): 71-102.

Roques, F.A., Nuttall, W.J., Newbery, D.M. and de Neufville, R. (2006), Nuclear Power: a Hedge against Uncertain Gas and Carbon Prices?, *The Energy Journal*, 27 (4): 1-24.

Rothwell, G. (1986), Steam-Electric Scale Economies and Construction Lead Times, *Working Papers 627, California Institute of Technology*.

Rothwell, G. (1996), Organizational structure and expected output at nuclear power plants, *Review of Economics and Statistics*, 78 (3): 482-488.

Rust, J. and Rothwell, G. (1995), Optimal response to a shift in regulatory regime: the case of the US nuclear power industry, *Journal of Applied Econometrics*, 10(S): 75-118.

Söderholm, P. and Sundqvist, T. (2007), Empirical challenges in the use of learning curves for assessing the economic prospects of renewable energy technologies, *Renewable Energy*, 33: 2559–2578.

Sturm, R. (1995), Why does nuclear power performance differ across Europe?, *European Economic Review*, 39 (6): 1197-1214.

Taylor, S. (2007), *Privatization and financial collapse in the nuclear industry - the origins and causes of the British Energy crisis of 2002,* Routledge, London.

Van Zeebroeck, N. (2010), The puzzle of patent value indicators, *Economics of Innovation and New Technology*, 20 (1): 33-62.

Verma, K., Mitnick, B.M. and Marcus, A.A. (1999), Making incentive systems work: incentive regulation in the nuclear power industry, *Journal of Public Administration Research and Theory*, 9 (3): 395-436.

WANO (2011), *2011 Performance Indicators*, World Association of Nuclear Operators.

Warren, P.L. and Wilkening, T.S. (2012), Regulatory fog: the role of information in regulatory persistence*, Journal of Economic Behavior & Organization*, 84: 840-856.

Wooldridge, J.M. (2002), *Econometric analysis of cross section and panel data*, Cambridge, MA: MIT Press.

World Nuclear Association (2012), World energy needs and nuclear power. Available at: http://world-nuclear.org/info/inf16.html (last accessed August 2012).

Wright, T. (1936), Factors affecting the cost of airplanes, *Journal of Aeronautical Sciences,* 3: 122-128.

Zhang, F. (2007), Does electricity restructuring work? Evidence from the US nuclear energy industry, *Journal of Industrial Economics,* 55 (3): 397-418.

Zhao, J. and Kling, C.L. (2003), Policy persistence in environmental regulation, *Resource and Energy Economics*, 25: 255-268.

Zimmerman, M. (1982), Learning effects and the commercialization of new technologies: The case of nuclear power, *The Bell Journal of Economics*, 13: 297–310.

# Appendixes

## Appendix of Chapter 1

We perform a number of robustness checks to verify the soundness of our results. We find that our main results are generally robust when the main hypotheses of our main models are modified. In particular, we undertake three kinds of robustness checks:

1. Use of a Negative Binomial estimator, as this estimator is more suited to handle over-dispersion of our dependent variable (Table 1.4).

2. Removal of Belgium, the Netherlands and Spain from the sample as these three countries have very few patents filed in nuclear reactor technologies (Table 1.5).

3. Alternative value of the discount factor $\delta$ used to build the knowledge stocks and omission of the NPPs built by the Soviet Union and then Russia (within or outside the former Soviet Union) for the foreign demand-pull as one may argue that these NPP constructions were within the captive market of the Russian nuclear industry (Table 1.6).

**Table 1.4: Estimated coefficients of the Negative Binomial fixed-effect regressions**

| | **Model (1)** | **Model (2)** |
|---|---|---|
| **Dependent variable** | $Patent_{i,t}$ | $Weighted.Patent_{i,t}$ |
| $\ln.Know_{i,t}$ | 0.815 *** | - |
| | (0.114) | |
| $\ln.Weighted.Know_{i,t}$ | - | 0.571 *** |
| | | (0.070) |
| $\ln.RD_{i,t}$ | 0.052 ** | 0.093 *** |
| | (0,022) | (0,021) |
| $\ln.CAP_{i,t+4}$ | 0.036 *** | 0.062 *** |
| | (0.013) | (0.014) |
| $\ln.CAP.RoW_{i,t+4}$ | 0.122 ** | 0.116 |
| | (0.057) | (0.073) |
| $\ln.Cancelled_{i,t}$ | -0.041 ** | -0.033 ** |
| | (0.016) | (0.013) |
| $\ln.Reg.outage_{i,t}$ | -0.106 | -0.392 |
| | (0.368) | (0.351) |
| $\ln.Inspection_{i,t}$ | 0.594 *** | 0.263 |
| | (0.167) | (0.183) |
| Observation | 309 | 309 |
| Control for GDP | Yes | Yes |
| Country FE | Yes | Yes |
| Time FE | Yes | Yes |

Note : ***, ** and * indicate that results are significant at 1%, 5% and 10% confidence levels, respectively. Standard errors are reported in brackets.

## Table 1.5: Estimated coefficients of the Poisson fixed-effect regressions

|  | **Model (1)** | **Model (2)** |
|---|---|---|
| **Dependent variable** | $Patent_{i,t}$ | $Weighted.Patent_{i,t}$ |
| $\ln.Know_{i,t}$ | 0.380 *<br>(0.210) | - |
| $\ln.Weighted.Know_{i,t}$ | - | 0.328 **<br>(0.142) |
| $\ln.RD_{i,t}$ | 0.076 ***<br>(0.029) | 0.117 ***<br>(0.016) |
| $\ln.CAP_{i,t+4}$ | 0.058 ***<br>(0.012) | 0.080 ***<br>(0.012) |
| $\ln.CAP.RoW_{i,t+4}$ | 0.120 **<br>(0.023) | 0.138 ***<br>(0.033) |
| $\ln.Cancelled_{i,t}$ | -0.056 ***<br>(0.020) | -0.046 **<br>(0.023) |
| $\ln.Reg.outage_{i,t}$ | -0.631 ***<br>(0.152) | -0.642 ***<br>(0.035) |
| $\ln.Inspection_{i,t}$ | 0.370 ***<br>(0.152) | -0.035<br>(0.165) |
| Observation | 235 | 235 |
| Control for GDP | Yes | Yes |
| Country FE | Yes | Yes |
| Time FE | Yes | Yes |

Note: ***, ** and * indicate that results are significant at 1%, 5% and 10% confidence levels, respectively. Robust-clustered standard errors are reported in brackets.

Table 1.6: Alternative specifications of the explanatory variables

| | **No Russian built NPPs (1)** | **No Russian built NPPs (2)** | **δ = 0.2 (3)** | **δ = 0.2 (4)** |
|---|---|---|---|---|
| **Dependent variable** | $Patent_{i,t}$ | $Weighted.Patent_{i,t}$ | $Patent_{i,t}$ | $Weighted.Patent_{i,t}$ |
| $\ln.Know_{i,t}$ | 0. 416 **<br>(0.208) | - | 0. 593 ***<br>(0.154) | - |
| $\ln.Weighted.Know_{i,t}$ | - | 0.269 **<br>(0.136) | - | 0.392 ***<br>(0.087) |
| $\ln.RD_{i,t}$ | 0072**<br>(0.03) | 0.125 ***<br>(0.026) | 0.044<br>(0.030) | 0.125 ***<br>(0.026) |
| $\ln.CAP_{i,t+4}$ | 0.059 ***<br>(0.013) | 0.079 ***<br>(0.014) | 0.046 ***<br>(0.010) | 0.060 ***<br>(0.014) |
| $\ln.CAP.RoW_{i,t+4}$ | 0.114 ***<br>(0.024) | 0.132 ***<br>(0.020) | 0.097 ***<br>(0.026) | 0.119 ***<br>(0.026) |
| $\ln.Cancelled_{i,t}$ | -0.056 ***<br>(0.020) | -0.042 *<br>(0.023) | -0.046 ***<br>(0.016) | -0.029<br>(0.020) |
| $\ln.Reg.outage_{i,t}$ | -0.613 ***<br>(0.153) | -0.342<br>(0.246) | -0.430 ***<br>(0.149) | -0.130<br>(0.196) |
| $\ln.Inspection_{i,t}$ | 0.459 **<br>(0.182) | 0.251 *<br>(0.152) | 0.487 ***<br>(0.157) | 0.192 *<br>(0.132) |
| Observation | 309 | 309 | 309 | 309 |
| Control for GDP | Yes | Yes | Yes | Yes |
| Country FE | Yes | Yes | Yes | Yes |
| Time FE | Yes | Yes | Yes | Yes |

Note-: ***, ** and * indicate that results are significant at 1%, 5% and 10% confidence levels, respectively. Robust-clustered standard errors are reported in brackets.

# Appendix of Chapter 2

Table 2.8: Correlation Matrix

| | UF | PUF | UUF | SHARE | Mwe | AGE | NATKNOW | INTKNOW | INTRA_SITE | INTER_SITE | INTER_FIRM | YEAR |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| UF | 1 | | | | | | | | | | | |
| PUF | .743 | 1 | | | | | | | | | | |
| UUF | .497 | -.047 | 1 | | | | | | | | | |
| SHARE | -.039 | .044 | -.038 | 1 | | | | | | | | |
| Mwe | -.121 | -.077 | -.046 | .349 | 1 | | | | | | | |
| AGE | -.205 | -.164 | -.134 | .106 | -.133 | 1 | | | | | | |
| NATKNOW | -.009 | .008 | -.021 | -.055 | .223 | .060 | 1 | | | | | |
| INTKNOW | .091 | .106 | -.074 | -.368 | .027 | -.152 | .734 | 1 | | | | |
| INTRASITE | .031 | -.013 | .068 | .294 | .130 | .218 | -.269 | -.393 | 1 | | | |
| INTERSITE | .000 | .007 | .106 | .664 | .272 | .084 | .156 | -.347 | .268 | 1 | | |
| INTERFIRM | -.218 | -.193 | -.143 | -.345 | .148 | .362 | .555 | .488 | -.253 | -.275 | 1 | |
| YEAR | -.317 | -.212 | -.224 | .430 | .353 | .674 | -.006 | -.316 | .376 | .318 | .293 | 1 |

## Table 2.9: Robustness checks with different discount factors for knowledge stocks

| | δ = 0.05 | | | δ = 0.15 | | |
|---|---|---|---|---|---|---|
| | **(17)** | **(18)** | **(19)** | **(20)** | **(21)** | **(22)** |
| *VARIABLES* | $ln.PUF$ | $ln.UUF$ | $ln.UF$ | $ln.PUF$ | $ln.UUF$ | $ln.UF$ |
| $ln.UUF_{i,t}$ | -0.488*** | | | -0.488*** | | |
| | (0.127) | | | (0.127) | | |
| $ln.PUF_{i,t}$ | | 0.0619 | | | 0.0627 | |
| | | (0.0463) | | | (0.0464) | |
| $ln.SIZE_{i,t-1}$ | -0.459 | 1.395*** | 0.489 | -0.479 | 1.376** | 0.479 |
| | (0.624) | (0.538) | (0.402) | (0.625) | (0.539) | (0.400) |
| $ln.AGE_{i,t}$ | -2.505*** | -1.135** | -0.954*** | -2.526*** | -1.135** | -0.965*** |
| | (0.596) | (0.501) | (0.152) | (0.596) | (0.501) | (0.153) |
| $ln.AGE2_{i,t}$ | 0.854*** | 0.312* | 0.348*** | 0.862*** | 0.314* | 0.355*** |
| | (0.200) | (0.168) | (0.0682) | (0.200) | (0.168) | (0.0683) |
| $ln.NATKNOW_{c,t-1}$ | -0.102 | -0.253*** | -0.148** | -0.131* | -0.216*** | -0.149*** |
| | (0.0822) | (0.0790) | (0.0666) | (0.0680) | (0.0648) | (0.0466) |
| $ln.INTKNOW_{c,t-1}$ | -0.744*** | -0.286 | -0.463** | -0.232** | -0.129 | -0.227*** |
| | (0.268) | (0.250) | (0.220) | (0.110) | (0.0998) | (0.0660) |
| $ln.INTRASITE_{i,t-1}$ | -0.109** | -0.113*** | -0.151*** | -0.112** | -0.115*** | -0.154*** |
| | (0.0522) | (0.0435) | (0.0305) | (0.0523) | (0.0435) | (0.0305) |
| $ln.INTERSITE_{i,t-1}$ | -0.0647 | -0.0235 | 0.0121 | -0.0711* | -0.0255 | 0.0110 |
| | (0.0416) | (0.0360) | (0.0263) | (0.0414) | (0.0360) | (0.0267) |
| $ln.INTERFIRM_{i,t-1}$ | -0.370** | 0.566*** | -0.270* | -0.347* | 0.573*** | -0.251* |
| | (0.179) | (0.169) | (0.152) | (0.179) | (0.168) | (0.150) |
| $TMI$ | -0.716** | -0.699** | 2.744*** | -0.797** | -0.780*** | 2.517*** |
| | (0.326) | (0.285) | (0.582) | (0.332) | (0.286) | (0.561) |
| $CHERNO$ | -3.039*** | -1.359** | -1.557*** | -3.036*** | -1.452** | -1.772*** |
| | (0.727) | (0.613) | (0.530) | (0.732) | (0.614) | (0.526) |
| Instruments | $\Delta lnUUF_{i,t-1}$<br>$\Delta lnUUF_{i,t-2}$ | $\Delta lnPUF_{i,t-1}$<br>$\Delta lnPUF_{i,t-2}$ | na | $\Delta lnUUF_{i,t-1}$<br>$\Delta lnUUF_{i,t-2}$ | $\Delta lnPUF_{i,t-1}$<br>$\Delta lnPUF_{i,t-2}$ | na |
| Hansen J P-value | 0.325 | 0.889 | na | 0.320 | 0.883 | na |
| Size distortion | <10% | <10% | na | <10% | <10% | na |
| Shea Part $R^2$ | .0139 | .0593 | na | .0139 | .0593 | na |
| F stat | 35.075 | 205.275 | na | 35.090 | 205.398 | na |
| Control variables, Time FE & country time trend | Yes | Yes | Yes | Yes | Yes | Yes |
| Obs. | 7,428 | 7,428 | 8,130 | 7,428 | 7,428 | 8,130 |
| # reactor code | 335 | 335 | 343 | 335 | 335 | 343 |
| Adjusted R-squared | 0.037 | 0.045 | 0.225 | 0.038 | 0.044 | 0.225 |

Note: *** p<0.01, ** p<0.05, * p<0.1. Robust standard errors in brackets.

# Appendix of Chapter 3

Table 3.8: List of states with wholesale market

| State | Year implemented |
|---|---|
| Arkansas | 2004 |
| California | 1998 |
| Connecticut | 1997 |
| Delaware | 1997 |
| Illinois | 2002 |
| Indiana | 2002 |
| Iowa | 2002 |
| Kansas | 2004 |
| Kentucky | 2002 |
| Louisiana | 2004 |
| Maine | 1997 |
| Maryland | 1997 |
| Massachusetts | 1997 |
| Michigan | 2002 |
| Minnesota | 2002 |
| Mississippi | 2004 |
| Missouri | 2002 |
| Montana | 2002 |
| Nebraska | 2004 |
| New Hampshire | 1997 |
| New Jersey | 1997 |
| New Mexico | 2004 |
| New York | 1999 |
| North Carolina | 2002 |
| North Dakota | 2002 |
| Ohio | 2002 |
| Oklahoma | 2004 |
| Pennsylvania | 1997 |
| Rhode Island | 1997 |
| South Dakota | 2002 |
| Tennessee | 1997 |
| Texas | 1997 |
| Vermont | 1997 |
| Virginia | 2002 |
| West Virginia | 2002 |
| Wisconsin | 2002 |
| District of Columbia | 2002 |

### Table 3.8: List of divested nuclear reactors

| Reactors | Year divestiture |
|---|---|
| Beaver Valley 1 & 2 | 2006 |
| Braidwood 1 & 2 | 2001 |
| Byron 1 & 2 | 2001 |
| Calvert Cliffs 1 & 2 | 2000 |
| Clinton | 1999 |
| Comanche Peak 1 & 2 | 2002 |
| Davis-Besse | 2006 |
| Dresden 2 & 3 | 2001 |
| Duane Arnold | 2006 |
| Fitzpatrick | 2000 |
| Ginna | 2004 |
| Hope Creek 1 | 2000 |
| Indian Point 2 & 3 | 2001 |
| Kewaunee | 2005 |
| La Salle 1 & 2 | 2001 |
| Limerick 1 & 2 | 2001 |
| Millstone 2 & 3 | 2001 |
| Nine Mile Point 1 & 2 | 2001 |
| Oyster Creek | 2000 |
| Palisades | 2007 |
| Peach Bottom 2 & 2 | 2001 |
| Perry 1 | 2006 |
| Pilgrim 1 | 1999 |
| Point Beach 1 & 2 | 2007 |
| Quad Cities 1 & 2 | 2001 |
| Salem 1 & 2 | 2000 |
| Seabrook 1 | 2002 |
| South Texas 1 & 2 | 2003 |
| Susquehanna 1 & 2 | 2000 |
| Three Mile Island 1 | 2000 |
| Vermont Yankee | 2002 |

# Appendix of Chapter 4

Table 4.6: Alternative model specification for equations (4.5) and (4.6)

| | Model 5 | | Model 6 | |
|---|---|---|---|---|
| **Variables** | **Cost** | **Leadtime** | **Cost** | **Leadtime** |
| $HHI.mo$ | 1.249** | -0.400*** | 0.247 | -0.444** |
| | (0.490) | (0.141) | (0.481) | (0.185) |
| $Ln.exparqmo$ | -0.153*** | 0.00548 | | |
| | (0.0411) | (0.0112) | | |
| $Ln.exparqnomo$ | 0.0284 | 0.0246** | | |
| | (0.0354) | (0.00952) | | |
| $Ln.expnoarqmo$ | 0.0461 | 0.0148 | | |
| | (0.0411) | (0.0117) | | |
| $Ln.ExpNoArqNoMo$ | -0.0950 | 0.152*** | | |
| | (0.103) | (0.0172) | | |
| $Inv.exparqmo$ | | | 0.335*** | -0.0256 |
| | | | (0.0670) | (0.0276) |
| $Inv.exparqnomo$ | | | -0.0976 | -0.00738 |
| | | | (0.0800) | (0.0329) |
| $Inv.expnoarqmo$ | | | -0.150* | -0.0168 |
| | | | (0.0797) | (0.0329) |
| $Inv.expnoarqnomo$ | | | 0.181 | -0.337*** |
| | | | (0.245) | (0.0762) |
| $ln.Know$ | | | 1.291** | |
| | | | (0.598) | |
| $ln.Cap$ | -0.839*** | 0.117** | -0.609*** | 0.174*** |
| | (0.221) | (0.0505) | (0.182) | (0.0611) |
| $ln.NPP.UC$ | 0.498*** | -0.101** | 0.318*** | -0.0405 |
| | (0.182) | (0.0432) | (0.105) | (0.0403) |
| $Arq.Utility$ | -0.255*** | -0.00852 | -0.292*** | 0.0245 |
| | (0.0965) | (0.0275) | (0.0870) | (0.0343) |
| $ln.Demand$ | | -1.202*** | | -1.467*** |
| | | (0.108) | | (0.125) |
| $ln.Leadtime$ | 2.270*** | | 1.133* | |
| | (0.820) | | (0.686) | |
| $Ln.ement$ | 0.392 | | 0.00336 | |
| | (0.538) | | (0.359) | |
| $Ln.Labour$ | -2.020 | | -0.710 | |
| | (1.365) | | (0.808) | |
| $TMI.US$ | -0.0558 | 0.292*** | 0.0756 | 0.300*** |
| | (0.197) | (0.0413) | (0.177) | (0.0494) |
| $TMI.FR$ | -0.00196 | -0.0535 | -0.184 | -0.00437 |
| | (0.252) | (0.0711) | (0.223) | (0.0899) |
| $Cherno$ | -0.107 | 0.0538* | -0.0516 | 0.0538 |
| | (0.140) | (0.0300) | (0.122) | (0.0362) |
| $Constant$ | 7.841* | -2.220*** | -3.776 | -3.056*** |
| | (4.597) | (0.428) | (5.726) | (0.507) |
| Country FE | Yes | Yes | Yes | Yes |
| Country specific trend + trend$^2$ | Yes | Yes | No | No |
| Trend + trend$^2$ | No | No | Yes | Yes |
| Obs. | 128 | 128 | 128 | 128 |
| Adj. R$^2$ | 0.823 | 0.960 | 0.873 | 0.940 |

Note: Standard errors in brackets. *** p<0.01, ** p<0.05, * p<0.1

### Table 4.7: Alternative model specifications for lead-time in OECD countries

| **Variables** | **(3)**<br>**ln_Leadtime** | **(4)**<br>**ln_Leadtime** |
|---|---|---|
| $HHI.Mo$ | -0.509*** | -0.458** |
| | (0.189) | (0.200) |
| $Ln.Cap$ | 0.225*** | 0.240*** |
| | (0.0516) | (0.0526) |
| $Ln.ExpArqMo$ | -0.0102 | |
| | (0.0317) | |
| $Ln.ExpArqNoMo$ | 0.0411*** | |
| | (0.0134) | |
| $Ln.ExpNoArqMo$ | 0.0141 | |
| | (0.0184) | |
| $Ln.ExpNoArqNoMo$ | 0.0806* | |
| | (0.0413) | |
| $Inv.Exparqmo$ | | 0.0514 |
| | | (0.111) |
| $Inv.Exparqnomo$ | | 0.00306 |
| | | (0.0323) |
| $Inv.Expnoarqmo$ | | 0.00948 |
| | | (0.0480) |
| $Inv.Expnoarqnomo$ | | -0.238 |
| | | (0.163) |
| *ln_Demand* | -17.01*** | -21.24*** |
| | (3.857) | (3.387) |
| $TMI.Abroad$ | 0.126* | 0.124* |
| | (0.0665) | (0.0691) |
| $TMI.US$ | 0.432*** | 0.448*** |
| | (0.0600) | (0.0627) |
| $Cherno$ | 0.214*** | 0.214*** |
| | (0.0293) | (0.0278) |
| $Constant$ | 2.111*** | 2.542*** |
| | (0.450) | (0.576) |
| Time FE | Yes | Yes |
| Country FE | Yes | Yes |
| Obs. | 286 | 286 |
| Adj. $R^2$ | 0.876 | 0.872 |

Note: Robust standard errors in brackets.

*** p<0.01, ** p<0.05, * p<0.1

Table 4.8: List of nuclear reactor models by manufacturer in France and the US

| **Model** | **Manufacturer** | **# reactors built** |
|---|---|---|
| B&W (L-loop) DRYAMB | Babcock & Wilcox | 9 |
| BWR-3 | General Electric | 1 |
| BWR-41 | General Electric | 15 |
| BWR-42 | General Electric | 4 |
| BWR-5 | General Electric | 5 |
| BWR-6 | General Electric | 4 |
| CE (2-loop) DRYAMB | Combustion Engineering | 13 |
| COMB CE80 DRYAMB | Combustion Engineering | 2 |
| CP0 | Areva | 6 |
| CP1 | Areva | 18 |
| CP2 | Areva | 10 |
| N4 | Areva | 4 |
| P4 | Areva | 8 |
| P'4 | Areva | 12 |
| W (2-loop) DRYAMB | Westinghouse | 3 |
| W (3-loop) DRYAMB | Westinghouse | 8 |
| W (3-loop) DRYSUB | Westinghouse | 4 |
| W (4-loop) DRYAMB | Westinghouse | 21 |
| W (4-loop) DRYSUB | Westinghouse | 1 |
| W (4-loop) ICECND | Westinghouse | 9 |
| **Total** | | **157** |

# L’Economie de l’Energie Nucléaire: Quatre Essais sur le Rôle de l’Innovation et de l’Organisation Industrielle

**RESUME:** Cette thèse étudie le rôle de l’innovation et des structures industrielles dans l’industrie nucléaire. L’analyse de l’innovation est basée sur l’utilisation de données de brevets comme mesure de l’effort d’innovation. Nous étudions d’une part les déterminants de l’innovation et, d’autre part, son impact sur la performance économique et de sureté des réacteurs nucléaires existants et sur les coûts de construction. Nous montrons que la régulation de sureté nucléaire peut promouvoir l’innovation et permet d’améliorer la performance de sureté, mais dans le même temps contribue à l’augmentation des coûts de construction. L’analyse du rôle des structures industrielles permet d’étudier l’effet des opportunités d’effets d’apprentissage, à la fois pour la construction et l’exploitation des réacteurs, ainsi que l’effet de la libéralisation des marchés de l’électricité sur la performance d’exploitation. En particulier, nous montrons que la séparation entre les activités de production et de distribution d’électricité induit une importante amélioration de la disponibilité des réacteurs nucléaires.

**Mots clés:** Nucléaire, Sureté nucléaire, Innovation, Effets d’apprentissage

# The Economics of Nuclear Power: Four Essays on the Role of Innovation and Industrial Organization

**ABSTRACT:** This thesis studies the role of innovation and industrial structures in the nuclear power sector. The analysis of innovation is based on the use of patent data as a measure of innovation effort. On the one hand, we study the determinants of innovation and, on the other hand, its impact on operating and safety performance of existing nuclear reactors and on construction costs. We show that nuclear safety regulation can induce innovation and improve safety performance, but at the same time contributes to increases in construction costs. The analysis of the role of industrial structures allows us to study the impact of learning by doing opportunities both for construction and operation of reactors, as well as the effect of electricity market liberalization on operating performance. In particular, we show that the divestiture of electricity production and distribution activities induces a substantial improvement in the availability of nuclear reactors.

**Keywords:** Nuclear, Nuclear safety, Innovation, Learning by doing

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