Economics of Nuclear Power : Construction Costs and Safety Regulation

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Economics of Nuclear Power : Construction Costs and Safety Regulation

L'Économie de l'Énergie Nucléaire : Coûts des Construction et Régulation de la Sûreté

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Economics of Nuclear Power: Construction costs and Safety Regulation

by

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"There are things known and there are things unknown, and in between are the doors of perception"

Aldous Huxley

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Abstract

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This thesis studies the role of the construction costs and safety regulation on nuclear power competitiveness. The analysis of the construction costs is based on the use of the actual data coming from the american and french nuclear fleet. In particular, we study different channels from which cost reductions might arise. We show that standardization is a key criterion for the economic competitiveness of nuclear power, first because the positive learning effects are conditional to the technology, this means that cost reductions will arise only if the same type of reactor is built several times, but also because it allows to reduce the cost indirectly through shorter construction lead-times. In the analysis of the role of safety regulation, we first asses the effect of the latest major nuclear accident (i.e Fukushima Dai-ichi) in the probability of occurrence of such an event and then the effects of the uncertainty regarding how safety care reduce the probability of a nuclear accident in setting safety standards under moral hazard and limited liability. We find that the standard will be stricter when the regulator is optimistic in the safety care effectiveness to reduce the risk of an accident, but simultaneously this policy might induce no compliance of the most inefficient operators.

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Preface

This PhD thesis is embedded in a research program called *The new economics of nuclear energy* directed by François Lévêque and financially supported by *Électricité de France EDF.* This project aimed to study the challenges of nuclear energy through an economic perspective, focusing on three research axes: innovation, competitiveness and industrial organization. This thesis tacked the second issue by studying the construction costs and nuclear safety regulation. This document presents four papers that have been presented in seminars and conferences. The opinions expressed in this document do not necessarily coincide with those of EDF.

Chapter 1 is entitled *How Fukushima Dai-ichi core meltdown changed the probability of nuclear accidents* and was co-written with François Lévêque. This paper was presented in the seminar organized by the Finance for Energy Market Research Center FIME at the Institut Poincaré in Paris (22 March 2013), at the 20th EAERE conference in Toulouse, France (26-29 June 2013) and was accepted and published in *Safety Science*, Volume 64 on April 2014.

Chapter 2, *Revisiting the Cost Escalation Curse of Nuclear Power. New Lessons from the French Experience* also co written with François Lévêque was submitted and is currently under revision to be published in Economics of Energy and Environmental Policy. This paper was presented at the Conference of Energy Markets organized by Toulouse School of Economics in Toulouse, France (17-18 January 2013) and afterwards at the IAEE International Conference held in Daegu, South Korea (16-17 June 2013).

Chapter 3, *Nuclear reactors' construction costs: The role of lead-time, standardization and technological progress* is co-authored with Michel Berthélemy. This paper has been presented in: the Séminaire de recherches en économie de l'énergie held in Paris, France (12 February 2014), in the Environmental Economics Lunch Seminar organized by Paris School of Economics (6 March, 2014), the International WPNE Workshop on Project and Logistics Management in Nuclear New Build, organized by the OECD Nuclear Energy Agency (NEA) in Paris, France (11 March 2014), the 3rd Mannheim Energy Conference (May 5-6, 2014) and the IAEE International Conference held in New York, U.S (16-18 June 2014). This paper was accepted to be published in *Energy Policy.*

Chapter 4 is called *Setting optimal safety standards for nuclear operators subject to uncertainty, moral hazard and limited liability* at the moment, it has not been yet presented in any conference.

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General Introduction

0.1 Context

On March 11 2011, the coast of Tôhuku, the region located at the northeast of Japan's main island, was devastated by a series of tsunami waves resulting after a 9.0 earthquake. This disaster affected several reactors in different nuclear power stations on the Pacific coast. Fukushima Dai-ichi was the most impaired nuclear plant, four of its six units were severely damaged and three reactors suffered core meltdowns followed by massive releases of radioactive material outside their containment structures. Undoubtedly, this has been one of the most severe accidents in the history of nuclear power for civil uses.

Briefly, the timeline of the events that lead to the core melt at Fukushima Dai-ichi happened as follows: after the earthquake, reactors 1 to 3 shouted down automatically following the japanese safety protocols. The emergency generators were activated to power the cooling systems, in order to keep below the melting point the fission products that were in the fuel rods. The tsunami 14 meters waves arrived 50 minutes after the earthquake and overpassed the unit's sea walls, which had 10[1] meters only. The sea water flooded the room where the emergency generators were located and they failed to power the cooling systems. Once the batteries of the active cooling systems ran out, the reactors began to heat up. As workers struggled to supply power to the reactors' cooling systems and control rooms, multiple hydrogen-air chemical explosions occurred from 12 March to 15 March.

As soon as the images of this terrible catastrophe were broadcasted worldwide, they revived the memories of the core melt at Chernobyl in Ukraine in 1986 and materialized the hazards associated with the operation of a nuclear power plant. After the accident, the reactions from both the nuclear industry and anti-nuclear groups were swift. As expected, this accident deepened the divergence in their views regarding the role that nuclear power can play in the world's energy production. But beyond the passionate

[1] For further details of the affected reactors hit by the earthquake and tsunami, see Phillip Lipscy and Incerti (2013).

views of these groups, the debate following after Fukushima Dai-ichi accident raised important issues that put into question the convenience of nuclear power, both in safety and economical terms.

Paradoxically, Fukushima Dai-ichi accident happened in a period when, after a long time, prospects of nuclear deployment were positives. Throughout the 90s, the construction of new reactors had stagnated and the progressive aging of the fleet worldwide seemed to indicate the inevitable narrowing of nuclear power's share in the world's energy production. However, since about 2001 the interest for nuclear power revived. In fact, the term *nuclear renaissance* appeared in the energy policy debate because many countries gave an important role to nuclear power in their agendas, with projections for new build similar to, or even exceeding, those of the early years of nuclear power. For instance, before the accident occurred 159 reactors were planned to be constructed around the world (WEC, 2012), which would have meant an addition of 178.123 MWe (i.e. 47% of the present capacity).

The renewed interest in nuclear power was not fortuitous, on the contrary it appeared as a solution to multiples concerns. The high oil prices registered in 2000 and the fact that much of the oil and gas production is located in politically unstable countries recalled the importance of reducing the dependence of fossil fuels and secure the energy supply. Given that nuclear power uses an abundant mineral (uranium) in the earth's crust made it attractive from an energy security standpoint. In addition, the growing awareness of the possible damages linked with climate change led to the implementation of different policies aimed to reduce CO2 emissions. Although most of the attention has been focused in renewables, it was acknowledge that nuclear power is the only technology that can provide base load electricity without carbon emissions (See Nuttall (2005), Joskow and Parsons (2009), Kessides (2012)).

Unquestionably, the accident meant a set back in terms of public perception about nuclear safety and induced a revision of the forecast of nuclear power expansion in many countries. The clearest example of how this accident triggered the political pressure against nuclear power was the decision to accelerate the nuclear phase-out in Germany. Just a couple of months after the accident, the Chancellor Angela Merkel decided to accelerate the phase-down and to move the shut down deadline to 2022, which reversed the decision that was taken one year before, when the life-time extension of nuclear power up to 2038[2] was granted.

This accident marked a breaking point in nuclear history, however the effect of Fukushima Dai-ichi in new nuclear builds is yet to be address. According Power Reactor Information System (PRIS) of the International Atomic Energy Agency (IAEA) 62 new reactors

[2] See: Edenhofer and Bruckner (2012)

were under construction in 2011 and in 2014, there are 72 reactors being built. Although this current level of new built is not as high as it was expected before the accident, it represents a record for nuclear industry and shows that public opinion is not the only barrier that nuclear power faces today. For the above, the materialization of the *nuclear renaissance* in those countries that still have a favorable opinion of nuclear power will depend, in some extent, on the responses that nuclear industry gives to the issues and challenges raised after this accident.

0.2 The risks of nuclear power and the probability of major accident

The first issue for nuclear power development reemerged right after the accident. The possibility of a core melt down and the harm that such an event might provoke is the reason why nuclear power has been perceived as a latent hazard and has had to struggle with public opposition in many countries. At that moment, perhaps one of the subjects that raised more controversy in the public debate was how likely nuclear meltdowns could occur. Despite that this issue seems only a matter of applying a statistical formula, after Fukushima Dai-ichi supporters and opponents to nuclear power claimed diametrically opposite things.

On the one hand, nuclear industry claimed that Fukushima Dai-ichi core melts were the result of an unpredictable and very rare situation, they argued that core melts are not likely to occur and they claimed that new designs can resist natural events of similar magnitude of those that hit Japan. This point of view was supported with the results of the Probabilistic Risk Assessments (PRA) that have been done in different reactors around the world. For instance, the report EPRI (2008) estimated that the average core melt frequency for the U.S nuclear fleet is equal to 2.0E-5, which means 1 core melt every 50.000 reactor years, or equivalently, 1 core melt each 1000 years for a fleet of 500 reactors in operation (today, world's nuclear fleet has around 430 reactors in operation).

On the other hand, nuclear opponents claimed that the observed frequency is higher than the (theoretical) expected frequency coming from the PRAs. Just dividing the total number of operating hours of all civilian nuclear reactors around the world, that is approximately 14.500 reactor-years, by the number of nuclear reactor meltdowns that have actually occurred (i.e. 4 nuclear meltdowns, 1 at Chernobyl and 3 at Fukushima), translates into one major accident every 3.625 reactor years. Which is substantially greater than what the nuclear industry suggested.

In this context, how to assess properly the probability of a major accident is an important question for nuclear power development, not only to clarify this debate, but also because it will allow a proper management of the risk. This means that societies can be better informed not only about the hazards that nuclear power entails but also on how likely is that major accidents occur. Nuclear regulators will be able to set attainable and coherent goals, in terms of the accepted risk level below which nuclear power plants should operate. In addition, operators can allocate better the safety investments aiming to reduce the probability of major accidents and finally, it could also be helpful to determine insurance policies.

0.3 The cost escalation curse in the construction of new nuclear power plants

The second concern raised after Fukushima Dai-ichi accident is related with the safety investments that might have to be done to allow reactors under operation to resist natural aggressions, as those that impacted the Japanese nuclear fleet. But even more important for the future development of nuclear power are the consequences that this accident might have in terms of construction costs for new reactors. Investment costs are the main driver[3] of nuclear electricity generating costs, thus any unexpected and significant increase of the expenses on the construction will undermine the profitability of a new build. It is possible to think that the lessons learned after Fukushima Dai-ichi may encourage nuclear vendors to include other safety features, safety authorities might impose stricter licencing rules, and greater public opposition to installing new nuclear power plants can result in an increase in the construction costs.

The potential effect of Fukushima Dai-ichi in the costs of new reactors worsen the doubts about the possibility of building nuclear power plants at a reasonable cost. It is important to mention that these concerns began to emerge before the accident, due to the continuous revisions in the costs estimates for new reactors in the U.S. Taking into account the changes made by utilities in the application forms filled for the Nuclear Regulatory Commission, the cost expectation of an AP1000 reactor passed from US$2,000 in 2003 (See: Base case in Parsons and Du (2003)) to US$4,000 per installed kilowatt in 2009 (See: Parsons and Du (2009) and Rosner and Goldberg (2011*a*)).

These concerns were also supported by the press releases announcing delays and important cost overruns in the construction of the first of a kind Generation III+ EPR[4]

[3] According to the IEA (2010) the share of the capital costs in the leveled cost of electricity in nuclear power is between 60% to 80%

[4] European Pressurized Reactor

reactors in Europe. In Finland, the construction of Olkiluoto 3 started in 2005 and was supposed to be ready in 2009. This delay will be by far failed, the commercial operation of this reactor was expected to be in 2016. The most recent news informed that it will be in 2018[5]. Regarding the construction costs of the EPR at Flamanville unit in France, the continuous increases in the costs make the situation alarming. The first estimate was €3.3 billion in 2005 and passed to €6 billion in 2011. The most recent press release in 2012 announced a total cost of €8.5 billion. Not to mention, that Flamanville 3 was expected to start commercial operation in 2013, but due to delays during the construction is expected now to start up in 2016.

As if this were not enough, the doubts about nuclear power competitiveness were also supported by what has been registered in construction of the U.S and French nuclear fleet. For the former, it is possible to find a 7 times difference of the overnight cost[6] expressed in M€(2010)/MW and collected by Koomey and Hultman (2007) for the first and last installed nuclear reactors. For France, Grubler (2010) found that the difference between the construction costs of the units installed in 1974 and those constructed after 1990 is 3.5 times. For all these reasons, the escalation of the construction costs of new reactors has been seen as a curse for nuclear industry.

The economic literature about nuclear power construction cost has not provided a clear cut answer to explain the main drivers of the new build's costs overruns and how is it possible to reduce them. Most of the studies have used primarily U.S construction costs data, due to the lack of comparable data coming from other countries, therefore the results are restricted to the american case. It is generally accepted that the heterogeneity of the nuclear U.S fleet, the longer lead-times that took to construct bigger reactors and the closer regulatory monitoring after Three Mile Island accident (Zimmerman (1982),David and Rothwell (1996), Rothwell (1986), Cantor and Hewlett (1988),McCabe (1996) and Cooper (2012)) were the main elements that explain the substantial increase in the costs per MWe installed.

The cost assessment done by Grubler (2010) for the french nuclear fleet concluded that although the French nuclear fleet was constructed under a centralized industrial structure and it has a more homogenous nuclear fleet compared with the U.S fleet, it suffered of *forgetting by doing*. Making allusion to the fact that while EDF accumulated experience, nuclear construction costs per unit of capacity have been increasing instead of decreasing.

[5] See: http://www.helsinkitimes.fi/finland/finland-news/domestic/11836-olkiluoto-3-to-be-ready-in-2018.html

[6] Overnight cost includes the investments linked with site preparation and construction, but it excludes financing expenses. Therefore, it shows the cost of the plant as if it had been fully built in one night.

In this context, it has been argued that nuclear power is characterized by increasing investment costs and it is inevitable to build a new reactor without cost overruns and delays. However, in 2012 the actual construction costs for the French nuclear fleet were published in the *Cour des Comptes* report and by using this new information, it is possible to find that the cost escalation computed by Grubler (2010)[7] was not as severe as argued. In fact, the ratio between the last and the first reactor installed in France using Grubler's estimates is 3, while by taking the actual construction costs is 1.4. This difference suggests that there must be a way to curb the construction costs of nuclear reactors. Using the new information coming from the *Cour des Comptes* report is key to identify which have been the factors that allowed to ease the cost escalation in the construction of new nuclear power plants in France, compared with what happened in the U.S.

Nowadays, determine the main drivers of the construction costs of new reactors and the possible sources of cost reductions is of paramount importance for nuclear industry. As mentioned before, currently there are 72 reactors *under construction* in 14 different countries[8], this is quite an achievement for nuclear power given that level of new build in 2014 has not been observed since 1987. It is likely that the success of the projects under construction, in terms of meeting the schedules and budgets, will represent a step towards the materialization of the *nuclear renaissance*, because it will give a green light for further deployment of nuclear power. While if this projects repeat the errors of the past, this might lead investments to other competing energy technologies, which have shown decreasing costs. For instance, Lindman and Söderholm (2012) found that the kW from onshore wind farms decreases by more than 10% each time the installed capacity doubles. In the same direction, Isoarda and Soria (2001) and C. Yu and Alsema (2011) have identified significant learning effects in the photovoltaic industry, result that is confirmed by the dramatic reductions in the underlying costs and market prices of solar panels in the last years.

0.4 Nuclear safety regulation

One last issue, that also came as a result of Fukushima Dai-ichi accident is the role of safety regulation as an effective way to prevent these events. As described above, the height of tsunami waves was the cause of the flood, that made impossible to run the emergency generators to cool down the reactors, that eventually led to the core melts.

[7] The costs assessment done by Grubler (2010) did not use the actual construction costs but some estimations based on EDF financial statements

[8] See the list published by the World Nuclear Association (WNA) `http://world-nuclear.org/NuclearDatabase/rdresults.aspx?id=27569&ExampleId=62`

Right after the accident, it was somehow spread in the media that a tsunami of such magnitude was a surprise and it was not predictable, therefore the whole situation could be considered as a *black swan*. Nevertheless, different nuclear safety experts carried out investigations after the accident and discovered that the Japanese safety authority knew that similar tsunamis had happened in the past and it was possible to witness them again (see Gundersen (2012), Wang et al. (2013)).

This revelation harmed the reputation of the safety authority and the laxity of the Japanese nuclear regulator is now seen as the main cause of this accident (Lévêque, 2013). Indeed, the investigation showed that it was never required to Tokyo Electric Power Company (TEPCO), the operator of Fukushima Dai-ichi, to back fitted the sea walls even if they knew that it was likely to observe a violent tsunami in that region. Today, it is possible to argue that upgrading the unit's sea walls would have been much cheaper, than the costs of damages that the accident has caused. However, before the accident, the investment decision was not as clear cut as it might be seen now. First, because even if the regulator knew that a tsunami of that magnitude was possible, still its probability was very small. Second, because the potential damages in case of an event like this were highly uncertain. Finally, because it is hard to measure how the sea wall's upgrade would have reduced the probability of this accident. In consequence, before the accident the costs of upgrading the walls could have been seen as unnecessary, thus harmful for the profitability of the company.

Taking into account the above, it is clear that safety regulation aside from preventing nuclear accidents, also plays its role in the economics of nuclear power. Safety authorities are in charge of determining and enforcing the acceptable risk level at which nuclear power plants should operate. However, to attain the envisioned risk levels they can not demand the first thing that comes to mind. First, because it might not be effective to reduce the probability of an accident and second, because it might be too costly. In economics, this tension simply means that the regulators will have to identify the standards that allow to reduce the risk of major accident in a cost-efficient way. In other words, they have to determine the optimal balance between the marginal private costs of providing safety and the social marginal benefits of achieving that level of safety.

Although this balance between the costs and benefits of providing safety is also present in other sectors, like transport, food, drugs, etc; nuclear safety authorities have to deal with several particularities. First, the damages left after an accident are huge and its consequences are long-lasting. For instance, the preliminary cost estimates of the Fukushima Dai-ichi accident are around 250 billion USD. Schneider and Froggatt (2014) claimed that 11 municipalities in Fukushima Prefecture covering 235 km^2 will have to undertake decontamination efforts, not to mention the costs related with all the people that had to be relocated after the accident. In the literature, Shavell (1984), Kolstad et al. (1990) and Hansson and Skogh (1987) showed that when the magnitude of the harm is huge, as is the case of nuclear accidents, liability rules although they are necessary to provide incentives to exert safety care, are not enough to achieve sufficiently high safety levels.

Second, nuclear safety regulators have to monitor that operators comply with the requirements established in the safety standards, due to the unobservability of their action (although this is not specific for nuclear power). In the economic literature, Strand (1994), Hiriart and Martimort (2004), Hiriart et al. (2004), inter alia, have shown that this information asymmetry (moral hazard) means that it is not possible to enforce the first best safety level at zero cost. Therefore, the challenge for nuclear safety authorities is to be able to define a policy that induce the compliance of the safety standard as the operator's optimal response.

Finally, another problem present in nuclear safety regulation is the epistemic uncertainty regarding the probability of a major accident, but in particular how safety care can reduce it. Nuclear regulators have some statistical tools, as the PRA, to evaluate how operator's safety care translates into reductions/increases in the probability of an accident, however the results coming from these techniques are random variables with unknown distribution functions. This last feature means nuclear regulators do not have a single and precise probability measure when setting the safety standards, but instead they have some partial information (i.e. an interval of values coming from the PRA) about the link between safety care and the probability of an accident.

How to set optimal safety standards in the presence of all the particularities mentioned above is an important challenge for nuclear power development. In the first place, because safety authorities have to be able to guarantee that nuclear facilities run under the accepted risk level. Second, because safety standards are an effective way to complement liability rules and achieve higher safety levels. Finally, because it is in the interest of both, the society and the operator to avoid the damages linked with major nuclear accidents.

0.5 Methodological approach, structure and contribution of this thesis

All the issues described before make nuclear power a passionate subject and pose research questions, that are far from dull. Specifically in this thesis, we will try to give an answer, from a positive perspective, to the following questions: how to assess properly the probability of a nuclear accident?, which are the determinants of the nuclear construction costs and the possible sources of reductions? and finally how to set optimal safety standards in the nuclear power sector?, taking into account the particularities of major nuclear accidents. To answer to these questions, this thesis is composed by four chapters that aim to study rigorously these three issues, in order to derive conclusions that shed some light in current debate, but also that allow us to predict to the possible trends in nuclear power development and help to shape future energy policies.

Chapter 1 is entitle *How Fukushima Dai-ichi core meltdown changed the probability of nuclear accidents* and was co-authored with François Lévêque. This chapter investigates how to compute the probability of a nuclear accident by using past observations. But in particular, how the observation of the last catastrophe at the Fukushima Dai-ichi nuclear power plant changed the expected frequency for such events. In this chapter we aimed to answer these questions by using historical data and testing different statistical models. We have compared four Poisson models using three different definitions of nuclear accidents from 1952 to 2012.

Our results allow us to conclude that as the definition of accident takes into account other events, (i.e. not only the major nuclear disasters but also less serious accidents) the independence assumption underlying the classical Poisson models is violated. This result called for a time-varying mean model, such as the Poisson Exponentially Weighted Moving Average (PEWMA). By using this last model we find a greater increase in the risk of a core meltdown accident, owing to the accident that took place in Japan in 2011, than the estimates that we obtained using the classic Poisson models.

Chapter 2 is entitle *Revisiting the Cost Escalation Curse of Nuclear Power: New Lessons from the French Experience* and it was also co-written with François Lévêque. This chapter studies the so called *cost escalation curse* that has affected the construction of new nuclear power plants, ever since the completion of the first wave in 1970 to the ongoing construction of Generation III+ reactors in Europe. As we have mentioned, this phenomenon has been studied for the U.S., and it has been argued that the escalation can partially be explained by a heterogeneous nuclear fleet, which has made it difficult to learn from experience. The French nuclear power program has followed a standardization strategy, however, previous cost assessments have also pointed to an increase in the capital costs. This observation implied that even in the best economic conditions, cost escalation is inherent to nuclear power.

In this chapter we reexamine the drivers of cost escalation in France, based on construction costs taken from a recent report by the *Cour des Comptes*. Using this new information, we find that the cost escalation observed in previous studies was lower than argued. Our results indicate that the scale-up resulted in more costly reactors, however we were not able to disentangle the effect of the technological change embedded on bigger reactors, from the effect of the increase in the size. In parallel we find positive learning effects, but they were restricted to the same type of reactors (i.e. the construction cost of decrease as the experience in the same type increases). Finally, we find that those reactors with better safety performance were also more expensive. This last result suggests that safety concerns have played a role in the cost escalation observed in France.

Chapter 3, *Nuclear reactors' construction costs: The role of lead-time, standardization and technological progress* is co-authored with Michel Berthélemy and complements the previous chapter by analyzing the nuclear reactor construction costs and lead-times in France and the United States. We estimate a regression model for both the overnight costs and construction time. In this chapter, we test the presence of standardization gains in the short term and long term. The former might arise when the diversity of nuclear reactors' technologies under construction is low, and the latter might arise as the result of learning by doing, that in this context means the experience in the construction of the same type of reactor. In addition, we study the effect of innovation in the construction of new reactors, by using priority patent data as a proxy for technological progress.

We find that overnight construction costs benefit directly from learning by doing, but the spillovers were only significant for nuclear models built by the same firm. In addition, we show that the standardization of nuclear reactors has an indirect and positive effect in the short run, 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

Chapter 4 is entitle *Setting optimal safety standards for nuclear operators under uncertainty, moral hazard and limited liability.* It examines the features of an optimal safety regulatory policy under uncertainty about how safety care reduces the probability of accident, moral hazard and limited liability. The regulatory policy consists in setting a safety standard and choose a probability of inspection to the nuclear facilities. After the inspection, the regulator can impose a fine in case the nuclear operator did not comply with the safety standard. The main objective of this paper is to characterize the optimal regulatory policy that induce compliance by the operator, when the regulator does not know perfectly how the safety care level will reduce the probability of a nuclear accident. To tackle this issue we use robust optimization techniques: worst case and regret robustness.

Our results suggest that under the most conservative approach, i.e. when the regulator minimizes the maximum expected costs, the regulatory policy will be less strict, than when he is better informed. On the contrary, when the regulator attempts to minimize regret, the safety standard might be stricter but it also increases the risk of no compliance.

Finally, Chapter 5 concludes. This chapter outlines the main results of this PhD thesis and links them with the challenges that nuclear power faces today. In short, we claim that the development of nuclear power in the world will depend predominantly, on how the industry is able to curb the cost escalation. For this reason, nuclear vendors should direct their innovation efforts not only on achieving better safety performance (as they have done so far), but also on reducing the construction costs. Countries with ambitious nuclear power programs should adopt a standardization strategy by reducing the technologies to be installed, but also they have to determine which will be the pace of technological change. Finally, nuclear regulators should concentrate their efforts in fostering better safety performance levels within the operators through stricter operating standards, once the reactors guarantee that they have reached an acceptable ex ante risk level.

Chapter 1

How Fukushima Dai-ichi core meltdown changed the probability of nuclear accidents?

1.1 Introduction

The triple core meltdown at Fukushima Dai-ichi power plant on March 11, 2011 is the worst nuclear catastrophe after Chernobyl in 1986. The substantial losses of this accident have aroused in the public opinion an old age debate: Is nuclear power safe? Critics claim that nuclear power entails a latent threat to society and we are very likely to witness an accident in the near future. Proponents say that the conditions that provoked the Fukushima disaster were unlikely, assert that new reactors can successfully face extreme conditions and conclude that the probability of a nuclear accident is very low.

In the media this debate is far from be clear. For instance, two months after the Fukushima Dai-ichi meltdown, a French newspaper published an article[1] saying that the risk of a nuclear accident in Europe in the next thirty years is not unlikely but on the contrary, it is a certainty. The authors claimed that in France the risk is near to 50% and more than 100% in Europe.

Their striking result comes from dividing the number of reactor explosions (one in Chernobyl and 3 in Fukushima Dai-ichi) over cumulated experience (14.000 reactor-years) and multiplying this ratio by the number of reactors and 30 years. So if we take 58 operative reactors in France, we get 0.49 and if we consider 143 reactors in Europe we

[1] Benjamin Dessus and Bernard Laponche, June 3, 2011, available at http://www.liberation.fr/politiques/01012341150-accident-nucleaire-une-certitude-statistique

obtain 1.22; hence, their conclusion that a nuclear accident is a certainty in the European Union.

Although their methodology is essentially flawed since the figures they found are larger than 1, the estimated frequency of a major accident reported by nuclear industry is not very convincing neither. According to a report issued by EPRI (2008) , the probabilistic risk assessment for the U.S nuclear fleet estimates an average expected rate of core meltdown of the order of 2.0E-5. This figure means that in average we can expect one accident per 50.000 reactor years, which seems quite optimistic with respect to what has been observed in the history of nuclear power. As of today, one accounts approximately 14.500 operating years of nuclear reactors and 10 core meltdowns. This implies an observed frequency of 1 accident per 1450 reactor years, which is a higher rate than what is predicted by the probabilistic risk assessments (PRA, hereafter).

From this debate we can conclude that assessing properly the probability of a nuclear accident with available data is key to shed light in the risks that nuclear power will entail on tomorrow. For this reason, the main objective of our paper is to discuss different statistical approaches to estimate the expected frequency of nuclear accidents. Our results suggest that although the Poisson model is the most used for addressing this problem, it is not suitable when the independence assumption is violated. In such cases a time-varying mean model, like a Poisson Exponentially Weighted Moving Average (PEWMA) is more suitable to estimate the expected frequency of core meltdown.

The remainder of this paper is structured as follows. Section 1.2 outlines the literature about nuclear risk assessment. Section 1.3 investigates how to estimate the expected frequency and compute the probability of a nuclear accident using successively a frequentist and a Bayesian approach. Section 1.4 presents the PEWMA model and its results. Section 1.5 concludes.

1.2 Literature review

It is possible to distinguish two approaches to assess the probability of nuclear accidents: PRA models and statistical analysis. PRA models describe how nuclear reactor systems will respond to different initiating events that can induce a core meltdown after a sequence of successive failures. This methodology estimates the core damage frequency

(CDF, hereafter)[2] based on observed and assumed probability distributions for the different parameters included in the model.

The use of PRA in commercial reactors is a common practice in the U.S, because the results are a key input for the risk-based nuclear safety regulation approach (Kadak and Matsuo, 2007). The Nuclear Regulatory Commission (NRC, hereafter) has been doing PRA studies since 1975, when the so-called WASH-1400 was carried out. This first study estimated a CDF equal to 5E-05 and suggested an upper bound of 3E-04.

The lessons from Three Mile Island accident and the ensuing improvements in PRA techniques allowed the NRC to perform a PRA for 5 units in 1990; the average CDF found was 8.91E-05. In 1997 the NRC published the Individual Plant Examination Program NUREG-1560, which contains the CDFs, for all the 108 commercial nuclear power plants in the U.S.

The latest EPRI (2008) report about the U.S nuclear fleet pointed out that this metric has shown a decreasing trend from 1992 to 2005 (see Figure 1) due to safety enhancements that have induced significant reductions in the risk of core melt down. As mentioned before, it claimed that the average CDF is 2.0E-5.

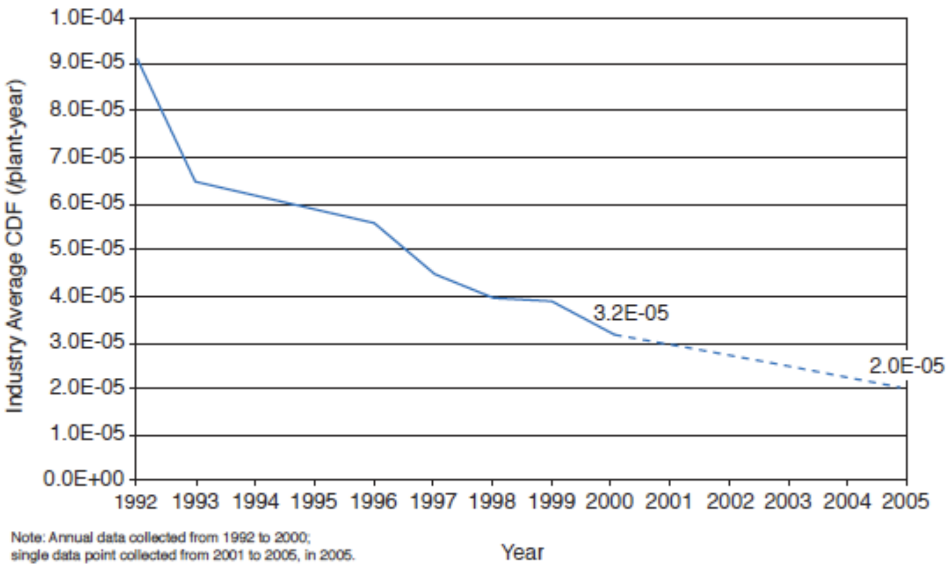

FIGURE 1.1: Core Damage Frequency Industry Average Trend (EPRI, 2008)

[2] PRA can be done at 3 levels. The first one considers internal or external initiating events followed by a series of technical and human failures that challenge the plant operation and computes the CDF as a final outcome. Level 2 evaluates how the containment structures will react after an accident, at this level the Large Early Release Frequency (LERF) is computed. The last level determines the frequencies of human fatalities and environmental contamination.

The second approach to assess the probability of nuclear accidents is statistical analysis. Basically this approach combines theoretical probability functions and historical observations, to estimate the parameters of interests.

Hofert and Wüthrich (2011) is the first attempt in this category. The authors used Poisson maximum likelihood (MLE) to estimate the frequency of annual losses derived from a nuclear accident. The total number of accidents is computed as a Poisson random variable with constant arrival rate denoted by λ.

The authors recognized that the λ estimates change significantly depending on the time period taken. This suggests that there are doubts about the assumption of a non-time dependent arrival rate. If the arrival rate depends on time, it means that the events are correlated somehow, which in turns means that one of main assumptions underlying this model is violated and therefore the results coming from the classic Poisson model are no longer valid. The main purpose of our paper is to fill this gap in the literature by using a structural-time series approach. This model has been developed by Harvey and Fernandes (1989) and used in political science by Brandt and Williams (1998), but is yet to be used to assess nuclear risks.

1.3 How to properly estimate the expected frequency of a nuclear accident using theoretical probability and past observations?

How to compute the probability of a serious accident is a key input to assess the risk of nuclear power. Nevertheless, the use of a theoretical probability distribution to predict an outcome, like a nuclear accident, requires a clear interpretation of the estimates that we are obtaining.

The results that we will present in the following sections correspond to an arrival rate of a Poisson distribution, which corresponds to the expected frequency of an accident (the mean of the distribution). Given that we are dealing with a rare event, the estimates for this rate will tend to be close to zero, and this feature make it possible to approximate the value of the arrival rate to the probability of observing at least one accident.

The usual interpretation for an arrival rate, for instance equal to 5E-0.5, is that in average we will observe at least one accident each 20000 reactor-years. Following Aven and Reniers (2013) we can have a better interpretation and think this arrival rate, as the equivalent uncertainty that a person will assign to drawing a specific ball from an urn containing 20000 balls.

1.3.1 Data

Defining which events can be considered as nuclear accidents was the first step in our study. As we will explain in this section, the scope of the definition of accident will determine the number of observations to be used in the statistical models that we are going to test.

In general, the criterion used to define nuclear accidents is closely linked with the amount of radioactive material that is released outside the unit. The International Atomic Energy Agency introduced the INES scale inspired by the so-called Birds pyramid that seek to determine the ratio between the fatal and less serious accidents. As we can see in Figure 1.2, this scale ranks nuclear events into 7 categories. The first 3 are labeled as incidents and only the last 4 are considered as accidents. The *major nuclear accident* is rated with 7 and is characterized by a large amount of radioactive material release, whereas the *accidents with local consequences* are rated with 4 because only minor releases of radioactive material have occurred.

FIGURE 1.2: Core Damage Frequency Industry Average Trend Source: IAEA: http://www-ns.iaea.org/tech-areas/emergency/ines.asp

This pyramid is a good representation of both the severity and frequency nuclear incidents/accidents. On the top, we find the major nuclear accidents that are rare events. Since the installation of the first commercial nuclear reactor in 1952 unit nowadays, there have been only 2 events classified in this category: Chernobyl and Fukushima Dai-ichi. On the base, we find minor incidents that are more frequent but less serious. As we climb the pyramid, we have fewer observations but each one represents a more serious accident.

The International Atomic Energy Agency has recorded every single event reported by nuclear operators since 1991 using the INES scale[3]. Unfortunately, not all the nuclear incidents recorded previous to 1991 are rated with this scale; only the most significant events have been evaluated and rated accordingly. Table 1.1 summarizes the number of observations that we gathered in each category.

Table 1.1: INES Events

INES	3	4	5	6	7
Observations	20	13	5	1	2

As we can see in Table 1.1, the low frequency of a major nuclear accident (Level 7) makes difficult to appraise its probability. However, if we expand the definition of nuclear accident more observations make the cut. For instance, we can consider nuclear accidents as all the events rated with more than 3 in the INES scale. Table 1 shows that with this new definition, we count 21 accidents.

From the above it can be deduced that the definition of nuclear accident is an important empirical issue, because as it gets narrower (i.e. more serious accidents) the number of observed events is reduced. This tension implies a trade-off between estimation reliability and the meaning of the results. A broader scope will result in better estimates, but they will not give a precise insight about major nuclear accidents. On the contrary, if we restrict our attention only to the most dramatic accidents, we only have 2 cases, which undermine the degrees of freedom, therefore the reliability of any statistical model.

In order to avoid the sparseness when focusing only on major nuclear accidents, we considered 3 definitions. The first definition corresponds to events rated with more than 2 in the INES scale (serious incidents + accidents), the second counts those accidents rated with more that 3 within the same scale. The third definition is core meltdowns with or without radioactive releases, this events have been recorded by Cochran (2011), who counted 9 nuclear commercial reactors that have experienced partial core meltdown from 1955 to 2010, including the well-known Three Mile Island accident in 1979.

Given that this last definition (core melt downs) is the narrowest, we can compare it with the CDF computed in the PRA studies. Another advantage of using this definition is that the magnitude of internal consequences of a core meltdown (i.e., the loss of the reactor and its clean-up costs) do not differ much between a major and less severe

[3] The data is available in their webpage http://www-news.iaea.org/

accidents[4]. Therefore, knowing the expected frequency of a core meltdown as we have defined, could be useful to design insurance contracts to hedge nuclear operators against the internal losses that will face in case of any of these events.

It is important to recognize that given that the broader definitions (events with INES> 2 and >3) contain heterogeneous events, it is possible that the magnitude of internal consequences that they had had differ substantially, therefore they cannot be used to insurance purposes. Nevertheless, we consider it is worthwhile to consider these two definitions despite this shortcoming, because the results can be seen as an upper bound for the expected frequency of serious catastrophes.

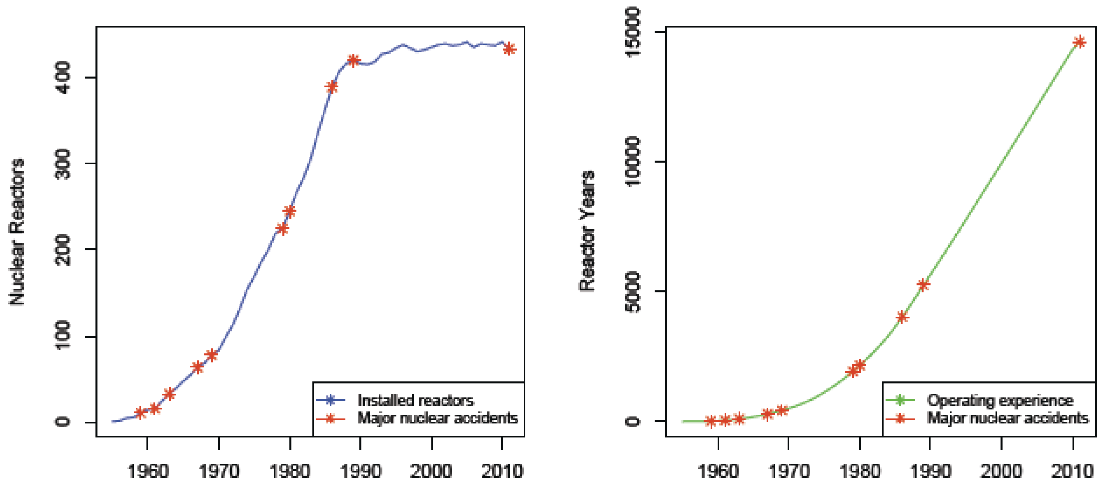

FIGURE 1.3: Major nuclear accidents, reactors and operating experience 1955-2011

Figure 1.3 plots the number of core melts downs (CMD, hereafter) collected by Cochran (2011) as well as the number of installed reactors, on the left panel and cumulated nuclear operating experience (in reactor years) published in the PRIS[5] database, on the right panel.

At first glance, we can conclude that PRA results might not be completely wrong, given that most of the accidents were recorded at the early stages of nuclear power history. It is important to highlight that during the period in which nuclear experience grew exponentially (i.e., over the last 10 years), only (and fortunately) the Fukushima Dai-ichi meltdowns have been observed. This intuitively suggests that there have been safety improvements in the operation of the worldwide nuclear power fleet.

Figure 1.4 shows how many times we have observed in our sample nuclear accidents using our three definitions. As we can see in this Figure, the most frequent value for an

4 By contrast, the damages in case of radioactive elements releases in the environment could vary in several orders of magnitude depending on the meteorological conditions and the population density in the areas affected by the nuclear cloud

5 The Power Reactor Information System

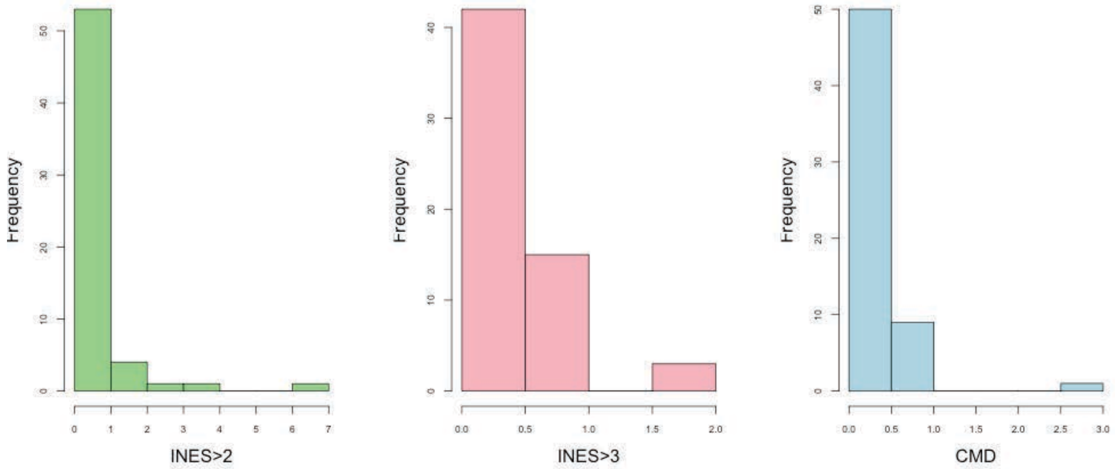

FIGURE 1.4: Histogram for nuclear accidents 1952-2011

event rated with more than 2 and 3 in the INES scale, as well as CMD is zero. This means that that sparseness remained, even if the scope of accidents that we have taken is broader.

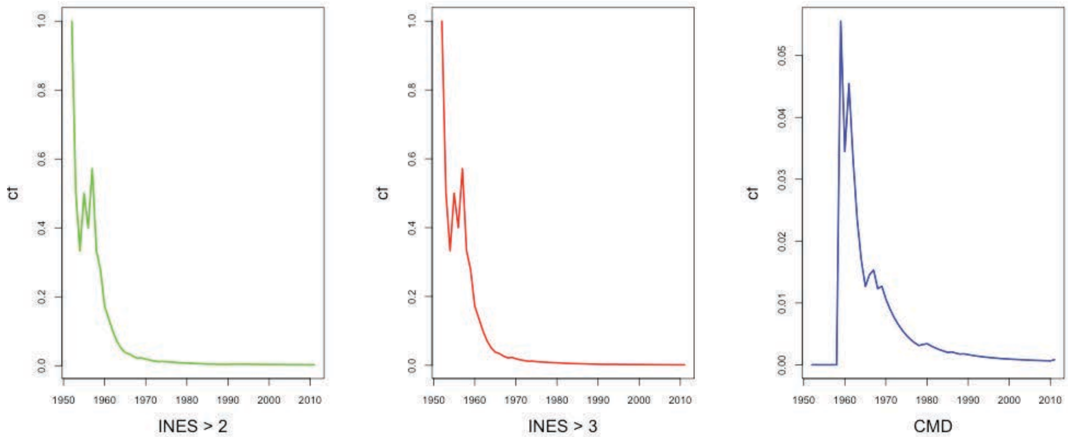

FIGURE 1.5: Cumulate frequency (Accidents/ReactorYears) for nuclear accidents 1952-2011

1.3.2 Models

Once we had defined the scope of accident, we parameterized the problem. We assumed that nuclear accidents are realizations that follow a Poisson distribution. This function computes the probability of a number of discrete events occurring in a continuous but fixed interval of time, given an arrival rate. In our case, the events correspond to nuclear accidents and the interval time to one year.

Assumption 1: Let y_t denote the number of nuclear accidents observed at year t. Assume that y_t is a Poisson random variable with an arrival rate λ and density function given by:

$$f(y_t|\lambda) = \frac{(\lambda E_t)^{y_t} \exp(-\lambda E_t)}{y_t!} \tag{1.1}$$

Although the time period is one year, we have to offset the observations by E_t, that is the exposure time within this interval. It corresponded to the number of operative reactors at year t.

Under Assumption 1, the problem is fully parameterized and we only need to estimate the arrival rate, denoted by λ that in our case represents the expected frequency of a nuclear accident, to compute the probability of a nuclear accident at time t.

Before we proceed further, we want to reiterate the necessary conditions for a count variable to follow Poisson distribution:

i. The probability of two simultaneous events is negligible

ii. The probability of observing one event in a time interval is proportional to the length of the interval

iii. The probability of an event within a certain interval does not change over different intervals

iv. The probability of an event in one interval is independent of the probability of an event in any other non-overlapping interval

In the case of nuclear accidents, the first two assumptions do not seem far from reality. Even if in Fukushima Dai-ichi the core melts occurred the same day, the continuous nature of time allows us to claim that they did not happen simultaneously; and it is not unreasonable to expect that as we reduce the time interval, the likelihood of an accident goes down.

On the contrary, conditions (iii) and (iv) might be more disputable. In this section, we assumed that the data satisfy these assumptions; in the next section they will be relaxed.

The simplest procedure to estimate λ is to use the observations in the sample $(\{y_t\}_{t=0}^{T}, \{E_t\}_{t=0}^{T})$ a and compute the maximum likelihood estimate. Which simply means that $\hat{\lambda}$ equals the cumulative frequency. Using the three definitions of nuclear accidents, we computed the estimate for λ. Table 1.2 summarizes the results.

Table 1.2: Poisson with constant arrival rate (1952-2011)

Database	$\hat{\lambda}$	Coefficients	Estimate Std.	Error z value	Pr(> |z|)
INES > 2	0.00273	-5.902	0.156	-37.8	<2e-16 ***
INES > 3	0.00139	-6.571	0.218	-30.12	<2e-16 ***
CMD	0.00066	-7.312	0.316	-23.12	<2e-16 ***

If we compute $\hat{\lambda}$ using the information available up to year 2010, we can define Δ as the change in the estimated arrival rate to measure how Fukushima Dai-ichi affected the rate.

$$\Delta = \frac{\hat{\lambda}_{2011} - \hat{\lambda}_{2010}}{\hat{\lambda}_{2010}} \tag{1.2}$$

Using this first model, the Fukushima accident represented an increase in the arrival rate of the CMD equal to 0,079. In other words, after assuming a constant world fleet of 433 reactors on the planet from 2010 to 2011, was equal to 6.17E-04 in the absence of Fukushima Dai-ichi accident. By including this accident, it went up to 6.66E-04 (i.e., about a 8% increase).

However, the simplicity of this model comes at a price. First, the estimation only took into account the information contained in the sample (i.e. observed accidents), it would been suitable to incorporate the knowledge brought by nuclear engineers and scientists over the past 40 years on the potential causes that may result in major accidents, especially core meltdowns.

Second, it is assumed that all the reactors built over the past 50 years are the same and their safety features are time invariant. This basic Poisson model does not measure if there have been safety improvements that reduce the probability of a nuclear accident progressively, as PRA studies have shown.

To address the first limitation, our second alternative was to consider λ as a random variable. Under this approach, using Bayes law, the observations were combined with a prior distribution, denoted by $f_0(\lambda)$, that encoded the beliefs about our parameter, to update the distribution of our parameter of interest.

$$f(\lambda|y_t) = \frac{f(y_t|\lambda)f_0(\lambda)}{\int f(y_t|\theta)f_0(\theta)d\theta} \tag{1.3}$$

Equation 1.3 shows the updating procedure for a continuous random variable. Note that once we have updated $f_0(\lambda)$ using the available information $\{y_t\}_{t=0}^{T}$, we can use mean of the posterior distribution $f(\lambda|y_t)$ in Equation 1.1 to compute the probability of an accident.

The choice of the prior distribution has always been the central issue in Bayesian models[6]. Within the possible alternatives, the use of a conjugate prior has two important advantages: it has a clear-cut interpretation and it is easier to compute.

Inasmuch as we have already assumed that accidents come from a Poisson distribution, we have also assumed that λ followed the conjugate distribution for this likelihood, which is a Gamma distribution with parameters (a, b).

Assumption 2: The arrival rate λ is a Gamma random variable with parameters (a, b) and density function given by:

$$f_0(\lambda) = \frac{\exp(-b\lambda)\lambda^{a-1}b^a}{\Gamma(a)} \tag{1.4}$$

Due to the properties of the gamma distribution, it is easy to interpret the chosen parameters. The intuition is the following: Prior to collecting any observations, our knowledge indicates that we can expect to observe a number of accidents in b reactor years. This gives us an expected rate equal to a/b, that will be the mean of the gamma (prior) distribution. The parameter that reflects how confident we are about this previous knowledge is b. Given that it is closely related with the variance ($V(\lambda) = a/b^2$), the greater b, the more certain we are of our prior. Once we collect observations, y_t accidents in E_t reactor years, we update our prior following a simple formula:

$$a_u = a + y_t \tag{1.5}$$

$$b_u = b + E_t \tag{1.6}$$

Which gives a new expected rate given by a_u/b_u.

PRA estimates have valuable information to construct the prior. For instance, the WASH-1400 report found an upper bound CDF equal to 3E-04, it means approximately 1 accident over 3.500 reactor years, that can be expressed in terms of prior parameters as $(a = 1, b = 3.500)$. Likewise, the NUREG-1150 study computed a CDF equal to 8.91E-05, that in terms of prior parameters is $(a = 1, b = 10.000)$.

[6] For an extended discussion on the prior's selection, see Carlin and Louis (2000) or Bernardo and Smith (1994)

As we can see in Figure 1.6, using the WASH-1400 information as prior, the Bayesian model predicted both a higher expected arrival rate and a wider confidence interval, because the low value of b. In this case, the results were driven by the observations and quickly converged towards the results of the previous model. However, by taking the NUREG-1150 study as a source for the prior, we needed a larger number of observations to move far from the prior.

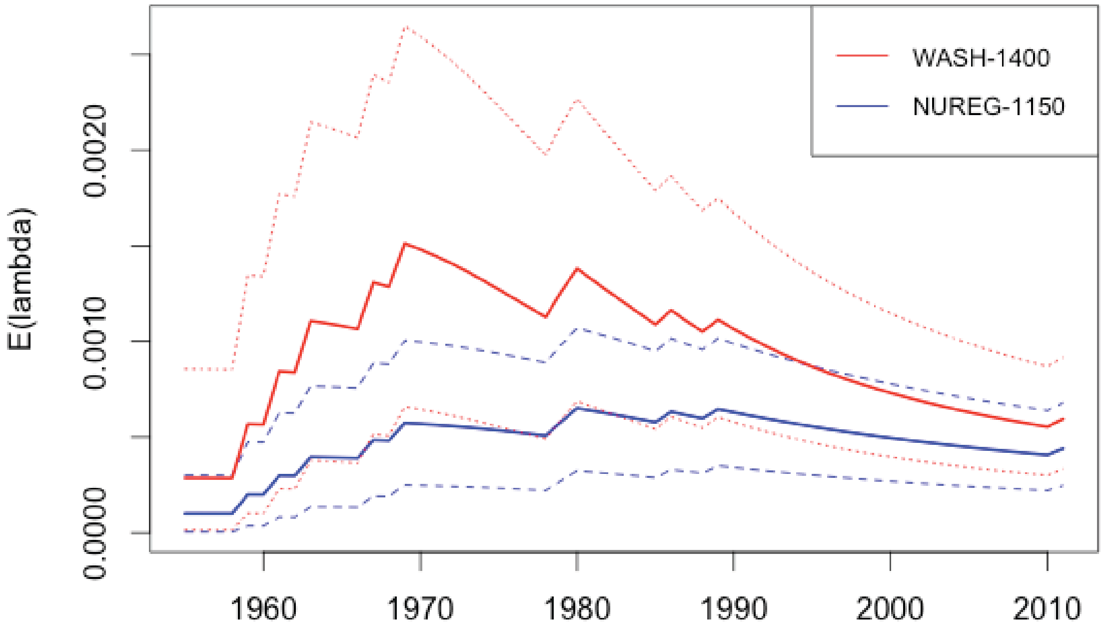

FIGURE 1.6: Bayesian updating with Poisson-Gamma model

In fact, by using $(a = 1, b = 3.500)$ as prior, we found similar results for the CMD. The Poisson-gamma model predicted an expected arrival rate equal to $\hat{\lambda}_{2011} = 5.99\text{E-}04$ and Δ represented an increase of 7.09%. After using the figures form the NUREG-1150 $(a = 1, b = 10.000)$, we found an expected arrival rate equal to $\hat{\lambda}_{2011}$ =4.3E-04 and Δ= 8% for CMD.

To deal with the second limitation of the Poisson model, we defined λ as a function of a time trend. With this third model, is possible to test if that there has been a sustained decrease in the expected rate of nuclear accidents over the past 10 years. However, note that such an approach challenges what is stated in condition (iii) because we are allowing that the arrival rate changes in each time interval (i.e., one year in our case).

Assumption 3: The systematic component (mean) λ_t is described by a logarithmic link function given by:

$$\lambda_t = \exp(\beta_0 + \beta_1 t) \tag{1.7}$$

TABLE 1.3: Poisson with deterministic time trend

		Coefficients	Estimate Std.	Error z value	Pr(> $\|z\|$)	
INES>2	Intercept	106.261	24.823	4.281	1.86e-05	***
	time	-0.056	0.012	-4.509	6.52e-06	***
INES>3	Intercept	244.902	39.192	6.249	4.14e-10	***
	time	-0.126	0.019	-6.387	1.69e-10	***
CMD	Intercept	221.886	55.788	3.977	6.97e-05	***
	time	-0.115	0.028	-4.091	4.29e-05	***

Results in Table 1.3 are maximum likelihood estimates for (β_0, β_1). Given the clarity of these results, there is every reason to believe that the expected frequency of a nuclear accident has changed along this period. As expected, the estimates were negative and significant. Therefore, if the effect of regulatory strictness, technological improvements and safety investments can be summarized in this variable, we have found some evidence that supports the decreasing trend for the core damage frequency that the PRA studies have shown.

In the CMD case, the $\hat{\lambda}_{2011}$=3.20E-0.5 that is close to the estimated CDF of last PRA studies. After computing the Fukushima Dai-ichi effect on the arrival rate, we found an increase of =2.3. Unlike in the previous two models this increment is substantial[7].

In this last set of results, we found a negative and significant time trend, which in a nutshell means arrival rate is decreasing in time. Although this feature does not seem controversial, it invalidates condition iii (non time varying arrival rate) and we cannot make use the traditional Poisson models, as we have done so far. We need a model in which the parameter of interest (i.e $\hat{\lambda}$) is function of time.

Regarding the no correlation hypothesis (i.e., condition iv), at first glance one could say that nuclear accidents fulfill this condition. Three Mille Island accident is not related with what happened in Chernobyl, etc. Nevertheless, we have a long time series data that in some sense reflect the evolution of nuclear power technology and knowledge. It is important to recognize that nuclear reactors have a long lifetime thus there is some technological inertia in the world nuclear fleet, but at the same time innovations have been adopted and new reactors have been installed along the time period that we have analyzed. For this reason, it is possible that our data exhibit some correlation. In fact

[7] The Poisson regression can also be done under a Bayesian approach, nevertheless the prior is not as easy to construct as in the previous case, because in this setting the coefficients (β_0, β_1) are the random variables. Generally it is assumed that they come form a normal distribution $\beta \sim N_k(b_0, B_0)$. Where $k = 2$ (in our case) is the number of explanatory variables; b_0 is the vector of prior means and B_0 is the variance-covariance matrix. Then to construct the prior will require a lot of assumptions not only in the level and precision of the coefficients, but also in how they are related. Given that precisely what we want is to relax as much assumptions as possible, we are not going to consider such a model.

as we pointed out before, it is clear from Figure 1.3 that the early stages of nuclear power industry are related with more accidents than the lasts years of our sample.

To confirm or reject the validity of this assumption, it is customary when using a time series, to check if there is a stochastic process that governs data dynamics. In our case, this means to know if accidents are somehow correlated, or if instead we can assume that they are independent events (condition iv). To test this we propose to use a time series state-space approach.

Before turning to the last model, it is worthwhile to understand why conditions (iii) and (iv) are relevant? As in the classical regression analysis, the maximum likelihood estimation assigns an equal weight to each observation because under these assumptions, all of them carry the same information. However, if observed events are somehow correlated, some of them bring more information about the current state than others, therefore past observations have to be discounted accordingly.

1.4 Poisson Exponentially Weighted Average (PEWMA) model

Autoregressive Integrated Moving Average (ARIMA, hereafter) models are the usual statistical frameworks to study time series, however there are two limitations to use them in the case of nuclear accidents. First, it is inappropriate for discrete variables because ARIMA models are based on normality assumptions (thus it is incompatible with Assumption 1). Second, Harvey and Fernandes (1989) noted that when the mean of the process tends to zero, ARIMA estimates could result in negative predictions, which cannot be the case for nuclear accidents.

To deal with these two limitations, Harvey and Fernandes (1989) and Brandt and Williams (1998) proposed to use a structural time series model for count data. This framework has a time-varying mean as in the ARIMA models but is based on a Poisson or a negative binomial conditional distribution.

The idea is to estimate the coefficients in the exponential link as in a Poisson regression, but each observation is weighted by a smoothing parameter, this is the reason why the model is called Poisson Exponentially Weighted Moving Average (PEWMA).

We briefly describe below the structural time series approach[8], following what has been developed by Brandt and Williams (1998) and (2000). The model is defined by three equations: measurement, transition and a conjugate prior. The first is the models

[8] Harvey and Shepard (1993) have elaborated a complete structural time series statistical analysis

stochastic component; the second shows how the state λ_t changes over time and the third is the element that allows identifying the model.

We keep Assumption 1, which corresponds to the measurement equation $f(y_t|\lambda_t)$. In this setting λ_t has two parts, the first shows the correlation across time and the second captures the effect of the explanatory variables realized in the same period, which corresponds to an exponential link.

Assumption 3': The mean λ_t has an unobserved component given by λ^*_{t-1} and an observed part denoted μ_t described by an exponential link.

$$\lambda_t = \lambda^*_{t-1}\mu_t \tag{1.8}$$

At its name implies, the transition equation describes the dynamics of the series. It shows how the state changes across time.

Assumption 4: Following Brandt and Williams (1998), we assume that the transition equation has a multiplicative form given by:

$$\lambda_t = \lambda_{t-1}\exp(r_t)\eta_t, \tag{1.9}$$

Where r_t is the rate of growth and η_t is a random shock that follows a Beta distribution.

$$\eta_t \sim Beta(\omega a_{t-1}; (1-\omega)a_{t-1}) \tag{1.10}$$

As in an ARIMA model, we are interested in knowing for how long random shocks will persist in the series systematic component. In the PEWMA setting, ω is the parameter that captures persistence. It shows how fast the mean moves across time, in other words, how past observations should be discounted in future forecast. Smaller values of ω means higher persistence, while values close to 1 suggest that observations are highly independent.

The procedure to compute $f(\lambda_t|Y_{t-1})$ corresponds to an extended Kalman filter[9]. The computation is recursive and makes use of the advantages of the Poisson-Gamma Bayesian model that we discussed in the previous section.

The idea of the filter is the following. The first step consists in deriving the distribution of λ_t conditional on the information set up to $t-1$. We get it by combining an unconditional

[9] The derivation of this density function is described in Brandt and Williams (1998)

prior distribution λ^*_{t-1} that is assumed to be a Gamma, with the transition Equation 1.9.

Using the properties of the Gamma distribution, we obtain $f(\lambda_t|Y_{t-1})$ with parameters $(a_{t|t-1}, b_{t|t-1})$

$$\lambda_t|Y_{t-1} \sim \Gamma(a_{t|t-1}, b_{t|t-1}) \tag{1.11}$$

Where:

$$\begin{aligned} a_{t|t-1} &= \omega a_{t-1} \\ b_{t|t-1} &= \omega b_{t-1} \exp(-X'\beta - r_t) \end{aligned}$$

The second step consists in updating this prior distribution using the information set Y_t and Bayes rule. This procedure gives us a posterior distribution $f(\lambda_t|Y_t)$. As we have seen in the previous section, the use of the conjugate distribution results in a Gamma posterior distribution and the parameters are updated using a simple updating formula.

$$\lambda_t|Y_t \sim \Gamma(a_t, b_t) \tag{1.12}$$

Where:

$$\begin{aligned} a_t &= a_{t|t-1} + y_t \\ b_t &= b_{t|t-1} + E_t \end{aligned}$$

This distribution becomes the prior distribution at t and we use again the transition equation and so on and so forth.

1.4.1 PEWMA Results

Given that we had not included covariates in the link function in the previous models, we are not going to include them in the PEWMA model to be able to compare the results. Thus the only parameter to estimate is ω. We used PEST[10] code developed by Brandt and Williams (1998). The estimates for the PEWMA model for the three definitions of nuclear accident are summarized in Table 1.4.

An important characteristic of PEWMA is that it nests the previous models. When $\omega = 1$ we can obtain the results from the first Poisson model, if the prior is $(a = 0, b = 0)$. Those from the Poisson-Gamma are reached, if we use the same prior parameters, for instance $(a = 1, b = 3.500)$.

[10] The code is available in http://www.utdallas.edu/ pbrandt/pests/pests.htm

Table 1.4: PEWMA Estimates for Prior a=1 b=3.500

		Parameters	Std. Errors	Z-score
INES>2	$\omega_{I\hat{N}ES>2}$	0.599	0.024	24.666
INES>3	$\omega_{I\hat{N}ES>3}$	0.729	0.055	13.134
CMD	$\omega_{C\hat{M}D}$	0.801	0.024	32.850

Using this last prior, we obtained the results shown in Table 1.4. As we can see, the estimates for ω with all the definitions are smaller than one. After computing a Wald statistic to test independence assumption and reduction to simpler Poisson models, we concluded that we do not have evidence to assume that the observations are independent. The results for this test are presented in Table 1.5

Table 1.5: Test for reduction to Poisson $H_0 : \omega = 1$

	Wald test	p-value
INES>2	272.523	<2e-16
INES>3	23.663	1.147e-06
CMD	66.193	4.440e-16

On the basis of these results, we can conclude that the use of Poisson models based on the independence assumption is definitely not suitable to estimate the frequency and compute the probability of nuclear accidents.

The results in Tables 1.4 and 1.5 also shown that as the definition of the accident narrowed, meaning passing from INES>2 to INES>3 and CMD, the estimate of ω got closer to one. This suggested that it is likely to accept the independence assumption, when focusing only on major nuclear accidents, because what the data reflect are the particular conditions in which these accidents occurred. On the contrary, when we took a broader set of accidents, we estimated a lower ω, because the data set had more information about nuclear safety as a whole.

1.4.2 Arrival rate estimates from 1952 to 2012

The predictions at each period of time t in the filter for λ_t vary substantially depending on ω. As we have already mentioned, if all the events are independent $\omega \to 1$, thus they are considered equally important in the estimation. As ω gets smaller, recent events become more important than those observed in the past, then the latter are discounted.

Figure 1.7 plots the mean of $f(\lambda_t|Y_t)$ for the Poisson-Gamma and PEWMA model for CMD. Note that for the former model, the changes in the arrival rate are subtler with each observation, because the effect of a new accident is diluted over the cumulated experience. In the case of the latter model, we discount past events heavily, thus the observations in the latest periods are the most important and the distant are almost irrelevant. For this reason, the changes in the expected arrival rate are more drastic.

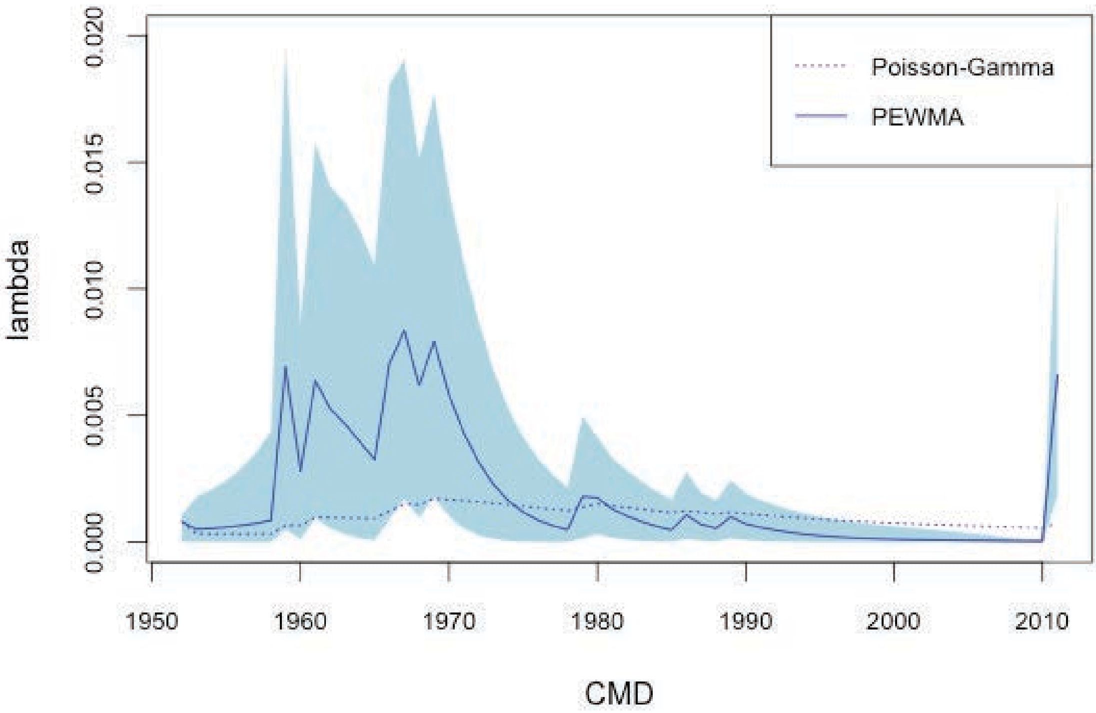

Figure 1.7: Poisson-Gamma vs PEWMA for CMD

As we can see in Figure 1.7, from 1952 to 1970 the arrival rate grew quickly until it reached a high peak. This can be explained by the different accidents occurred between 1960 and 1970 and the slow growth of the worldwide nuclear fleet. After 1970, several accidents occurred but the operating experience increased substantially. Between 1970 and 2010, we can observe a decreasing trend in the arrival rate, even though this period is featured with the most well known accidents of Three Mile Island and Chernobyl.

The Fukushima Dai-ichi results in a huge increase in the expected frequency of an accident. The arrival rate in 2011 is again similar to the arrival rate computed in 1980 after the Three Mile Island and the Saint Laurent des Eaux core meltdown. In other terms, Fukushima Dai-ichi accident has increased the nuclear risk for the near future in the same extent it has decreased over the past 30 years owing to safety improvements. In informational terms, the adding of a new observation (i.e., new accident) is equivalent to the offsetting of decades of safety progress.

The PEWMA model estimates an arrival rate for CMD $\hat{\lambda}_{2010}$ = 4.42e-05 and $\hat{\lambda}_{2011}$ =1.954e-3 which implies a Δ =43.21. This huge change could appear as unrealistic. In fact, at first glance the triple meltdown seems as the result of a series of exceptional events (i.e., a seism of magnitude 9 and a tsunami higher than 10 meters). However, for most observers, the Fukushima Dai-ichi accident is not a black swan[11]. Seisms followed by a wave higher than 10 meters have been previously documented in the area. It is true that they were not documented when the Fukushima Dai-ichi power plant was built in 1966. The problem is that this new knowledge appeared in the 80s and has then been ignored, deliberately or not, by the operator. It has also been ignored by the nuclear safety agency NISA because as well-demonstrated now the Nippon agency was captured by the nuclear operators (Gundersen, 2012).

Unfortunately, it is likely that several NPPs in the world have been built in hazardous areas, have not been retrofitted to take into account better information on natural risks collected after their construction, and are under-regulated by a non-independent and poorly equipped safety agency as NISA. For this reason, the Fukushima Dai-ichi accident entails general lessons regarding the underestimation of some natural hazardous initiating factors of a core meltdown and the over confidence on the actual control exerted by safety agency on operators.

Note also that such an increase seems more aligned with a comment made after the Fukushima Dai-ichi accident: a nuclear catastrophe can even take place in a technologically advanced democracy. It means that a massive release of radioactive elements from a nuclear power plant into the environment is no longer a risk limited to a few unstable countries where scientific knowledge and technological capabilities are still scarce. The 10 times order of magnitude of the Fukushima Dai-ichi effect computed by us could therefore be realistic and consistent.

1.5 Conclusion

Results in Table 1.6 recapitulates the different numbers for the arrival rate and the Fukushima Dai-ichi effect we obtained in running the 4 models.

Table 1.6: Summary of results

Model	$\hat{\lambda}_{2010}$	$\hat{\lambda}_{2011}$	Δ
MLE Poisson	6.175e-04	6.66e-04	0.0790
Bayesian Poisson-Gamma	4.069e-04	4.39e-04	0.0809
Poisson with time trend	9.691e-06	3.20e-05	2.303
PEWMA Model	4.420e-05	1.95e-03	43.216

[11] See Fukushima Dai-ichi NPS Inspection Tour (2012)

We can conclude that when it is assumed that the observations are independent the arrival of a new event (last nuclear catastrophe) did not increase the estimates. The Fukushima effect is close to 8% regardless of whether you use a basic Poisson model or a Bayesian Poisson Gamma model.

This result does not take any safety progress into account nor the new risks that the last accident revealed. The arrival rate is computed as if all the reactors have been the same and identically operated from the first application of nuclear technology to energy to this day. This is a strong limitation because it is obvious that over the past 50 years the design of reactors and their operation have improved. The current worldwide fleet has a higher proportion of safer reactors than the 1960s fleet.

On top of that, the Fukushima Dai-ichi accident revealed potential risks associated with a poor feedback on natural hazards in old facilities as well as the possibility of regulatory capture even in developed countries.

By contrast, the introduction of a time-trend into the Poisson model has led to a high decrease in the 2010 arrival rate. The time trend captures the effect of safety and technological improvements in the arrival rate. Being significant, this variable allows predicting a lower frequency of nuclear accidents. If we use a Poisson regression, we find a tripling of the arrival rate owing to the Fukushima Dai-ichi accident. Note that both findings seem more aligned with common expertise. In fact, the expected frequency of an accident by reactor-year as derived by the 2010 arrival rate is closer to PRAs studies.

Nevertheless, the Poisson regression is also based on the assumption of independent observations. The PEWMA model has allowed us to test the validity of this hypothesis and we find that it is not the case. This seems to be more suitable because nuclear reactors have a long lifetime and the construction of new reactors, investments in safety equipment, learning process and innovations take time to be installed and adopted by the whole industry. Of course, the dependence hypothesis leads to a higher arrival rate because it introduces some inertia in the safety performances of the fleet. A new accident reveals some risks that have some systemic dimension.

With the PEWMA model the Fukushima Dai-ichi event represents a very substantial, but not unrealistic increase in the estimated rate. By construction each observation in this model does not have the same weight. Past accidents are discounted more than new accidents. This captures the idea that lessons from past accidents have been learnt in modifying operations and design and that a new accident reveals new safety gaps that will be progressively addressed later in order to avoid a similar episode.

Chapter 2

Revisiting the cost escalation curse of nuclear power. New lessons from the French experience

2.1 Introduction

In OECD countries the choice to include or not include nuclear power in the energy mix is commonly seen as primarily a matter of public opinion. The very long lifetime of nuclear waste and the risk of large radioactive materials being released into the environment have raised major acceptability concerns. The Fukushima Dai-ichi catastrophe in March 2011 has demonstrated again how public attitude vis--vis nuclear technology may dictate political decisions and U-turns. For instance, German people were so stunned by the new accident that the Chancellor, Angela Merkel, immediately decided to shut down eight operating reactors and later on to accelerate the phasing-out of the nuclear fleet. Four months before Fukushima Dai-ichi, a new German law was passed to extend their life. Nuclear power was viewed then by Angela Merkel and her party as a bridge technology, before renewables and storage could cover all electricity demands.

However, public opinion is not the only barrier that nuclear power faces today: a less addressed but also an important issue is whether new nuclear power plants can be built at a reasonable cost. The construction cost is the major component of levelized costs of nuclear power generation. Depending on assumptions on the cost of capital and the number of years to build the nuclear plant, the construction cost represents between 60%

and 80% of levelized costs[1]. In other words, whether or not nuclear power generation is cheap enough to compete with other electricity sources is critically dependent on construction costs.

In OECD countries[2] where public opinion is supportive of nuclear power, policy makers, investors and utilities are very concerned by construction costs. In countries such as the U.K., Finland, France and Poland, nuclear generation is viewed as needed to achieve a low carbon energy transition. The technology is also considered to contribute towards reducing energy dependency from abroad. These two drivers of nuclear energy deployment are well illustrated by the example of the U.K. The U.K. has adopted an ambitious CO2 emissions reduction policy in a very specific context: a medium-term shortage of capacity owing to the closure of its old nuclear and coal power plants. After several years of debate and consultation, the U.K.s decarbonization policy includes an increasing carbon tax reaching up to 70 per ton in 2030, and a mechanism that provides operators over a long-time period with a fixed price for electricity; therefore fluctuations in electricity price on the power exchange will take place regardless. The so-called contract-for-difference ensures money to generators when the wholesale market price is below a reference or strike price set by the government and conversely generators pay the difference between the market price and the strike price when it is positive. Both renewable energy and nuclear energy could benefit from this mechanism. The U.K.s vision as elaborated in the 2008 White Paper and in the 2010 Coalition Programme is that nuclear energy has a role to play alongside renewables to reduce greenhouse gas emissions by 80% in 2050 and to secure energy supply. By the end of the 2020s, 16 GW of new nuclear capacity are envisaged.

Noticeably, the Fukushima Dai-ichi accident has not changed the situation. Six months after the Japanese catastrophe, a national policy statement for nuclear power generation reiterated the need for new nuclear power plants and the benefits of early deployment. In March 2014, according to a survey commissioned by the Department of Energy and Climate Change[3], 42% supported nuclear power and 20% opposed it. On the 21st October 2013 a commercial agreement was reached between the EDF Group and the U.K. Government for the building of two EPR reactors at Hinkley Point C in Somerset. A strike price of £92,5 per MWh over a 35-year period was agreed. It is supposed to

[1] See NEA (2000) and NEA (2000)

[2] In non-OECD countries nuclear cost-competitiveness is a less sensitive issue. The adoption and continuation of nuclear technology are mainly driven by political considerations. See Goldemberg (2009)

[3] The Department of Energy and Climate Change publishes the DECC Public Attitudes Tracker Survey periodically since 2012. The figures cited here correspond to the Wave 9 document that is available here: https://www.gov.uk/

cover the £14 billion[4] that EDF estimated as the expenses to construct the plant. These figures have generated an intense debate between those that argue that nuclear power is not competitive and needs subsidies to survive Greenpeace (2013) and those that claim that the strike price and the construction cost correspond to a first of a kind and that the following reactors will be much cheaper to build[5].

More generally speaking, concerns about the cost of nuclear new-builds have been raised with the updating of academic cost studies in the U.S. and the long delays and budget overshoots observed in the construction of EPR in the EU (Lévêque (2013)). In 2009 the MIT published a report updating the findings of an initial study that was done six years before called The Future of Nuclear Power (see Parsons and Du (2003); Parsons and Du (2009)). The increase in the construction cost was spectacular: expressed in current dollars and leaving aside interests during construction, costs doubled, rising from $2,000 to $4,000 per kW. In particular, this latter figure took into account the estimated costs of 11 projected plants in the U.S., for which the relevant utilities had applied to the regulatory bodies for reactor licencing. Likewise in 2011, the University of Chicago estimated that, on average, the construction cost of AP 1000 reactors quoted in applications by utilities was $4,210 per kW, which meant an increase by a factor of 2,1 in constant dollars in comparison with a study carried out seven years earlier (see Rosner and Goldberg (2011*a*)).

New-builds in Olkiluoto in Finland and Flamanville in France have been plagued with successive revisions of budget and completion dates. The construction of the Finnish plant started in 2005 and was supposed to last four-and-a-half years with a grid connection in 2009. Commercial operation is now expected in 2016 at best. Construction costs were first estimated at €3 billion, and were revised upwards in 2010 to €5.7 billion and in 2013 to €8,5 billion. Similarly, the initial anticipated cost of the Flamanville EPR reactor currently under construction by EDF, increased from €3.3 billion in 2005 to €6 billion in 2011 . EDFs most recent press release in 2012 downgraded the situation further, announcing an estimated cost of 8.5 billion. Flamanville was expected to start commercial operation in 2013, but due to delays is expected now to start up in 2016.

Looking at costs in the past to build the two largest nuclear fleets in the world, recent concerns about nuclear cost escalation do not seem unfounded. In the case of the U.S. (see Figure 2.1), if we compare the overnight cost in Koomey and Hultman (2007) for the first and last nuclear reactors installed, we can see that the costs expressed in

[4] EDF Energy Press release, 21 October 2013 available at http://newsroom.edfenergy.com/News-Releases/Agreement-reached-on-commercial-terms-for-the-planned-Hinkley-Point-C-nuclear-power-station-82.aspx

[5] Nutall, W. (2013). Hinkley C goes ahead, but future nuclear costs must fall, The Conversation, 31 October 2013 http://theconversation.com/hinkley-c-goes-ahead-but-future-nuclear-costs-must-fall-19407.

M€(2010)/MW are seven times higher for the latter than for the former. It is worth mentioning that the overnight cost includes the investments linked with site preparation and construction, but it excludes financing expenses. Therefore, it shows the cost of the plant as if it had been fully built in one night.

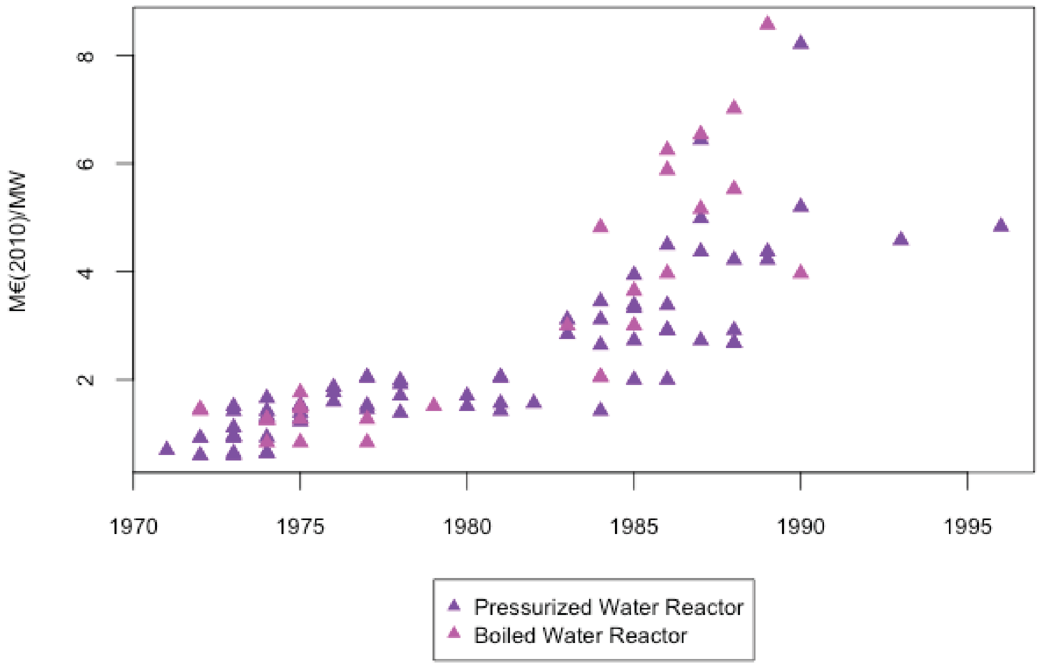

FIGURE 2.1: Overnight costs for the U.S Nuclear Fleet € $_{2010}$/MW

The severe escalation in the construction cost of the U.S. nuclear fleet is partially explained (see infra) as the result of the heterogeneity in the reactors that were installed (i.e., different types and models) and the consequent lack of standardization, that together with the multiplicity of utilities, vendors and constructing firms, reduced the possibility of establishing long-term relationships and building the same reactor design repeatedly. All this resulted in an erosion of the potential benefits associated with learning effects.

Alike, Grubler (2010) analyzed the investments made in France to build its fleet of 58 reactors. His comparison of construction costs in FF98/kW between units installed in 1974 and those constructed after 1990 shows an increase by a factor of about 3.5. This finding suggests that, even under better economic and institutional conditions, such as those prevailing in France (i.e., centralized decision making, vertical integrated utility, single nuclear vendor, high degree of standardization and regulatory stability), cost escalation is inherent to nuclear power. According to Grubler (2010) negative learning-by-doing effects characterize nuclear technology: while accumulating experience, nuclear construction costs per unit of capacity have been increasing instead of decreasing.

By contrast, as comprehensively reviewed by Martin Junginger and Faaij (2010), historical trends for other base-load technologies such as gas and coal and for other zero carbon technologies such as onshore wind and photovoltaic systems, show positive learning effects. Experience curves are especially impressive for renewables. Lindman and Söderholm (2012) found that the kW from onshore wind farms decreases by more than 10% each time the installed capacity doubles. Meanwhile, Isoarda and Soria (2001) and C. Yu and Alsema (2011) have identified higher learning effects in the photovoltaic industry, confirmed by the dramatic reductions in the underlying costs and market prices of solar panels.

On top of this, we can expect the Fukushima Dai-ichi accident to have consequences in terms of construction costs for new reactors. Lessons learned from this accident may encourage nuclear vendors to include other safety features and lead to redundancies in new reactors and site designs; safety authorities might impose stricter licencing rules, and greater public opposition to installing new nuclear power plants could induce construction delays and therefore cost overruns.

In the debate about nuclear plants, current opinion is directed against their construction. Taking into account the above, it seems that there is no escape from the cost escalation curse. However, before giving up, it is worth reviewing the French nuclear power programme experience using new data recently released by the *Cour des Comptes*. It is important to mention that Grubler made his cost assessment using estimations based on an annual EDF investment report covering 1972 to 1998, because at the time of his publication reliable data on the costs of the French nuclear programme were not available. Following a request from the Prime Minister to the national audit agency *Cour des Comptes*, past construction and R&D expenses related to French nuclear power were first made known to the public in 2012. The *Cour des Comptes'* report brought together all data concerning current construction costs for the 58 reactors installed in France, as well as investments in other nuclear facilities.

When we compared costs from this new source of information with previous cost estimates, we found that the escalation is less severe than argued. In the light of this result, in this paper we re-examine the cost drivers for the French nuclear power programme. We consider that by revisiting the French experience, it will be possible to draw useful policy recommendations to ease cost escalation in the construction of new nuclear power plants and therefore determine the elements that will allow nuclear power to remain competitive.

In particular, we are interested in investigating the existence of scale and learning effects, as well as the relationship between safety performance and costs, in order to see if it is possible to expect cost reductions when increasing the size of the reactor, when building the same type of reactor repeatedly, and if safer reactors are more expensive.

The literature regarding nuclear construction drivers is large for the U.S. case, given that the data have been available to the public ever since the construction of the first wave of reactors. We can mention the pioneering papers of Komanoff (1981) and Zimmerman (1982). Later, Krautmann and Solow (1988), Cantor and Hewlett (1988) and McCabe (1996) revisited the existence of economies of scale and established that the construction of larger reactors[6] increased the cost per MW installed, once the increase in construction lead time was taken into account. According to Cantor and Hewlett (1988), bigger units increase projects complexity, subjecting them to managerial problems, longer lead times and stricter regulatory scrutiny. Learning effects were only found to be positive and significant when public utilities constructed the plant. This striking result was later addressed by Cantor and Hewlett (1988) and McCabe (1996). The former suggested that the market power of experienced firms allows them to charge higher prices, so the learning effects are kept as profits, whereas the latter explained this difference by the poor incentives of cost-plus contracts[7] under which nuclear power plants were procured by external constructors.

More recent studies, like Cooper (2012), have observed that the number of rules and fines issued by the Nuclear Regulatory Commission (hereafter NRC), even before Three Mile Island accident in 1979, led to an increase in construction costs. According to this author, the NRC was convinced that the risk of accident would increase dramatically as the number and size of operating reactors grew and their locations moved closer to population centers. Therefore, they sought to reduce the risk by increasing the required safety measures.

Our paper is the first to use the actual construction costs of the French nuclear fleet. As mentioned previously, the cost assessment done by Grubler (2010) used estimations. As in previous literature, we deal with a multicolinearity problem, but, in addition, we have a smaller sample; therefore, we propose using a principal component regression approach to deal with both econometric limitations. In addition to using the common explanatory variables to identify the main drivers of construction costs, we also included operating performance indicators, in particular those linked with safety, to see if cost escalation can be justified with better safety features.

[6] Except Komanoff (1981), a pioneering study that suggested a 13% cost decrease when a reactors size is doubled; nevertheless subsequent papers rejected this result.

[7] McCabe (1996) explains that for the second wave of nuclear reactors (the one that began in the late 60s) the nuclear vendors ceased to be in charge of the construction process and in turn, utilities contracted external firms to preform plant engineering, management and construction. All these contracts were cost-plus.

After revisiting construction costs for the French nuclear fleet, we find that neither the scale-up nor cumulative experience induced cost reductions; on the contrary, these variables have positive and significant coefficients. We have called this phenomenon the *big size syndrome*, and we have identified it as the main driver of cost escalation in France. The big size syndrome summarizes the fact that as the nuclear industry gained experience, bigger and more complex reactors were designed and installed, and this resulted in a cost increase.

Although the increase in the size of the reactors was done with the expectation of reducing the cost per MW installed, with our results we cannot discard the existence of economies of scale in the French nuclear fleet. We have to recognize that by using only French data, it is not possible to disentangle the effect due to increase in the reactors capacity, caused by technological change. Thus, it is true that bigger reactors were more expensive per MW installed, but we have to keep in mind that we are not talking about the same reactor design.

Our second important result is that we have identified positive learning effects within similar types of reactors. This finding is good news for nuclear power deployment, given that it supports the idea of standardization as an effective strategy to reduce cost overruns linked with uncertainty when constructing complex technologies, such as nuclear reactors, and therefore offers a possible way of overcoming the cost escalation curse. This result supports the idea that to avoid the cost escalation curse, building the same type of reactor repeatedly in the same sites was one of the key features of the French nuclear programme.

The last result that we found is that reactors that perform better, according to the safety indicators that we included in the regression, cost more. This last result shows that improvements in safety can also be considered as a driver of cost escalation. This result is also linked with our first one, because it tells us that technological improvements embedded in new designs either because the reactor is larger or because vendors seek to achieve better safety performance (perhaps to fulfill regulatory requirements) have resulted in a rise in the cost per MW installed.

The rest of the paper is organized as follows. Section 2.2 briefly describes the French nuclear power programme and the cost data from the *Cour des Comptes* report, then sets out the model and estimation procedure. The results of the model are presented and discussed in Section 2.3. Finally, our conclusion is in Section 2.4.

2.2 Data and Model

2.2.1 French construction cost escalation

The inception of nuclear power for civil use in France began in the early 1960s. From 1963 to 1972, EDF installed 7 reactors with different technologies that represented approximately 2600 MW. These units (Table 2.1) were later decommissioned, according to Roche (2004) due to their technological and economic limitations. In particular, safety concerns were raised after the partial core meltdown in Saint Laurent A1 reactor in 1969.

Table 2.1: First Generation of French Reactors

Unit	Type	Year of connection
Chooz A	Pressurized water	1967
Brennilis	Heavy water reactor	1967
St. Laurent A1	Natural uranium gas-cooled	1969
St. Laurent A2	Natural uranium gas-cooled	1961
Chinon A2	Graphite-Gas	1965
Chinon A3	Graphite-Gas	1966
Bugey 1	Graphite-Gas	1972

The early adoption of nuclear power by EDF and the oil price peak in 1973 triggered the design of the French nuclear power program with the aim of substituting fossil energy sources. This program has been described as the opposite of the situation in the U.S. nuclear industry, because the French nuclear fleet is less diverse and investment decisions were made by a centralized institutional structure.

In France, only one technology was installed, corresponding to the Pressurized Water Reactor (hereafter PWR). From 1978 to 2002, 58 reactors were built in 19 units (see Figure 2.2). Today, all of these reactors are in operation and provide almost 78% of French annual electricity consumption. The nuclear fleet is composed of three groups called *paliers*. In each *palier* all reactors have the same size. The first *palierpalier* comprises 34 reactors with a 900MW nameplate capacity; the second *palier* includes 20 reactors with 1300 MW; and the last one contains 4 reactors with 1450 MW of installed capacity. This corresponds to a total installed capacity of 62.510 MW.

Each *palier* includes different types of reactor. The first *palier* has 3 types of reactor: CP0, CP1 and CP2. Their main difference lies in the design of the intermediary cooling system. In the second *palier*, there are two types of reactor: P4 and P4, which differ in the layout of the structure containing fuel rods and circuitry. Finally, the last *palier* comprises only one type of reactor, called N4. This design differs from the other reactors in terms of capacity, as well as the design of its steam generators, primary pumps and command room .

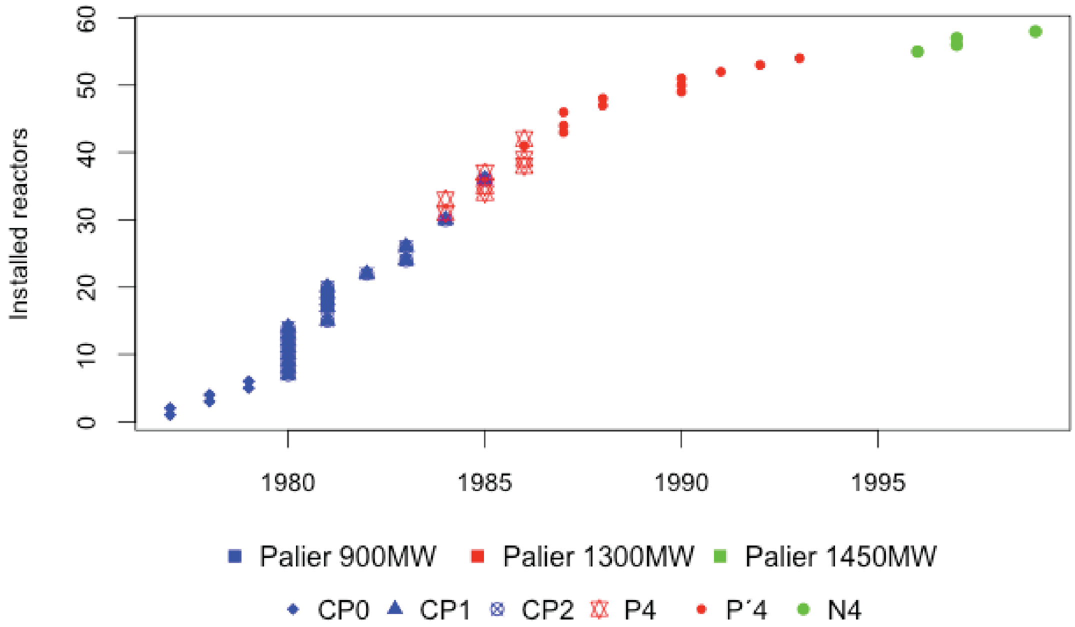

FIGURE 2.2: Evolution of French Nuclear Power Fleet by *palier*

As mentioned before, the institutional setting in which the French nuclear power program developed was highly centralized. Finon and Staropoli (2001) described it as a close-knit network between: EDF, the public monopoly generator; Framatome (today AREVA), the reactor vendor; and the Atomic Energy Commission (CEA), the nuclear research and development agency. This centralized decision-making setting resulted in effective coordination of the programs investments and reduced uncertainty regarding safety regulations. The downside is that it also shielded the program from public scrutiny and accountability.

However, with the decommissioning deadlines for the oldest reactors approaching, public debate about the role of nuclear power in the French energy mix calls for clear accountability of EDFs past, present and future investments. For this reason, in 2011 the former Prime Minister of France asked the national audit agency, *Cour de Comptes*, to undertake a study of EDFs past expenditure on constructing nuclear facilities, including the 58 PWR commercial reactors .

This report was published at the beginning of 2012 and for the first time presented to the public the actual construction costs of the nuclear fleet. It is important to point out that we used the construction costs and not the overnight costs, because in the report the latter were presented for the whole nuclear fleet and not for each observation. However, they represent 88% of the total overnight costs. The costs in the report are presented by pairs of units in current and 2010 constant euros[8]. Figure 2.3 compares the cost data presented in the *Cour de Comptes* report with the estimated costs computed by Grubler (2010). We can conclude that the figures for the first reactors were quite accurate, but that figures for the latest ones were overestimated. In fact, by taking Grublers cost estimates expressed in €$_{2010}$/ kW, the average annual increase is equal to 5.7%; taking the construction costs in the *Cour de Comptes*, we find an average annual increase of 4.7%.

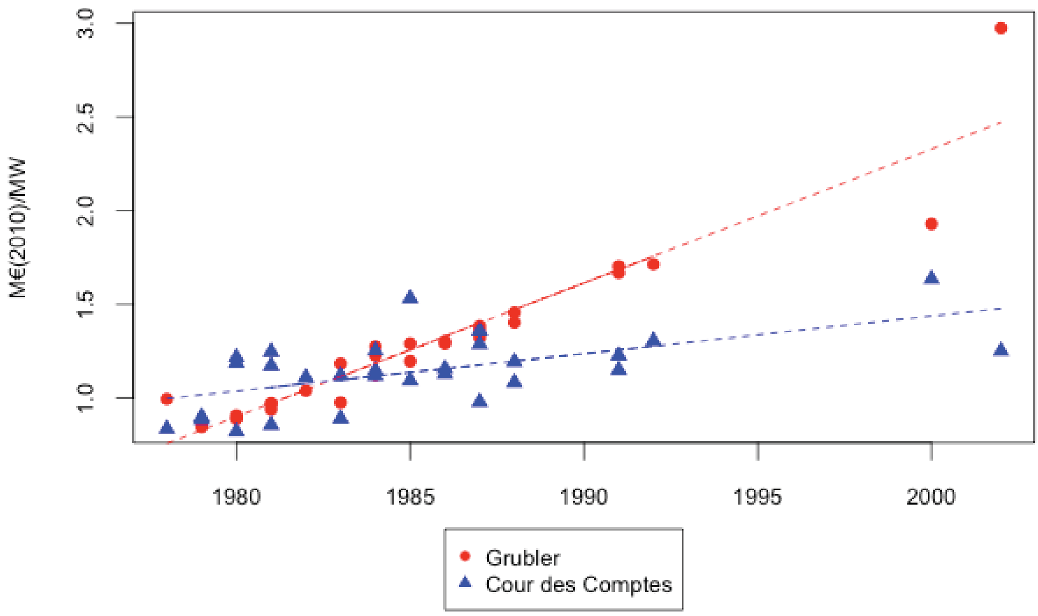

FIGURE 2.3: Grubler vs Cour de Comptes construction costs

Since the cost escalation was not as severe as argued, it is worth reviewing the French nuclear power program experience with the actual data published in the *Cour de Comptes* report in order to see if new lessons can be learnt to overcome the cost escalation curse.

2.2.2 Model and data

Using a linear regression model, we seek to determine the construction costs main drivers. We assume a logarithmic cost function in which the explanatory variables are: capacity, input prices, experience, safety performance indicators and finally a random error. The regression equation that we have estimated is the following:

[8] The actual construction cost for the French nuclear fleet published in the *Cour de Comptes* are presented in Appendix A

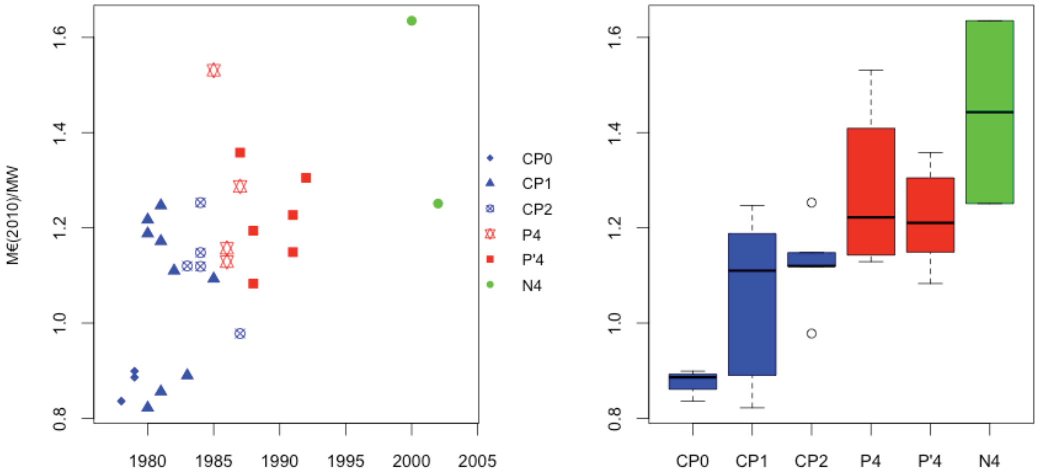

FIGURE 2.4: Cour de Comptes construction cost by *palier* and type

$$\ln(C_i) = \beta_0 + \beta_1 \ln(Cap_i) + \ln(ICHT_i) + \beta_2 EXPI_i + \beta_3 EXPP_i + \beta_4 EXPT_i + \beta_5 UCL_i + \beta_6 US7_i + u_i \quad (2.1)$$

Where:

- C_i: Construction cost for the pair of units i in €$_{2010}$ per MW
- Cap_i: Installed capacity in MW
- $ICHT_i$ Index cost of labor for the year in which the construction of reactor i started
- $EXPI_i$: Number of completed reactors at the time of the construction of plant i
- $EXPP_i$: Number of completed reactors within the same *palier* at the time of the construction of plant i
- $EXPT_i$: Number of completed reactors within the same type at the time of the construction of plant i
- UCL_i: Lifetime average Unplanned Capability Loss Factor for unit i
- $US7_i$: Lifetime average Unplanned Automatic Scram for unit i

Regarding capacity, Figure 2.4 clearly shows that the cost escalation in France is closely related to the progressive increase in reactor size. Nevertheless, it is important to mention that the scale-up also entailed a technological change, which means that there are substantial design differences between reactors belonging to each *palier*. For this reason, we have to keep in mind that with this variable we are capturing two effects, i.e. the size and the technological complexity of new reactors.

The second set of explanatory variables was included to test the presence of learning effects. We have defined three variables: the first corresponds to overall experience (EXPI), the second only adds the previous reactors existing within the same *palier* (EXPP), and the last one includes reactors of the same type (EXPT). All of these variables show the number of reactors previously built in each category.

Apart from scale and learning effects, we might also be interested in identifying whether cost escalation is linked to safety improvements. According to Cooper (2012), safety variables (i.e. fines and the number of safety standards and rules adopted by the NRC) are the most consistent predictors to explain the cost escalation in the U.S. In previous studies (Komanoff (1981), Zimmerman (1982), Cantor and Hewlett (1988), McCabe (1996)), safety improvements were related to the stringency of the regulatory agency that was represented with a time trend; in all of these studies it was found to be significant and positive.

For the French case, it is hard to measure regulatory activity. According to Grubler (2010), there is no regulatory documented incidence from 1970 to 1999, which is not surprising given that the *Autorité de Sûreté Nucléaire* (independent regulatory agency) was created in 2006. However, Roche (2004) and Finon (2012) argued that EDF integrated safety reinforcements into new reactors gradually, and thus these improvements should be reflected in better performance in terms of unplanned outages. To test how safety improvements are related to construction costs, we included in the model two indicators defined by The World Association of Nuclear Operators (WANO) and adopted by the International Atomic Energy Agency (IAEA).

The first of these is the Unplanned Capability Loss Factor (UCL_i), which reflects a reactors ability to maintain the reliability of systems and components. This indicator belongs to the first category of the safety performance indicators used by the IAEA, which seeks to quantify how smoothly a plant operates. The UCL indicator shows the percentage of energy that a plant was not capable of supplying due to deviations from normal operations.

The second indicator is Unplanned Automatic Scram ($US7_i$), which belongs to the category for identifying whether a plant is operating at low risk. The US7 tracks the number of automatic shutdowns during one year (i.e. 7000 hours) of operation. We have chosen this measure because it gives a direct indication of the frequency of actual

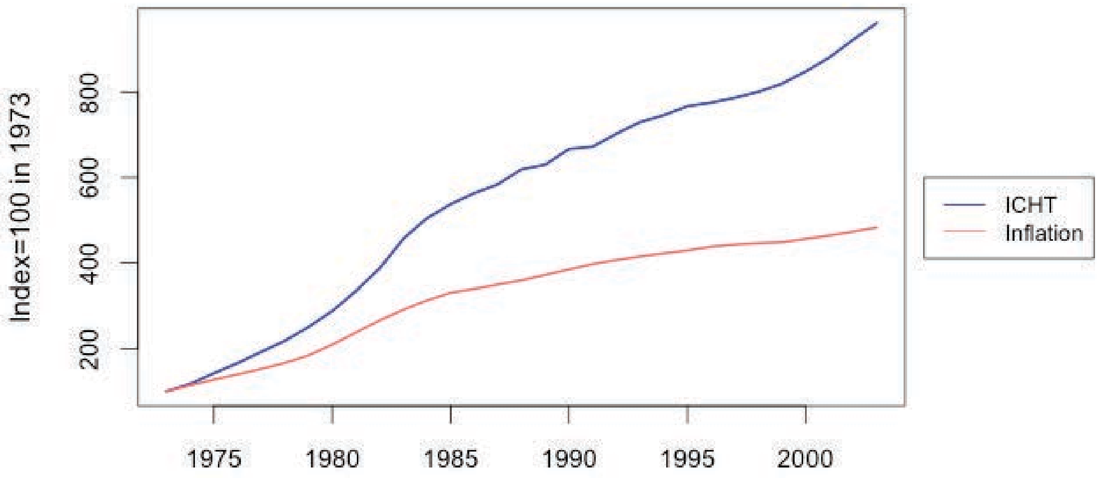

FIGURE 2.5: Labor cost index (ICHT) and Price index for France =100 in 1973

challenges to the systems that submit plant equipment to extreme thermal loads and increase the risk of serious accidents.

To count the changes in input prices, we have also included an index in the regression framework to take into account the cost of labor. Although the costs are expressed in constant currency, it is important to highlight that during the period we are analyzing (i.e.1978-2002), the labor cost increased more rapidly than the index prices. When we compared the evolution of the French GDP price index with the *Indice du coût horaire du travail* (ICHT) developed by INSEE, we found that the difference between the index in 1973 and 2000 is 4 times in the former and 9 times in the latter (see Figure 2.5). We have not included other commodity price indexes, such as cement, copper, steel or nickel, given that on average their growth rates were similar to the GDP deflector that was used to homogenize the cost data.

In addition to the *Cour de Comptes* costs, we gathered data from the IAEAs Power Reactor Information System (PRIS) database. We took the installed capacity in MW for the year when the reactor was constructed, the number of reactors that were built by EDF previously to audit the experience, and the average UCL and US7 lifetimes for each pair of units. Descriptive statistics of the data are presented in Table 2.2.

2.2.3 Multicollinearity and Principal Component approach

One of the main econometric problems identified in literature on nuclear construction cost escalation is the multicollinearity between the explanatory variables, and in particular, the high correlation between installed capacity and industry experience. To deal

TABLE 2.2: Descriptive statistics

Variable	Unit	Mean	Median	Minimum	Maximum	Std
Cost	€$_{2010}$/MW	1.14	1.14	0.82	1.63	0.19
Cap	MW	2156	1840	1740	2945	436.91
ICHT	Index 100= 1973	496.46	504.40	218.10	921.96	178.99
EXPI	# reactors	27.41	26	1	56	17.30
EXPP	# reactors	12.03	12	1	30	8.97
EXPT	# reactors	5.10	4	1	16	4.16
UCL	%	7.12	7.07	3.07	11.95	2.08
US7	events/7000 hours critical	0.77	0.69	0.18	1.40	0.31

with this problem, Zimmerman (1982) suggested using a monotonic transformation of overall experience instead of the original variable. In subsequent studies, such as those by Cantor and Hewlett (1988) and McCabe (1996), the issue was solved by taking the builders experience into account instead of the overall industry experience, which eased the high correlation among these variables.

For the French case, the multicollinearity problem is severe. There is a single builder (EDF), so experience increases with time, and also with installed capacity, because the scale-up has been progressive. On top of that, we observe a sustained increase in the labor cost index. As we can see in Table 2.3, these three variables are highly correlated, which illustrates the difficulty of obtaining significant results in a linear regression framework.

TABLE 2.3: Correlation Matrix

	Ln Cap	ICHT	EXPI	EXPP	EXPT	UCL	US7
Ln Cap	1.00						
ICHT	0.74	1.00					
EXPI	0.86	0.96	1.00				
EXPP	-0.44	0.18	0.03	1.00			
EXPT	-0.23	0.04	-0.02	0.54	1.00		
UCL	-0.02	-0.35	-0.28	-0.48	-0.50	1.00	
US7	-0.08	-0.26	-0.23	-0.29	-0.21	0.53	1.00

Indeed, when we include all of the coefficients in a linear regression, they are imprecisely estimated (see Table 2.4). This problem is confirmed with the high estimates for the Variance Inflation Factor (VIF) (see Table 2.5). The standard way of solving multi-collinearity problems is to eliminate one or more explanatory variables. Although we tried different specifications, none of them resulted in significant estimates and the VIF remained high. The results of these models are shown in Appendix B.

Unfortunately, within this framework it is not possible to figure out the main drivers because all of the explanatory variables move in the same direction, thus our data set appears redundant. By using a principal component regression, we have overcome

Table 2.4: Linear regression estimates

Coefficients	Estimate	Std. Error	t value	$Pr(>\|t\|)$
(Intercept)	-0.188	12.454	-0.015	0.988
Ln Cap	-0.092	1.477	-0.063	0.951
Ln ICHT	0.187	0.399	0.470	0.643
EXPI	0.002	0.021	0.127	0.900
EXPP	-0.003	0.015	-0.257	0.800
EXPT	-0.008	0.009	-0.825	0.419
UCL	-0.018	0.019	-0.967	0.345
US7	0.014	0.103	0.143	0.888

Table 2.5: VIF for explanatory variables

Ln Cap	Ln ICHT	EXPI	EXPP	EXPT	UCL	US7
116.728	32.345	183.909	26.865	2.273	2.166	1.482

this limitation. With this method we can obtain relevant information from our data set, reducing it to a smaller dimension and revealing simplified underlying correlations between the costs and the explanatory variables.

Principal component analysis is an established multivariate technique developed by Pearson (1901) and Hotelling (1933). In economics this method has been applied in a wide range of subjects , for instance, in macroeconomics and finance by Fifield and Sinclair (2002) and in development by Zanella and Mixon (2000), and used to construct socio-economic indexes by Filmer and Pritchett (2001).

The main idea of this procedure is to take the correlation matrix, which we denote by $\mathbf{C} = \mathbf{X}'\mathbf{X}$ (where $\mathbf{X}$ is the $n \times k$ matrix of centered and scaled explanatory variables) and then compute the $k \times k$ eigenvector matrix[9] $\mathbf{V}$.

Given that $\mathbf{VV}' = \mathbf{I}$, we can rewrite a lineal model $Y = X'\beta^*$ as follows.

$$Y = \beta_0^* \mathbf{1} + \mathbf{XVV}'\beta^* \tag{2.2}$$

$$Y = \beta_0^* \mathbf{1} + \mathbf{Z}\alpha \tag{2.3}$$

Where $\mathbf{Z}$ is the $n \times k$ matrix of principal components. This matrix contains the same information that $\mathbf{X}$ but the columns are arranged according their share in the variance.

[9] Recall that the eigenvectors of a square matrix $\mathbf{A}$ are defined as the vectors that solve $\mathbf{AW} = \lambda\mathbf{W}$, where λ is a real or complex number called eigenvalue. They can equivalently be defined as the vectors that solve $(\mathbf{A} - \lambda\mathbf{I})\mathbf{W} = \mathbf{0}$

Each principal component is a linear combination of the explanatory variables. The characteristic vectors define the weights or loadings (matrix **V**) and the roots (eigenvalues), denoted byλ, identify the most important components (the higher the eigenvalue, the higher the share in the variance).

Once this decomposition is done, the next step in this framework is to eliminate the principal components (columns of Z) associated with the smallest eigenvalues (λ) in order to reduce the variance that is causing the multicollinearity and estimate the significant coefficients.

2.3 Results

Although we are interested in the coefficients between the costs and explanatory variables, one of the main advantages of the principal component approach is that we can identify underlying relationships among the explanatory variables thanks to the loadings in each component. Table 2.6 shows the loadings and roots for the correlation matrix of our model.

TABLE 2.6: Loadings and roots

	Comp 1	Comp 2	Comp 3	Comp 4	Comp 5	Comp 6	Comp 7
Ln Cap	0.441	-0.398	-0.008	0.282	-0.088	0.475	-0.576
Ln ICHT	0.552	-0.086	0.218	-0.229	-0.015	-0.729	-0.232
EXPI	0.553	-0.173	0.165	-0.088	-0.054	0.282	0.738
EXPP	0.106	0.534	0.335	-0.605	-0.076	0.390	-0.256
EXPT	0.095	0.495	0.368	0.643	-0.433	-0.081	0.039
UCL	-0.313	-0.429	0.188	-0.262	-0.781	-0.035	0.016
US7	-0.274	-0.295	0.800	0.103	0.429	0.028	-0.009
λ	81.643	66.622	21.171	14.004	9.840	2.624	0.093

This decomposition can be interpreted as follows. The components are ordered according to their importance, which is represented in terms of variance percentage (i.e. the roots λ). As each component is a linear combination of the explanatory variables, those with the highest loadings show us what each component represents.

For instance, in our case the first component explains 41% of the total variance in which the variables with high loadings are: wages, capacity and cumulative experience. This component represents what we could call the *the large size syndrome* or, as Cooper (2010) termed it, the *Bupp-Derian-Komanoff-Taylor* hypothesis. This hypothesis stated that as the nuclear power industry (vendors and utilities) gained experience, they were able to identify how to improve reactors performance and ultimately design more complex and bigger units.

The second most important component accounts for 33% of the variance. The variables with high loadings are: experience within *palier* and type, and the two safety performance indicators. Given that these loadings have opposite signs, we can think of this component as a *safety feedback*. This second component shows that constructing similar reactors (either in size or type) resulted in better performance in terms of safety indicators in the most recent units of each series, in particular the reliability indicator (UCL).

Going in the same direction, Roche (2004) claimed that even when equipment inside plants of the same series was identical and laid out in the same manner, the experience gained by EDFs engineering division at series level resulted in specific and minor modifications in order to improve reliability and safety.

Even though this component decomposition gave us some insights on the French nuclear power program, we had to select the number of components to be included in the linear regression estimation. After selecting the optimal number of principal components, we were able to see how the explanatory variables were related to the variable we are interested in, i.e., construction costs. Among the possible criteria to determine the optimal number of components, we took the root mean squared error of prediction (RMSEP) criterion. Using the leave-one-out cross-validation method, we found that using the first two components minimizes the RMSEP.

Once the optimal number of principal components had been selected, we computed the coefficients for the original linear regression. In Table 2.7 we present the estimates for our set of explanatory variables. Given that we had to standardize our explanatory variables, we differentiated the coefficients that we obtained from the centered and scaled matrix with ($\hat{\beta}^*$) from those that we obtained for the original data, denoted by $\hat{\beta}$ in Table 2.7.

TABLE 2.7: Principal Component Regression Results

Coefficients	$\hat{\beta}^*$	$\hat{\beta}$	s.e($\hat{\beta}$)	t-value
LnCap	0.222	1.131	0.106	9.489
Ln ICHT	0.212	0.553	0.536	10.089
EXPI	0.226	0.226	0.020	9.996
EXPP	-0.048	-0.048	0.011	-3.581
EXPT	-0.046	-0.046	0.009	-3.074
UCL	-0.042	-0.042	0.022	-2.677
US7	-0.050	-0.050	0.016	-3.544

In the light of these results, we confirm that, as in the U.S. case, the scaling-up of the French nuclear program did not translate into cost reductions. The regression coefficient for capacity in Table 2.7 shows that an increase in this variable will induce higher construction costs per MW.

However, as we have mentioned in the previous section, we cannot overlook pure economies of scale given that this variable captures the size from the complexity effect. The lack of, or at least weak, economies of scale in nuclear power plant construction is a well-known phenomenon. It has been identified that constructing larger reactors means an increase in technological complexity and construction lead-times that requires better managerial coordination and induces closer and stricter regulatory standards, which in turn increase the construction costs. To sum up, we can conclude that the greater the size of the unit, the higher the risk of cost overruns (Cooper (2010)).

Regarding overall learning effects, we also found that cumulated experience did not induce a reduction in costs. This result is often seen as a consequence of the intrinsic characteristics of a complex technology such as nuclear power. In particular, we can argue that given that an important part of the design of a nuclear power plant depends on the characteristics of each site (Cooper (2010), Grubler (2010)), it is likely that the experience gained in the construction of any reactor in a given location would not be directly applicable to other projects and that this prevents achieving lower costs.

These first two results can be summarized in the large size syndrome component. As mentioned before, it has been observed in the nuclear industry that the experience gained by vendors and operators translates into adjustments and improvements, with the effect that new reactors are bigger, more complex and more expensive than their predecessors. In the French case, Grubler (2010) and Finon (2012) argued that the potential learning effects from the overall industry experience were not fully exploited, precisely because when EDF and Framatome gained experience, the decision was taken to construct an entirely new French nuclear reactor (i.e. P′4 series).

Nevertheless, when we take into account experience within the same *palier* and type, we find a positive learning effect. In Table 2.7, we can see that the estimates for these variables are negative, however their effect was less significant than that of the other variables. This result means that some cost reductions were achieved due to the standardization strategy adopted in the French nuclear power program.

The intuition behind learning effects within the same type of reactor is straightforward, but less clear at *palier* level, precisely because the reactors within them are not exactly the same. A possible justification is that each *palier* also represents a phase of the French nuclear program. Hence, reactors within the same *palier* were designed and built in the same time window and most of them were also built on the same sites, which suggests that suppliers, workers, engineers and locations did not change substantially during the construction of one *palier*, but that they did change between them.

To our knowledge, this is the first time in economic literature that public data has be used to justify the gains EDF claimed it obtained thanks to the standardization strategy. For instance, Roche (2004)pointed out that the construction of the same series of reactors made it possible to reduce the number of hours of skilled labor per unit and obtain better prices for components. In the light of our results, we can conclude that indeed these gains helped to reduce construction costs after the first unit of the series was built.

This result is also linked to another characteristic of the French nuclear program, i.e. multi-site construction, involving several reactors of the same type built at one location. This strategy is another factor in easing cost escalation, and citetRoche argued that a discrepancy in location conditions translates into a gap in costs when constructing the same type of reactor at different sites; however these projects do not require a completely new design or new components, and thus the costs are avoided.

Another important result shown in Table 2.7 is that reactors with better safety indicators, and so lower UCL and US7 values, are related to higher costs. Therefore, we have some evidence that the latest reactors, although more expensive, have also embodied safety improvements that have helped to reduce the number of unplanned outages that might induce an accident.

These two last results are summarized in the second component, which we call *safety feedback*. Here, we have two counteracting effects: on the one hand, we determined that constructing the same type of reactors induces cost savings, which reflects positive learning effects; and on the other hand, we observed that the newer reactors register better safety indicators but that this improvement means an increase in construction costs.

This result shows the implicit trade-off between standardization and technological change that is key to understanding the economics of nuclear power. Even if it is true that standardization reduces uncertainty and could lead to lower costs, as we found for the case of the French nuclear fleet, it is also true that when new technologies are available, there is no reason to keep using older and less efficient technology, especially when new designs improve safety.

In summary, this result indicates that building similar reactors reduces the technological uncertainty linked with adopting a new design, and at the same time, as Roche (2004) has pointed out, improves understanding of how minor modifications can be made to improve reactors safety performance. For this reason, standardization can been seen as one of the potential sources of savings for future nuclear reactors, and also a way to achieve better safety performance.

2.4 Conclusion and Policy Implications

In this paper, we sought to use the current construction costs recently published in the *Cour de Comptes* report in order to identify the main drivers of the cost escalation of nuclear power construction in France, to re-address the existence of learning effects, and to test whether the cost increase is related to safety improvements.

It was originally believed that cost escalation was a factor of about 3.5, when comparing the unit costs of units built in 1974 with those completed after 1990 (Grubler (2010)). Using the new data, we found that the escalation was a factor of about 1.5 from the first unit to the most recent, and that the escalation was thus less severe and by no means comparable with the U.S. case. For this reason, it is important to review the actual construction costs of the French nuclear power programme to identify the elements that should be taken into account to overcome, or at least mitigate, the cost escalation phenomenon.

This analysis is particularly important for those countries that are interested in embarking upon nuclear power programmes. Within the European context, nuclear power can play an important role in energy transition to a decarbonized electricity supply. It is important to recall, that despite the German nuclear phase out, there are other EU members states, like the United Kingdom for instance, that see in nuclear an alternative to meet their CO2 targets while securing their energy supply.

On the basis of our analysis using the *Cour des Comptes* data, there is every reason to believe that construction cost escalation is mainly due to a scaling-up strategy. The increase in the reactors size involved a technological change that induced the construction of more complex units, meaning longer lead times to build them, and ultimately an increase in costs per MW. As mentioned before, it is not possible to rule out the presence of economies of scale precisely because bigger reactors are more complex. The recent experience in the construction of the first of a kind EPR reactors has confirmed that larger reactors are likely to be more expensive.

For this reason, capacity could be one of the first features that nuclear vendors should rethink in the long run. In this direction, several authors, such as Rosner and Goldberg (2011*b*) and Kessides (2012), have outlined the advantages of installing small modular reactors[10]. They argue that these reactors have shorter construction schedules and lower market risks, which reduces capital costs. In addition, they consider that other cost savings can be achieved through off-site module fabrication, as well as from learning by doing in the production of multiple modules. Moreover, investments could be recovered

[10] Small Modular Reactors are nuclear power plants with 300MWe or less capacity.

quicker, because construction lead times are likely to be shorter than for bigger units (Rothwell and Ganda (2014)).

Nowadays, small modular nuclear reactors are still in an early stage of development. None of the existing concepts have been tested, licensed or constructed. However in the U.S., the Department of Energy has conceived a small modular reactor technical support programme to accelerate the design, certification and licensing of small modular reactors with different vendors and it is expected to have its first regulatory approval by 2018. If these reactors become affordable and meet all safety standards, they may be an interesting alternative.

Regarding our results on learning effects, we found that overall experience did not translate into lower costs, but that positive learning effects were achieved through constructing the same types of reactor. Given the nature of this result, it would appear that the French nuclear power programmes standardization and multi-unit location strategy has been successful, because it has helped to overcome delays and uncertainties during the construction process and thus has reduced the costs of subsequent reactors in the same series.

This lesson is particularly important for those countries that are interested in installing a high number of new nuclear power plants. Unlike other technologies, the construction of a nuclear power plant depends largely on on-site characteristics, and therefore one way of overcoming the cost escalation curse could be to reduce technological variety and construct multi-unit sites. Such a strategy could reduce the uncertainty that comes with adopting a new technology, as well as any design modifications required when reactors are built in other locations.

According to our result, we can argue that it is likely to expect that the cost for the EPR reactors that would be built after Hinkley Point C[11] will be lower, thanks to learning effects. Thus, the guaranteed price to construct and operate these reactors should be smaller. However, nuclear deployment in England takes into consideration the construction of different type of reactors at other sites. Therefore, our results also suggest that the experience gained in this project will not be directly transferable into cost reductions for other projects in other locations, given that the types of reactor that are planned to be constructed are not the same.

The results in terms of safety indicators show that reducing the risk of a serious accident has also played its role in French cost escalation, as found by Cooper (2010) for the U.S. case. Our estimates suggest that designing new nuclear reactors necessarily includes safety improvements (reflected in better safety indicators). In consequence,

[11] EDF Energy is also proposing to build two EPR reactors at Sizewell C in Suffolk

when safety concerns are partly internalized in the construction costs, safer reactors are inherently more expensive. For this reason, the economics of safety may constitute the most challenging issue for the future of nuclear power. On the one hand, the terrible consequences of a nuclear disaster, as seen after the Fukushima Dai-ichi accident, leave no room for laxity. On the other hand, the particular nature of serious nuclear accidents, i.e., huge damage but very low and uncertain probability of occurrence, makes it difficult to determine whether safety investments are cost-effective.

Once again, the French case teaches us an important lesson. An analysis of principal components shows that the most recent units in the same series perform better in terms of the safety indicators used in the model. Thus, standardization not only generates learning effects in the construction process, but can also play a role in terms of achieving better safety levels.

In conclusion, an analysis of the current construction costs of the French nuclear power programme provides important lessons for countries interested in building new nuclear power plants on how to ease cost escalation. This is an important issue given that the continual rise in the construction of the latest generation of reactors puts into question the competitiveness of this technology with respect to alternative sources of energy. Taking into account our results, a good strategy would be to reduce the variety or types of reactor to be installed in order to obtain positive learning effects, not only regarding construction costs, but also regarding operations, in particular safety performance. Another consideration is that new technologies, such as small modular reactors, might be an interesting alternative to reduce capital costs given the smaller scale of units, but also the possibility of off-site module manufacture might reduce the risk of delays and associated cost overruns.

Chapter 3

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

3.1 Introduction

3.1.1 Toward a nuclear renaissance?

By August 2014, the World Nuclear Association (WNA) lists 72 reactors *under construction* in 14 countries[1]. This level of new builds represents a record for the nuclear industry since 1987. Countries and investors interested in nuclear power have their eyes on the outcome of these projects,as their successes could represent a green light for further deployment of nuclear power, while failures might led to a stagnation of new builds and a decline of nuclear power share in the world's energy production.

Even though the current status of new builds can be seen as a first step towards the so-called *nuclear renaissance*, there is a long way to go in order to see the industry revival envisioned when this term emerged in the late 1990s. At the same time, most of the drivers that could favor a nuclear expansion are still valid today: increasing energy demands in particular from developing countries, the need to reduce fossil fuel dependence and the increased awareness of the dangers and possible effects of climate

[1] See the list http://world-nuclear.org/NuclearDatabase/rdresults.aspx?id=27569&ExampleId=62

change. Despite this positive environment, it is yet to be seen if a rapid expansion of nuclear power capacity is possible and - more important - if it is economically profitable.

If we take a closer look to the list of nuclear reactors *under construction*, there are reasons why one should be cautious when arguing that these projects could spur a rapid expansion of nuclear power, or even that they will come to term. As pointed out in the *World Nuclear Industry Status Report* (2014), 8 of these reactors have been under construction for more than 20 years, 1 for 12 years and 49 have already faced significant construction delays.

Unfortunately, this is not a new situation for the nuclear industry as the construction of new reactors has been characterized in the past with lengthy lead-times, in particular in western countries. For instance, Schneider and Froggatt (2014) noticed that the average construction time of the last 37 units that started since 2004 is 10 years. This is twice what is usually expected by nuclear vendors. It is also substantially longer than the 3 years period to build a combined cycle gas plant and the 6 years period to build a coal plant.

In addition to the concerns about unexpected construction delays, the second and probably most important challenge for nuclear power expansion is the economic profitability of building those reactors. Given that upfront investment costs are the main driver[2] of nuclear electricity generating costs, any unexpected and significant increase of the expenses during the construction can significantly undermine the profitability of the project. When the construction costs of a new nuclear power plant increase substantially, it can even be more attractive to abandon the project and for outsider investors to consider other energy sources.

These concerns regarding Generation III+ nuclear reactors competitiveness have initially emerged in the United States (U.S.), due to the escalation in the construction costs expectations for new reactors. The revised estimates took into account the changes made by utilities in the application forms filled to the Nuclear Regulatory Commission. In 2003, the cost expectation was US$2,000 (see Base case in Parsons and Du (2003))and this figure progressively increased to US$4,000 per installed kilowatt (see Parsons and Du (2009) and Rosner and Goldberg (2011*a*)).

Similarly, the recent experience in the construction of the first of a kind EPR[3] in Europe has also contributed to revising expected costs of building new nuclear power plants in OECD economies. Despite that Finland and France have successfully built nuclear reactors in the past, this did not prevent that both to face significant cost overruns. In

[2] According to the IEA (2010) the share of the capital costs in the leveled cost of electricity in nuclear power is between 60% to 80%

[3] European Pressurized Reactor

France, the construction of Flamanville 3 unit is almost 3 times more expensive than initially expected (€3 billion in 2009 versus €8.5 billion in 2012). Not to mention, that the plant should not be operational until 2016, which represents nearly a 100% increase in lead-time from 5 to 9 years.

The cost over-runs experienced in the past and the multiple upward cost revisions and delays in construction over the last decade represent important barriers for nuclear expansion, as they limit the countries where new reactors can be installed. These concerns mean that nuclear new builds are risky projects, first, because there is no early yield due to the lengthy lead-times and second, because the yield is uncertain in the long term due to possible cost escalations during the construction. These issues are heavily penalized by the financial markets, and further restrict the amount of capital to invest in the sector.

Consequently, more than 60% of the new build is located in countries where, instead of the financial markets (private investors), the government plays a central role as investor in the power sector through state electric companies. This is the case in China where the three national nuclear utilities are largely or entirely state-owned. In Russia, the 6 reactors that are under construction are designed and owned by the state-owned Rosenergoatom Corporation. Finally iIn South Korea, the 5 new builds care also designed and owned by the state-owned Korea Electric Power Corporation (KEPCO).

Few of the new entrant countries that have raised their interest in nuclear power over the last decade have started the construction of their first reactor. Most of them have postponed construction, probably due to difficulties to finance these projects . This has been the case of Vietnam, Poland and Turkey. In addition, even for countries with lower financial constraints, upfront investment costs have been the key driver to select reactor design. For instance, according to Schneider and Froggatt (2014) the United Arab Emirates chose a Korean design over France's EPR because it offered the highest capacity factors, lowest construction costs and shortest construction lead-times.

Taking into account the above, we can argue that the expansion of nuclear power today depends on how the industry identify the key elements that will curb investment cost escalation and allow it to meet construction schedules.

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

The economic literature on construction costs and lead-times of nuclear power plants, has so far failed to provide clear empirical evidence of their determinants, partly due to a lack of comparable and reliable data. Most of the existing econometric studies have focused on U.S construction costs and attribute the escalation in costs to a lack of standardization, an increase in complexity of new reactors and safety related regulatory interventions after Three Mile Island accident.

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

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

In this paper, we propose the first empirical investigation of the role of lead-times, standardization and learning opportunities on nuclear reactors' construction costs, using historical cost data from both the U.S 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 U.S 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 U.S. This means that by looking at French and U.S experience together one can benefit from more heterogeneity in the data in order to test more research hypotheses and derive robust estimates.

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

Our model is close to the one proposed first by Rothwell (1986) and then Cantor and Hewlett (1988). In particular to the latter, where a two-stage least squares equation model is estimated for construction costs and lead-time using U.S data. However, our analysis tackles a number of other empirical shortcomings. First, our study allows a direct comparison of nuclear reactors' overnight construction costs in the two countries using the access to data[4] on engineering and other related expenditures for French reactors, which are not detailed in the Cour des Comptes (2012) report.

Unlike other papers, we distinguish the potential benefits of standardization that might arise in the short term, from those that can appear in the long term. In the short term, we argue that a reduced diversity of designs under construction in a particular year can affect the costs and the lead-time of an ongoing project, due to coordination gains (for instance, scale effects in the component's supply chain or for the safety assessment by the regulatory agency). We also consider that standardization may allow long term benefits, through learning by doing spillovers gained from past experience in building similar units. In order to capture these spillover effects, we differentiate the previous experience based on reactor models and A-E firms.

At the same time, we study the possible effects of learning by searching (i.e innovation) on construction costs, given the importance of public R&D expenditures on nuclear power. Evidence of a positive learning by searching effect has only been found using cost and innovation data from energy economics modelling tools (Jamasb, 2006). In that respect, to the best of our knowledge, there is no existing literature that has looked at the effect of innovation using actual cost data. Hence, our study is the first to bring together data on nuclear power overnight construction costs and knowledge capabilities data, the latter measured as a stock of knowledge based on patent data.

Our results suggest that standardization of nuclear power programs is one of the main factors in limiting costs escalation. In the short term, a low diversity of reactors under construction leads to coordination gains that reduces costs indirectly through a reduction in lead-time. More importantly, this result is also confirmed by using data of lead-times of other OECD countries, with different market structure and technological paths, notably Asian countries (i.e Japan and South Korea) that have achieved to maintain relatively constant their construction lead-times.

[4] 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

We find that standardization allows learning effects. We have denominated this spillovers as the long term benefits of standardization, considering that the cost reductions will only appear, if the same nuclear model is built by the same A-E firm repeatedly. This highlights the importance of reactor design standardization and the role played by the A-E firm in reducing construction costs increases.

We further show that contrary to other energy technologies (Erickson and Drennen, 2006) there is a negative effect of learning by searching on reactors' overnight construction costs. This means that the variable that captures innovation and knowledge is one of the main drivers of the cost escalation registered in the U.S and France. This result opens the door for further research on the areas in which innovation in nuclear power technologies has focused. In the literature, (Berthélemy, 2012*a*) has found that innovation is closely linked better safety performance, which in some sense allow us to think that innovation has been partly driven by nuclear safety considerations.

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. For this reason, we have explore further the trends of the construction lead-times in other OECD countries.

The rest of the paper is organized as follows: in Section 3.2 we present the model, and main hypotheses regarding learning effects and the data. Section 3.3 describes our empirical strategy and the results. Section 3.4 further investigates international experiences with nuclear power construction using a larger dataset on nuclear power lead-time; and finally we conclude in Section 3.5.

3.2 Model, main hypothesis about learning opportunities and data

3.2.1 Model for construction costs and lead-times in nuclear power

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

Rothwell (1986) proposed a structural model to represent the involvement of multiple firms in the construction of a nuclear power plant. In his model, the utility seeks to maximize the net present value of the project by selecting an optimal construction lead-time, given the technical characteristics that were chosen in the tender (i.e capacity, reactor design, etc). The A-E firm will minimize costs given the the optimal lead-time selected by the utility.

In this paper we retake some of the elements in Rothwell (1986), but instead of a structural model, we opt for a reduced form model closer to Cantor and Hewlett (1988). We propose an two least squares estimation (2sls) for the construction costs and the lead-times, taking into account that there might be some unobserved variables that affect the simultaneously both variables. For instance, we can think that there are additional costs associated with longer construction periods, like rental of idle specialized equipment and labour force, or unexpected costs (and delays) due to defective components. Cantor and Hewlett (1988) also pointed out that longer lead-times increase the risk of regulatory intervention which might lead to construction changes and therefore cost increases.

Given that OLS estimators will be biased, we will use the expected electricity demand ($EDem_i$) as an instrument for lead-time as in Cantor and Hewlett (1988). They considered this variable as a valid instrument inspired in the structural model in Rothwell (1986). First because the lead-time is chosen based on the expected demand and second because it does not influence current construction costs. Our baseline model specification follows Equations (3.1) and (3.2) 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 next sub-section:

$$CT_i = \alpha_0 + \alpha_1 LT_i + \sum_{j=2}^{J} \alpha_j X_{ij} + \upsilon_i \tag{3.1}$$

$$LT_i = \beta_0 + \beta_1 EDem_i + \sum_{j=2}^{J} \beta_j X_{ij} + \epsilon_i \tag{3.2}$$

3.2.1.1 Hypotheses on the role reactor's design standardization

As aforementioned, we are interest in investigating the role of standardization in construction costs and lead-times. In our set of explanatory variables, we are going to test two potential efficiency gains may be expected from the standardization of nuclear programs. The first one aims to capture the benefits (in terms of cost reductions) that might arise in a short time period, while the others will test the presence of learning by doing, that can be seen as a long term effect.

Our first hypothesis is that standardization benefits can arise in the short term from a low diversity of nuclear reactors under-construction. We expect that when a reactor's design is being built in the same country in the same year, the project might benefit from coordination gains during the construction period. This can be motivated by the fact that similar high-tech components will be built during a short time window, such as steam generators or turbines, leading to economies of scale. Similarly, a low diversity in reactors under-construction also lowers technological uncertainty and therefore it reduces the number unexpected events that might delay the construction.

To measure this potential benefit of standardization during the construction period, we compute a Herfindahl Hirschman Index (HHI) index based on the number of specific reactor models under-construction when the construction of reactor starts. This index is defined according to Equation (3.3) 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.

$$HHI_{c,t} = \sum_{m=1}^{M} s_{mtc}^2 \tag{3.3}$$

3.2.1.2 Hypotheses on learning by doing

Regarding the potential benefits of standardization in the long term, David and Rothwell (1996) recognized that there is a trade-off between the ability to learn from diversity in nuclear reactors versus learning from similar models. Nowadays this trade-off is important, given that in some countries, like China, the current strategy is more directed to favor the construction the same type of reactor repeatedly, rather than to diversify the nuclear fleet. While in others, like the case of U.K, it is envisioned to construct different models in different sites.

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

Furthermore, the benefits of learning by doing might also be conditional on the A-E firm experience with specific nuclear design ($ExpArqMo_i$). This variable corresponds to the second potential benefit of standardization that we wanted to test. This more restricted level of learning by doing opportunities corresponds to the traditional definition used in the economic literature (Irwin and Klenow, 1994).

It is important to mention, that in the previous literature the learning by doing was measured using either the cumulated experience at the country or firm level. In this paper, we are going to decompose the country level experience ($ExpC_i$) into four level of learning effects: (i) The experience of the A-E with the reactor model ($ExpArqMo_i$), (ii) the experience of the A-E with other models ($ExpArqNoMo_i$), (iii), the experience of other A-Es with the same model ($ExpNoArqMo_i$) and (iv) the experience of other A-Es with other models ($ExpNoArqNoMo_i$).

$$ExpC_i = ExpArqMo_i + ExpArqNoMo_i + ExpNoArqMo_i + ExpNoArqNoMo_i \quad (3.4)$$

3.2.1.3 Hypotheses on leaning by searching

One standard hypothesis made in the energy economics literature is that learning by doing might not be the only source of cost reductions. In particular, learning by searching is often found in many empirical studies dealing with the energy sector, like Larsen and Sundqvist (2005) and Erickson and Drennen (2006), as a variable that contributes significantly to cut back costs. In the case of nuclear power, the impact of innovation activity on cost remains an empirical question.

According to Jamasb (2006) innovation activity may contribute to cost reduction, however it can also be argued that innovation in nuclear power essentially deals with safety improvements because of the role of safety regulation. 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, using a discounted stock of priority patent applications. We use the patent class Y02E30 which covers technologies specific to nuclear fission reactor technologies. The discounted stock is set at the country level, reflecting the fact that innovation can come both from R&D laboratories and nuclear vendors and can be understood to reflect national knowledge capabilities. We set the discount factor δ at 10%, a conservative parameter found in many studies on the dynamics of innovation (Peri, 2005). This variable is denoted $Know_{i,t}$ and is defined according to Equation (3.5) where for each nuclear reactor we use the discounted stock of patented innovations in country i when construction starts at time t.

$$Know_{i,t} = \sum_{k=1}^{\infty} (1-\delta)^k \, Patent_{i,t-k} \tag{3.5}$$

3.2.2 Data

In our model, we have taken the overnight construction costs expressed in 2010 € per MWe as our variable of interest. These costs comprise the engineering, procurement and construction expenses, but they exclude those related with financing or any cost escalation due to changes in the interests during construction. In short, this cost represents the lump sum up front that would have to be given, if the project was completed "overnight".

We have used the overnight costs instead of the actual construction cost for two main reasons. First, because the financing expenses of each project will depend not only on the lead-time but on the rate of interest on debt, the debt-equity ratio, and if it is regulated, how the capital costs are recovered. By excluding these costs, we get of rid of the variance linked with differences on the financial structure of each utility and the possible subsidies (that is very likely in the case of the French nuclear fleet) and we are able compare all the projects with an uniform measure. Second, because we can focus our attention on the potential effect of the observed lead-times in the engineering and construction cost escalation, if we have used the actual costs it would not have been possible to isolate this effect.

The cost data for the French nuclear fleet were collected from the French Audit Agency *Cour des Comptes (2012)* report. This sample only has 29 observations because the costs on the report were presented by pair of reactors. Regarding the U.S construction costs, we have included the cost data for 99 reactors (92 in operation and 7 shutdown), published in Koomey and Hultman (2007). Unfortunately the capital costs for the 12 remaining operational reactors are not available.

Figure 3.1 below highlights the strong differences between the trend in overnight construction costs in U.S and France. In particular, we observe that over the entire time period the costs have more than doubled in France, from 920€/MWe in 1980 for the Tricastin 3 and 4 reactors up to 2200€/MWe in 2000 for the Chooz 1 and 2 reactors. In the U.S, this increase has been much more rapid with the cost almost increasing by a factor of 14 from 600€/MWe in 1972 for Turkey Point 3 up to 8500€/MWe in 1989 for the Shoreham reactor.

One can also note that costs have been much more dispersed in the U.S. For instance, if we look at nuclear reactors completed in 1986 in the U.S, the costs range from 2000€/MWe for Catawba 2 and 6250€/MWe for the Hope Creek reactor. Since France and the U.S 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 an initial suggestion that the French experience has been more successful in containing the escalation of construction costs.

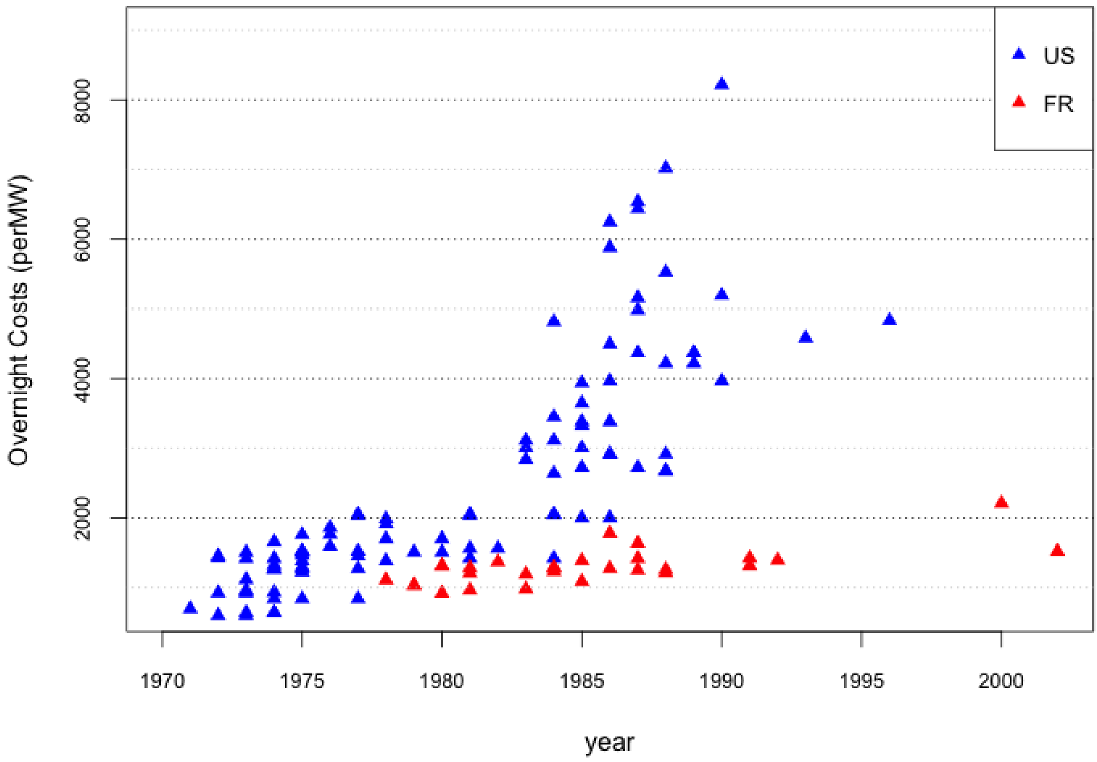

FIGURE 3.1: Nuclear reactors' overnight construction costs in the US and France

Following Rothwell (1986) we define the lead-time variable as the difference (in years) between the commercial operation date and the construction start date. This information was taken from the IAEA Power Reactor Information System (PRIS) database. From this same database, we have collected other reactor details as the net capacity (size of the reactor) in MWe, information on nuclear reactor cooling systems and containment structures[5], in order to define different reactor models. In Figure 3.2 we plot the construction lead-times 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 U.S than in France. This Figure suggest that it might be possible that long construction time will generate other expenses in addition to the financing 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.

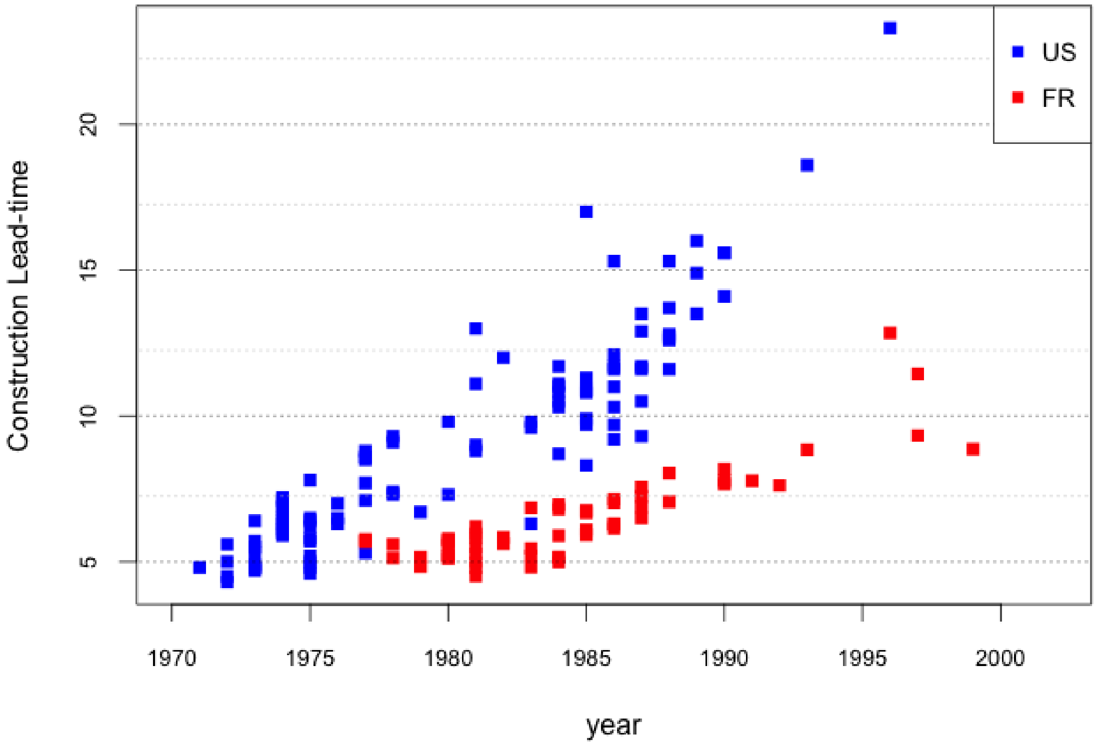

FIGURE 3.2: Nuclear reactors'construction lead-time in the U.S and France

The increase in lead-time still appears to be of a lower magnitude than the increase in cost. For instance, lead-time in the U.S 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.

As instrument, we have computed the 3 year time trend in the electricity consumption as a proxy of the expected electricity demand. For the French case, we have taken the national electricity consumption given that all the reactors are connected to the same grid, thus all the units intend to meet the national demands. For the U.S we consider the electricity consumption for the relevant market given that there is no common grid,

[5] Data about nuclear reactors cooling system and containment structure are detailed in the Appendix E

therefore we took the time trend only of the electric power market[6] where the reactor was located. The data was taken from the statistics of the Department of Energy (DOE) for the U.S and the French National Statistics Institute (INSEE).

In the model, we have also included a set of dummy variables. The first one aims to identify those projects in which the utilities were in charge of the construction project and did not delegate it to a A-E firm. For the U.S case, we turn to the information provided by the Nuclear Regulatory Commission (NRC). 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. The other dummy variables were included to 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 U.S, 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 U.S Census Bureau respectively for the two countries. All the definitions and descriptive statistics for our relevant variables are summarized in Table 3.1 below.

Table 3.1: Descriptive statistics

Variable	Definition	Mean	Std. Dev.	Min	Max
CT	Cost in €$_{2010}$/MWe	2282	1.639	599	8571
LT	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	582.51	103.96	326.48	903.39
$ExpArqMo$	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	0.382	0.487	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
$EDem$	Future electricity demand (3 year trend)	.043	.010	.017	.061
$NPP.UC$	Reactors under-construction	42.632	20.747	2	69

6 We added up the electricity consumption of the states that from each one of the 10 electric power markets: California, MISO, New England, New York, Northwest, PJM, Southeast, Southwest, SPP and Texas

3.3 Model specifications and results: France versus the US

3.3.1 Model specifications

The equations used to study construction costs and lead-time follows a Cobb-Douglas functional form[7], taking into account the endogeneity of lead-time we use expected demand of electricity as an instrument and we control for the effects of capacity and input prices. A set of explanatory variables to identify learning effects is 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 (3.1) and (3.2), the equations for the baseline model specification (Model 1) are as follows:

$$\begin{aligned}\ln(CT_i) = \alpha_0 + \alpha_1 \ln(LT_i) + \alpha_2 \ln(Cap_i) + \alpha_3 \ln(Cement) + \alpha_4 \ln(Labour) + \\ \alpha_5 ArqUtility_i + \alpha_6 \ln(ExpArqMo_i) + \alpha_7 \ln(ExpArqNoMo_i) + \alpha_8 \ln(ExpNoArqMo_i) + \\ \alpha_9 \ln(ExpNoArqNoMo_i) + \alpha_{10} HHI.Mo_i + \alpha_{11} NNP.UC + \\ \alpha_{12} Tmi.US + \alpha_{13} Tmi.FR + \alpha_{14} Cherno + \alpha_{15} Country + \alpha_{16} Trend + \upsilon_i \end{aligned} \tag{3.6}$$

$$\begin{aligned}\ln(LT_i) = \beta_0 + \beta_1 \ln(Cap_i) + \beta_2 ArqUtility_i + \beta_3 \ln(ExpArqMo_i) + \beta_4 \ln(ExpArqNoMo_i) \\ + \beta_5 \ln(ExpNoArqMo_i) + \beta_6 \ln(ExpNoArqNoMo_i) + \beta_7 HHI.Mo_i \\ + \beta_8 \ln(EDem) + \beta_9 NPP.UC + \beta_{10} Tmi.US + \beta_{11} Tmi.FR \\ + \beta_{12} Cherno + \beta_{13} Country + \beta_{14} Trend + \epsilon_i \end{aligned} \tag{3.7}$$

In Model 2, we consider the possibility of learning by searching in addition to standardization and learning by doing, therefore in Equation (3.6) we include $Know$. 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.

[7] 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)

3.3.2 Results

The estimated output for Equations (3.1) and (3.2) is presented in Tables 3.2 and 3.3 below, for the four different model specifications. In each table we find the estimates with the corrected standard errors in brackets underneath them.

Before we proceed to present the results, it is important to mention that the total effect of the explanatory variables in the overnight costs has to take into account the partial effect in the cost equation as well as the indirect impact in the costs through changes in the lead-time equation. As we can see in Tables (3.2) and (3.3), the estimate of the lead-time is positive and significant, therefore we have to offset the effect of the variables in the first equation with the indirect effect in the second one, as follows:

$$\frac{d\ln CT}{d\ln X_k} = \frac{\partial \ln CT}{\partial \ln X_k} + \frac{\partial \ln CT}{\partial \ln LT} * \frac{\partial \ln LT}{\partial \ln X_k} = \alpha_k + \alpha_1 * \beta_k$$

The first result of our analysis refers to the importance of model specification in identifying significant and positive 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. By comparing the results across the models, we can see that the estimates in Models 1 and 2, where we include the experience of the same A-E firm in the same model $ExpArqMo$, are those where we find the largest learning effects. While the learning effects are weaker in Model 3 and they do not exist in Model 4.

The estimates of Model 1 and 2 allow us to conclude that in average, we can expect that the costs for the second unit of a reactor model built by the same A-E firm will be reduced in 10% to a 12%[8]. This result goes in line with what is predicted in the economic literature on learning effects and coincides with recent evidence (Escobar-Rangel and Leveque, 2012) on the French nuclear fleet. To test the robustness of these results, we used different measures for the experience variables (i.e. $ExpArqMo$, $ExpArqNoMo$, $ExpNoArqMo$ and $ExpNoArqNoMo$) as shown in Appendix C[9].

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

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8 Here we have computed the total effect of $ExpArqMo$ in the cost. In Model 1 is equal to (0.022*2.17)-0.152=-0.10 and in Model 2 to (0.022*1.85)-0.1655=-0.12. If we consider that the experience from the first to the second unit represent 100% increase in the experience, we obtain these results.

9 For robustness tests we consider, in Appendix C, 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 Zimmerman (1982). Our results remain unchanged

TABLE 3.2: Estimation output of Equations (3.1) and (3.2)

	Model 1				Model 2			
	Cost		Lead-time		Cost		Lead-time	
$\ln(Cap_i)$	-0.897	***	0.188	**	-0.793	***	0.188	**
	(0.175)		(0.068)		(0.170)		(0.068)	
$\ln(Cement_i)$	-0.214				-0.230			
	(0.405)				(0.394)			
$\ln(Labour_i)$	0.873				0.154			
	(0.409)				(0.413)			
$\ln(LT_i)$	2.177	***			1.825	***		
	(0.468)				(0.465)			
$\ln.ExpArqMo_i$	-0.152	***	0.022		-0.166	***	0.022	
	(0.034)		(0.015)		(0.033)		(0.015)	
$\ln.ExpArqNoMo_i$	-0.036		0.039	**	-0.025		0.039	**
	(0.035)		(0.012)		(0.033)		(0.012)	
$\ln.ExpNoArqMo_i$	0.021		0.035	*	0.008		0.035	*
	(0.036)		(0.015)		(0.035)		(0.015)	
$\ln.ExpNoArqNoMo_i$	-0.296	*	0.156	***	-0.223	*	0.156	***
	(0.099)		(0.023)		(0.096)		(0.023)	
$Know_i$					1.464	***		
					(0.438)			
$HHI.Mo_i$	0.917		-0.415	*	0.865		-0.415	*
	(0.468)		(0.207)		(0.463)		(0.207)	
$\ln.NPP.UC_i$	0.429	**	-0.102	**	0.356	***	-0.102	**
	(0.102)		(0.045)		(0.099)		(0.045)	
$ArqUtility_i$	-0.332	***	0.052		-0.340	***	0.052	
	(0.084)		(0.037)		(0.081)		(0.037)	
$\ln(EDem_i)$			-0.404	***			-0.404	***
			(0.079)				(0.079)	
$Tmi.US$	-0.847	**	0.436	***	-0.504	*	0.436	***
	(0.248)		(0.050)		(0.246)		(0.050)	
$Tmi.FR$	-0.328		0.040		-0.230		0.040	
	(0.216)		(0.096)		(0.209)		(0.096)	
$Cherno$	-0.348	*	0.168	***	-0.331		0.168	***
	(0.142)		(0.037)		(0.137)	*	(0.037)	
$Constant$	4.829	***	-0.449		-0.828		-0.449	
	(1.573)		(0.510)		(2.714)		(0.510)	
Country FE	Yes		Yes		Yes		Yes	
Trend + trend^2	Yes		Yes		Yes		Yes	
Obs.	128		128		128		128	
Adj. R^2	0.856		0.914		0.865		0.914	

($ExpNoArqNoMo_i$), 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.

The estimates for the diversity index $HHI.Mo_i$ suggest that there might be some benefits of standardization in the short term through reductions in the lead-time. Recall, that when this index is close to zero, it means that the nuclear fleet under construction is diverse, then these potential benefits will vanish. This result can be explained by the fact that an heterogeneous demand in the components could lead to supply chain

Table 3.3: Estimation output of Equations (3.1) and (3.2)

	Model 3		Model 4	
	Cost	Lead-time	Cost	Lead-time
$\ln(Cap_i)$	-0.803***	0.170*	-0.814***	0.167*
	(0.184)	(0.067)	(0.184)	(0.064)
$\ln(Cement_i)$	-0.451		-0.360	
	(0.425)		(0.433)	
$\ln(Labour_i)$	0.711		0.464	
	(0.436)		(0.442)	
$\ln(LT_i)$	2.328***		2.322***	
	(0.514)		(0.501)	
$\ln.ExpArq_i$	-0.121**	0.048***		
	(0.041)	(0.012)		
$\ln.ExpNoArq_i$	-0.243	0.165		
	(0.108)	(0.021)		
$\ln.ExpMo_i$			-0.083*	0.036**
			(0.033)	(0.011)
$\ln.ExpNoMo_i$			-0.301**	0.188***
			(0.116)	(0.021)
$HHI.Mo_i$	1.388	-0.389*	0.920	-0.030
	(0.498)	(0.205)	(0.486)	(0.187)
$\ln.NPP.UC_i$	0.325*	-0.099	0.367***	-0.106*
	(0.109)	(0.045)	(0.108)	(0.042)
$Arq.Utility$	-0.410***	0.064	-0.257***	0.019
	(0.089)	(0.035)	(0.077)	(0.030)
$\ln.(E.Dem_i)$		-0.383***		-0.404***
		(0.078)		(0.074)
$Tmi.US$	-0.824*	0.441***	-0.784**	0.452***
	(0.277)	(0.049)	(0.274)	(0.047)
$Tmi.FR$	-0.238	0.052	0.111	-0.175
	(0.231)	(0.095)	(0.257)	(0.094)
$Cherno$	-0.391	0.194***	-0.267	0.155***
	(0.160)	(0.035)	(0.150)	(0.034)
$Constant$	5.503**	-0.301	6.500***	-0.474
	(1.678)	(0.503)	(1.851)	(0.472)
Country FE	Yes	Yes	Yes	Yes
Trend + trend^2	Yes	Yes	Yes	Yes
Obs.	128	128	128	128
Adj. R^2	0.837	0.902	0.827	0.890

constraints and therefore some 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 estimates of our model highlight positive and significant economies of scale. It is important to mention that both in the U.S and France, the nuclear industry decided to construct bigger reactors aiming among other things, to reduce the costs per MW installed. In the light of these results, we find that indeed, even if larger nuclear reactors took longer lead-times to be built, they were also cheaper per MWe. For instance, Model 2 indicates a net impact of -0.793+(1.825*0.188)= -0.45. This coefficient can be interpreted as an elasticity, meaning that a 10% increase in size reduces construction costs in average by 4.5%.

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 (1988) and McCabe (1996)) and it can be understood by the fact that a vertically integrated utility reduces potential asymmetric information problems with the other firms involved in the construction of nuclear reactors and this leads to cost reductions.

The results for Model 2 show that the estimate for the discounted stock of priority patent applications ($Know_i$) is positive and significant. This result contradicts the pattern observed in many energy technologies, such as renewable energy sources (Erickson and Drennen, 2006). If we compare the estimates obtained in Model 1 with those of Model 2, we can see that the inclusion this variable, that aims to capture the effect of innovation, reduces the importance of capacity and lead-times in the construction cost equation. This shows that bigger reactors embed innovations and that make them more complex and need more time to be constructed. The inclusion of this variable in the model allow us to isolate the effect of complexity in the construction costs, and as we can see in Table 3.2, this was one of the main drivers of the construction costs in the U.S and France.

This result can partially be explained by the fact that the requirements of nuclear safety authorities have induced innovations (Berthélemy, 2012*a*). According to Berthélemy (2012*b*), innovations in nuclear power sector are strongly related with improvements in the safety performance of existing reactors. This result 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, but on the other hand, 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 Jamasb (2006) 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 analyze the effect of the major nuclear accidents in our system of equations. As we can see in Table 3.3, the impact on the construction costs both in the US and in France due to TMI and Chernobyl (CH) 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.

3.4 Nuclear reactors lead-time: Insights from other OECD countries

The results presented in the previous section confirm that even discounting the financial costs, delays in construction affect the construction costs. In addition, they also point out that a standardized nuclear fleet was one of the elements that made it possible to reduce construction periods, which ultimately resulted in a cost reduction.

As mention in the introduction, meeting the construction schedules will have a positive impact in nuclear power competitiveness, besides avoiding the negative effect of delays in the construction costs. First, because it allows that the utilities generate revenues soon. This is particularly important in countries with private investors in the electricity sector, given that they employ higher discount rates than those used for public infrastructure. This implies that they 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).

Second, because a long lead-time might encourage a wait-and-see policy. For instance, if we take into account that with the pre-construction period it will take between 10 and 15 years for one reactor to be commercial, it can be reasonable to delay the investment and wait until the same technology is cheaper, or other technologies become affordable. Third, because in countries with increasing energy demands in the reactors should be ready when needed. Finally, we can expect a shorter lead-time reduces the risk of regulatory intervention and somehow it might even improve the perception of other stakeholders have with respect to nuclear power.

For the above, in this section we further investigate the potential standardization benefits on lead-time, using a larger dataset on nuclear reactors from 6 OECD countries. Our aim is to test if the results that we have obtained in the previous section for the lead-time equation hold when using a larger data set. In addition, we seek to gain some insights into the construction of other nuclear fleets for which cost information is not available, but the the average on lead-times is substantially lower than in the cases that we have studied.

3.4.1 Data and Model

The data used are also extracted from the Power Reactor Information System (PRIS) database developed by the IAEA . Similarly to the previous section, lead-time is computed as the difference in years between the construction and commercial dates, for reactors in 6 OECD countries. We have considered: the U.S, France, Canada, South Korea, Japan and the U.K. 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 3.3 and Table 3.4 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 licensing 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.

In the next table, we present the means for the explanatory variables that we have chosen to use in our regression model. As we can see, differences in the lead-time means between the Western and Asian countries are substantial. For Japan and South Korea the construction of a new reactor took only 4 years approximately, whereas in the U.S or in the U.K took more than the double, even when the average size of the reactors is similar.

TABLE 3.4: Mean for the explanatory variables

	Obs.	LT (in year)	$ExpArqMo$ (#reactors)	HHI (index)	Cap (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
U.K	17	8.63	4.80	0.861	645.1
U.S	98	9.27	2.10	0.152	972.4
All Countries	291	7.41	4.12	0.378	934.4

In Table 3.5 below we present the estimates similar to Equation (3.7) in previous Section. We have also included nameplate capacity, electricity demand and the structural break

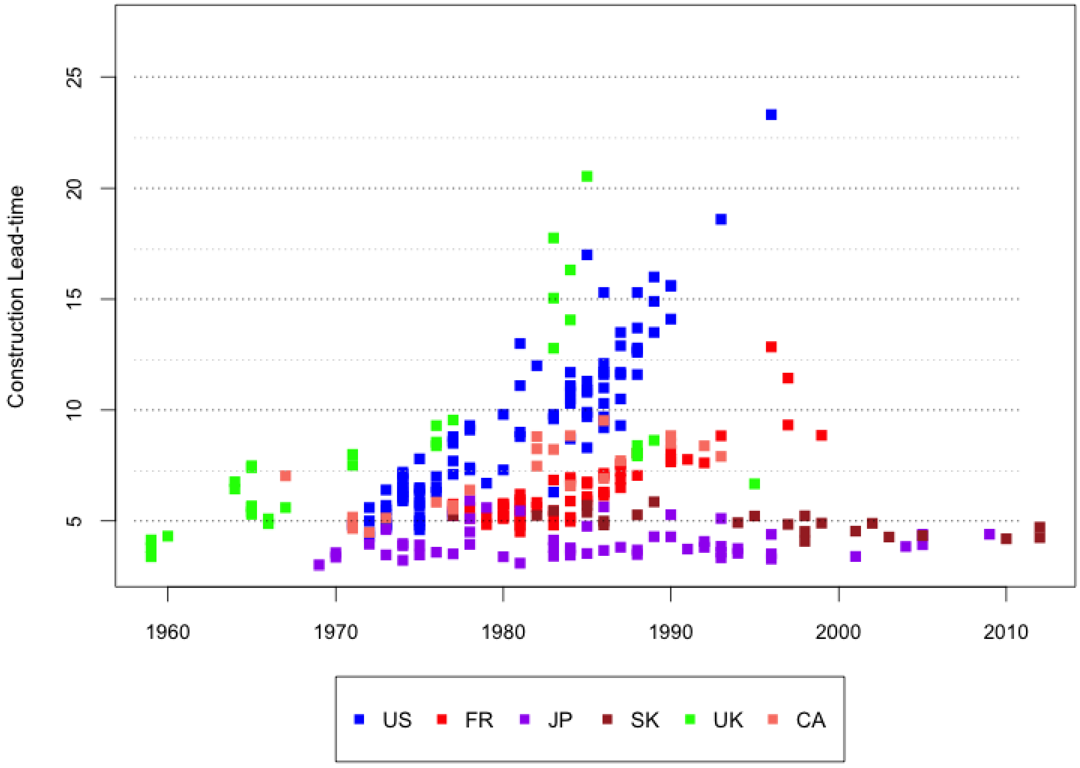

FIGURE 3.3: Nuclear reactors' construction lead-time in OCDE countries

dummies as controls. Two model specifications are considered, the second one introduces time fixed effects. Other robustness tests can also be found in Appendix D[10].

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

[10] In Appendix D we consider the four learning spillovers channels used in previous section and also define them both as $1/(1 + X)$ and $\ln(X)$. The results remain unchanged

Table 3.5: Regression results for lead-time with experience and the HHI index

Variables	(1) (ln LT)		(2) (ln LT)	
$HHI.Mo_i$	-0.291	**	-0.472	***
	(0.135)		(0.182)	
$\ln Cap_i$	0.395	***	0.254	***
	(0.052)		(0.052)	
$ExpArqMo_i$	0.019		-0.008	
	(0.032)		(0.029)	
$\ln EDem_i$	-16.970	***	-21.219	***
	(2.866)		(3.265)	
$\ln NPP.UC_i$	-0.020		-0.054	
	(0.033)		(0.047)	
$Tmi.US$	0.432	**	0.439	***
	(0.044)		(0.062)	
$Tmi.Abroad$	0.139	***	0.142	**
	(0.054)		(0.061)	
$Cherno$	0.188	***	0.214	***
	(0.029)		(0.027)	
$Constant$	1.105	***	1.977	
	(0.402)		(0.440)	
Country FE	Yes		Yes	
Time FE	No		Yes	
Trend + Trend^2	Yes		No	
Obs.	286		286	
Adj. R^2	0.840		0.869	

Note: Robust standard errors in parentheses

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.

3.5 Conclusion

In this paper we investigate the role of lead-times, the potential short and long term benefits of nuclear reactor standardization and the effect of innovation on the construction costs of nuclear reactors in the U.S 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 use a discounted stock of priority patent applications in the nuclear sector as a proxy of innovation.

We estimate a two stage least square regression model for construction 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, TMI and Chernobyl.

Our results identified the main drivers of the construction cost of the two largest nuclear fleets in the world, as well as the elements that explain the increase in the lead-times registered in the past. We show that the delays during the construction and technological innovations have led to an increase in the costs. In addition, we identified that the continuous changes of reactor designs and the scale-up in the size of the reactors explained part of the increase in the construction lead-times.

We also found that there are positive learning effects in the construction of nuclear reactors and the lead-times were shorter when the fleet under construction was less diverse. This result shows that the standardization strategy adopted in France was successful in curbing the construction costs and avoiding the long lead-times that were observed in the U.S.

3.5.1 Policy implications for nuclear new-build programs

While this paper focuses on the U.S and French construction costs, we argue that our results are useful to explain some of the latest experiences in the construction of nuclear reactors, as well to suggest what we can expect it will happen in the construction of other nuclear fleets. For instance, the continuous delays in the EPR construction in Finland and France can be seen as the conjunction of two elements. First, the fact that the EPR is a first of a kind means that the experience that AREVA or EDF had in the construction of other models, can not be directly transferable to this new project. According to our results, we can expect an increase in the construction lead-time due to this change. The second element that may explain the delays is that the EPR is a big reactor (it has a 1650 MWe capacity), in the light of our results, it is likely that it takes more time to construct compared with its predecessor (N4 model 1500 MWe).

Taking into account that the lead-times were found, regardless the model specification used, as one of the drivers of the construction costs, we can argue that the cost revisions in the Olkiluoto-3 and Flamanville-3 can partly be explained by the delays faced during the construction. According to our model, the construction costs of the EPR will decrease only if more units of this same model are built.

This last remark is important for ongoing nuclear new build programs. We found that the largest cost reductions due to learning by doing are 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. In that respect, one can expect that the cost of the last CRR-1000 reactors that are foreseen in the Chinese nuclear power program will be cheaper than the predecessors. The same argue could apply in India, where the nuclear fleet that is currently under construction includes 4 reactors of the same model (i.e PHWR-700) build and later operated by the same firm the Nuclear Power Corporation Of India. One also expect that the costs for the last APR-1400 in South Korea will decrease as KEPCO finish the ongoing constructions of this same design.

At the same time, we show that vertical integration of the utility and the A-E firm reduces construction costs. Therefore, it is possible that vertical integration will also contribute to lower costs for the reactors that are under construction in India, Korea and Russia. For new entrant countries, this potential cost reductions will not be achieved in the short term, given that most of reactors will be build as turnkey projects, like in United Arab Emirates.

We also 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 U.S. 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.

In fact, this result can be part of the explanation of the delays in the construction of the AP-1000 and EPR reactors in China. According to Schneider and Froggatt (2014), the four AP1000 reactors at Sanmen and Haiyang have 18-30 months of delays due, among other issues, to an insufficient support for regulatory review. They also point out that the first EPR at Taishan has a 13-15 month delay. In this case, the delays are linked with malfunctions in the equipment and along with a lack of understanding with the Chinese safety authorities. Whilst our model does not allow one to distinguish delays due to regulatory changes from those that arise from malfunctioning equipment or other technical problems during the construction; we can argue that when the nuclear fleet is more diverse, the safety assessment done by the safety authorities is likely to take longer. This might help to understand why the lead-times for the CRP-1000 model have been kept relatively constant (it is a well known design for the Chinese safety authority) while the difficulties during the safety assessment for other reactor models such as the AP1000 and EPR have increased the lead-times in those projects.

In parallel, we also find that the discounted stock of patents in the nuclear industry increases construction costs, reflecting that innovation has not been focused on improving nuclear competitiveness by reducing the amount of capital needed to build a reactor. This result goes in direct contrast to the pattern seen in other energy technologies, where technical progress contributes to costs reductions, notably in competing carbon-free technologies like wind power.

From a methodological perspective, this result might explain why forecasts of nuclear power share in energy mixes in energy economics modelling tools have not been met. The existing literature has shown that certain models' calibration (Jamasb, 2006) implicitly assumes that nuclear construction costs benefit from innovation effort, when in reality what we found is that technological progress have made new reactors more expensive. This result highlights the importance of building these models on evidence based on actual cost data.

However, the implications of this last result go beyond a methodological contribution. Why innovations have increased the costs of the each new generation of reactors?. Berthélemy (2012*b*) argues that innovation in nuclear power has allowed the industry to achieve better safety performance for existing reactors. In other words, one could argue that safety requirements have led vendors to include better and more reliable components and systems in new designs, aiming to improve safety features. For instance, Areva markets the EPR reactor as a Generation III+ precisely due to the level of safety obtained compared to previous designs and argues that this latter design ensures an *"unequalled safety level thanks to a drastic reduction of the probability of severe accidents as well as of their consequences on the environment. In addition, it is particularly resistant to external incidents (airplane crashes, etc.)"*.

3.5.2 Paths for future research

Our results allow us to conclude that nuclear power faces an interesting trade-off between reductions in costs permitted by standardization and potential gains from adopting new technologies with better operating and safety performance. Unfortunately, we cannot answer the question of the optimal pace of technological change in nuclear power technologies with our model. In addition, we have to recognize that by using patent data as a measure of innovation, we captured incremental innovation but we were not considering the possibility of radical technological change. In that respect, nuclear power has been characterized by incremental innovations from initial reactor designs in the 1950s. Conversely, radical innovations such as 4th generation of nuclear reactors could contribute to costs reductions and further work is needed to better understand the cost dynamic of such technologies.

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 U.S where, according to Cooper (2010), 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 U.S 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 last result opens the door for further research and also represents a challenge from a policy perspective in those countries with interest in nuclear deployment. In terms of possible research questions, we argue that it is important to identify clearly how different safety regulations have affected the design of new reactors and disentangle the effect of technical problems from the effect of regulatory interventions in the observed construction lead-times. In terms of policy, it is clear that a better coordination regarding nuclear reactor certification procedures, through cooperation between national nuclear authorities can improve nuclear competitiveness while ensuring an adequate safety level. For instance, enabling for a reactor design to be certified jointly in several countries, could reduce significantly regulatory uncertainty before and during construction without compromising required safety standards.

Chapter 4

Setting optimal safety standards for nuclear operators subject to uncertainty, moral hazard and limited liability

4.1 Introduction

Operating a nuclear power facility is a hazardous activity. One of the main concerns of nuclear power safety is the possibility of an accident releasing of significant amounts of radiation into the environment. Prolonged exposure to these radioactive materials could cause irreversible damage to living tissue in human bodies, poison animals and contaminate soil, leading to large economic and environmental losses.

Over the 14,500 reactor-years in the history of nuclear power for commercial use, two *major nuclear accidents*[1] have occurred (i.e. Chernobyl in Ukrania in 1986 and Fukushima Dai-ichi in Japan in 2011). Both accidents led to considerable economic and environmental damage. For instance, preliminary cost estimates for the Fukushima Dai-ichi accident range from 250 to 500 billion USD, not to mention that approximately 30,000

[1] The International Atomic Energy Agency designed the International Nuclear and Radiological Event Scale (INES) to explain the significance of nuclear or radiological events. Events are classed into seven levels, with each level taking into account the severity in three areas of impact: people and the environment, radiological barriers and control, and defense in depth. The scale is designed so that the severity of an event is about ten times greater for each new level on the scale. The most serious accident is rated 7 and is called a major nuclear accident.

km^2 of Japan's land surface was contaminated and more than 139,000 people had to be evacuated[2].

In case of an accident, nuclear operators are liable for all damages, even for those that are not directly caused by them. However, when the costs are as high as they are after a major nuclear accident, the operator does not internalize all of the damage done. In some countries, the nuclear operator's liability is limited by law, therefore if the damages exceed this limit the state has to pay for any harm that is not covered. However, even in countries with unlimited liability, it is possible that an operator will not possess sufficient assets to pay for the damages completely, and as a consequence society will have to bear part of risk.

The fact that nuclear operators might not completely internalize any harm they may inflict distorts their incentives for ensuring safety. This issue calls for ex ante regulation to correct this externality and attain higher safety levels. The under-provision of safety in presence of limited liability has been studied by Shavell (1984) and Kolstad et al. (1990). They showed that ex ante regulation (setting safety standards) improves welfare, in particular when the magnitude of harm is much greater than the injurer's assets (tacit limited liability) or when the parties shall not face the threat of lawsuit for any harm done (legal limited liability).

Concerning the above, it is not surprising that nuclear power is one of the most regulated industries in the world. Basically, all stages of nuclear power plant development (i.e. design, construction, operation, transport and use of radioactive material and decommissioning) are regulated by requirements and standards set by a safety regulatory agency, with the aim of reducing the risk of a nuclear accident. For instance, the US Nuclear Regulatory Commission requires that only noncombustible and heat resistant materials be used in the construction of a nuclear power plants containment and control room, in order to minimize the risk of fire and thereby the risk of accident.

Unfortunately, it took the devastating damages of the Fukushima Dai-ichi accident to act as a wake-up call of how important it is to have a competent and independent safety regulator. Following nuclear experts safety assessment of the accident, several scholars, such as Lévêque (2013) and Wang et al. (2013) concluded that the accident was the result of a regulatory failure and not a *black swan* as initially thought. The assessment revealed that the Japanese safety authority knew about the possibility of a tsunami waves exceeding 20 meters. Despite this information, the unit's sea walls were never back-fitted. For this reason, the credibility of the Japanese nuclear safety authority has

[2] See Schneider and Froggatt (2014) and `http://www.psr.org/environment-and-health/environmental-health-policy-institute/responses/costs-and-consequences-of-fukushima.html`

been severely questioned and regulatory capture has been suggested as the trigger of this tragedy. According to Gundersen (2012), the laxity of the Japanese regulator in enforcing safety standards was a key cause of this disaster.

In this context, safety regulation plays a decisive role, not only in maintaining a good record in terms of a low frequency of accidents, but also in the economics of nuclear power. On the one hand, safety authorities must determine and be able to enforce the acceptable risk level at which nuclear power plants should operate. On the other hand, safety regulators must keep in mind the cost for operators of complying to standards and rules in order to attain the envisioned risk level. Thus, regulators must identify standards that reduce the risk of a major accident, without compromising operator's profits.

Thus, the key question for a nuclear safety regulator is how to attain a sufficiently small probability of accident in a cost-effective manner. From an economic perspective, the answer is to set a standard that equates the marginal cost of providing safety with the marginal benefit of reducing the expected damages in case of accident. However, in the case of nuclear power, achieving this balance between costs and benefits is easy, due to the existence of several information-related problems.

First, the regulator cannot directly observe the operator's behavior (although this is not specific to nuclear power), therefore it is not possible to enforce the first best safety level at zero cost. As shown by Strand (1994) and Hiriart et al. (2004) in the presence of moral hazard, only second-best care levels are attained, and the only way to implement the first-best safety level is by heavily subsidizing the firm. Here, the challenge for nuclear safety authorities is to define a policy that induces compliance with the safety standards as the operator's optimal response. Compliance is a fundamental element in nuclear safety regulation, given that on the one hand, the safety authorities have to guarantee to the public that nuclear facilities run below the acceptable risk level and on the other, that their reputation and credibility will be severely damaged if non-compliance is widespread among operators.

The second informational problem present in nuclear safety regulation is the epistemic uncertainty regarding the probability of a major accident. Safety authorities cannot exactly determine the probability of a major nuclear accident based on the observed frequency. But even more importantly (for regulatory purposes), there is some uncertainty as to how safety care translates into a lower/higher probability of an accident. These factors result from the way in which nuclear reactors are designed. Nuclear power plants are complex: they have multiple safety systems, each with a backup, and they are designed to accommodate human error. This redundancy in the systems aims to control damage and prevent accidents and significant radioactive releases. Consequently, nuclear accidents are rare, making it difficult to measure the link between safety care and the risk of accident.

Considering the above, the main goal of this paper is to examine the features of an optimal safety regulatory policy for a nuclear operator that takes into account several particularities. First, in the case of a major nuclear accident, the operator is protected (tacitly or legally) by limited liability. In addition, the regulator cannot observe the safety care level chosen by the operator (moral hazard), thus the regulatory policy has to provide incentives to the operator to comply with it. Finally, there is epistemic uncertainty as to how safety care affects the probability of a nuclear accident.

The problem of a lack of incentives to provide safety care in the presence of limited liability has been studied by Shavell (1984), Kolstad et al. (1990) and Hansson and Skogh (1987). The provision of safety in presence of limited liability and moral hazard has been studied by Strand (1994) and Hiriart and Martimort (2004). Hiriart et al. (2004) also derived an optimal regulatory scheme in the presence of these two problems, as well as considering adverse selection.

One of the main features of these papers is that the regulator provides incentives to the firm through transfers that are state-contingent (i.e. accident/no accident). Nevertheless, this is not realistic in the case of nuclear power, because safety regulators cannot reward, at least not directly, operators in case of no accident. Broadly speaking, most of nuclear safety regulatory agencies are responsible for establishing legislative documents regarding nuclear safety and supervising activities on nuclear installations. For this reason, we prefer to model this situation as a compliance monitoring problem. In the literature, a general model was proposed by Becker (1968) and has since been extensively used afterwards to study environmental regulation (see Cohen (1998) for an extensive review). Our model is close to that put forward by Arguedas (2008). In this model, the regulator sets a safety standard and then, in order to provide incentives to comply with it, randomly inspects firms and is able to threaten operators with fines.

To tackle the problem of the uncertainty of how safety care reduces the probability of accident, the nuclear industry has come up with a procedure called Probabilistic Risk Assessment (PRA)[3]. This assessment employs a set of assumptions about the probability of events that may induce a core melt, as well as about the failure of each component and the back-up systems, and uses them to compute the core damage frequency (CDF). The CDF tells us (theoretically) how long the reactor will run before undergoing at least one core melt.

[3] The first PRA assessment carried out in the US is known as the WASH-1400 report. This study was done by Norman Rasmussen for the Nuclear Regulatory Commission, and concluded that the average CDF was equal to 5E-05 with an upper bound of 3E-04

The PRA identifies the main sources of risks and makes it possible to rank safety investments, according to their effectiveness in reducing CDF. In addition, CDF is a metric that the regulator can use to compare and monitor nuclear operators. Nevertheless, CDF is itself a random variable and unfortunately PRA assessments do not derive its distribution function; at most they determine the interval within which this parameter belongs. In summary, it is possible to claim that PRA gives the safety regulator some information regarding how safety care can reduce the probability of accident, but uncertainty remains.

This last feature means that although nuclear regulators do not possess a single precise probability measure when setting the safety standards, they at least have access to some information (i.e. an interval of values coming from the PRA) on the link between safety care and the probability of an accident. To capture this element in our model, we propose to use the concept of imprecise (interval) probabilities as in Aven and Hiriart (2013). In their paper, they studied safety care investments from the firm's perspective using two robust optimization concepts, i.e. worst-case and regret robustness. In our paper, we also use these approaches, but we assume that the operator has perfect information regarding its efficiency in reducing the probability of an accident. We can therefore focus our attention on how uncertainty affects the safety regulatory policies.

Our results suggest that when a nuclear safety regulator is conservative and seeks to minimize the expected social costs in the worst possible scenario, then safety standards will be less stringent and nuclear facilities will be inspected more often. Both results are derived from the fact that the regulator is pessimistic as to how safety care can reduce the probability of an accident. In the second approach, the regulator considers the possibility that it may be wrong in its beliefs regarding safety care effectiveness, and it attempts to minimize the biggest mistake that it may regret. In this case, safety standards will be stricter. Nevertheless, the risk of no compliance increases if the cost of the standard is too high for the operator.

In summary, the optimal regulatory policy subject to uncertainty of how safety care reduces the probability of accident will always imply a residual risk for society. In the worst-case approach, the regulator can guarantee that all nuclear facilities will comply with safety standards; however the safety standard corresponds to the lowest possible bound. This means that if a regulator is not as pessimistic as in the above case, it might be possible to enforce a stricter standard and further reduce the probability of accident. In this case, society bears the risk associated with the difference between the probability of an accident defined by the standard, and the probability that would be attained by inducing the compliance of the least efficient operator.

In the second case, when the regulator seeks to minimize the largest mistake, it sets a stricter standard. However, it cannot guarantee that all operators will operate below that risk level, given that some operators may prefer to pay a fine rather than comply with the standard. In this case, the risk that society has to bear depends not only on the difference between the standard and the least efficient operator, but also on how many operators cannot comply with the standard.

The rest of this paper is organized as follows. Section 4.2 presents the model and characterizes the optimal regulatory policy when moral hazard is the only issue. In Section 4.3, we assume that only the regulator does not perfectly know how safety care level reduces the probability of an accident, and we explore the optimal regulatory policy using two robust optimization approaches, i.e. worst-case and regret robustness. Finally, Section 4.4 concludes.

4.2 The Model

We consider a nuclear operator that may provoke an accident that would harm third-parties and/or the environment. In particular, we are interested in major nuclear accidents, mainly because in this case firms are unable to pay for the totality of the damage. When a firm does not completely internalize the harm that it produces, this is often represented with a limited liability constraint. In our case, we simply assume that, either tacitly or legally, the nuclear operator just pays only a fraction $\gamma \in (0, 1)$ of the total damage in case of accident. The accident damage is denoted by D.

The nuclear operator can exert a level of safety care that reduces the probability of a major accident. We are going to assume that the probability of an accident is given by the function $\alpha - \beta e$[4]. Where $e \in [0, 1]$ corresponds to the nuclear operator's safety care and the parameters α and β satisfy $1 \geqslant \alpha > \beta > 0$.

Note that the probability of an accident decreases linearly as safety care increases at a rate β. This parameter captures the firm's efficiency in reducing the probability of an accident while the reactor is in operation. If β is low, the operator's leeway to prevent an accident is reduced, meaning that the risks are strongly linked to the design itself. If β is high, it means that the main hazards are likely to arise during operation, and thus the safety care that the operator exerts is important to prevent a nuclear accident.

Note also, that even when the operator exerts no safety care $e = 0$, there is a positive probability of no accident $1 - \alpha$. For this reason, α could reflect the ex ante safety level that is guaranteed by the nuclear vendor before the reactor starts to operate, or the

[4] And the probability of no accident will be $(1 - \alpha + \beta e)$

minimum accepted risk that is ex ante required to obtain a license to operate a nuclear reactor.

We assume that the cost of safety care is given by $c(e)$, which satisfies the following conditions: $c'(e) > 0$, $c''(e) > 0$ and $c(0) = 0$. In the absence of safety regulation, if an operator seeks to minimize the expected cost given by $c(e) + (\alpha - \beta e)\gamma D$, the solution satisfies the following first order condition:

$$c'(e^{ps}) - \beta\gamma D = 0 \tag{4.1}$$

The private optimum safety care level e^{ps} equates the marginal cost of care with the marginal benefit of reducing the expected harm in case of accident. This safety care level differs from the first best outcome e^{fb} that is given by $c'(e^{fb}) - \beta D = 0$, due to the operator's limited liability. The lower the fraction γ, which is the share of the damages that the operator internalizes, the greater the difference between the private and social safety care levels. This gap arises because the marginal benefit of avoiding an accident is lower for the firm than for the society.

The difference between the optimal levels of safety care e^{ps} and e^{fb} has been identified in the literature as the one of the main reasons for using ex-ante regulation to complement the incentive to exert safety care created by liability rules (see Shavell (1984), Kolstad et al. (1990)). However, it has also been recognized that using safety regulation to reduce the risk of hazardous activities involves information asymmetries. In particular, the literature has focused on moral hazard arising because the regulator cannot directly observe the safety care level e chosen by the operator[5]. This problem is solved by allowing state-contingent transfers (i.e. accident / no accident). In general, the second-best policy requires giving a moral hazard rent to the firm in order to induce a given safety care level.

In our model, the regulator also provides incentives to the operator through transfers, however they are only feasible in one direction (from the firm to the regulator). This means that we opt for a monitoring and punishment scheme, which is a restricted set of general incentive schemes. We consider that this is a better setting for nuclear power, given that the mission of most nuclear safety authorities worldwide is to establish all the legislative documents to guarantee that nuclear power plants are designed, constructed, operated and decommissioned without jeopardizing public health (i.e. define safety standards). In addition, safety authorities should perform inspection activities on nuclear installations to verify that they comply with relevant legislation (i.e. monitoring).

[5] See Strand (1994), Hiriart and Martimort (2004), Hiriart et al. (2004), Hiriart et al. (2006)

Taking into account the above, we decided to follow the model in Arguedas (2008). In our model, the regulator defines a safety standard denoted by s. Given that it is not possible to observe directly whether operators are in compliance, the regulator inspects nuclear facilities with probability q and each inspection has a unit cost equal to m. If it is found that the safety care selected by an operator is below the standard ($e < s$), the regulator can impose a fixed penalty F_0. If it is found that ($e \geqslant s$) no penalty is imposed.

The safety standard s stands for the compendium of all regulatory requirements that are mandatory for the operator. These rules are conceived by the regulator and are considered essential to ensure the safe operation of nuclear power plants. In other words, the safety standard includes an overall review of how an operator should conduct its activities in order to perform effectively and prevent a serious accident.

Regarding the probability of inspection q, this can represent either; that the regulator visits all facilities but cannot perfectly detect whether an operator is complying with the standard (measurement errors), or even if the detection of no compliance is perfect, the regulatory agency's resources are limited and so only a fraction q of the facilities are inspected.

Finally, the fine F_0 represents all of the legal measures that the regulator possesses to deter non-compliance and that are costly for the firm[6]. We assume a fixed penalty because in practice, fines for nuclear operators are defined ex ante and do not depend on the degree of non-compliance, but rather on the fact that the violation has been detected.

Thus, for a given a policy $\{s, q\}$ the expected cost for the operator depends on its whether or not to comply with the safety standard.

$$C(s,q) \begin{cases} c(s) + (\alpha - \beta s)\gamma D & \text{if compliance} \\ c(e) + (\alpha - \beta e)\gamma D + (1 - \alpha + \beta e) q F_0 & \text{if non-compliance} \end{cases} \tag{4.2}$$

Note that the operator can only be punished with a fine in case of no accident, which occurs with probability $(1 - \alpha + \beta e)$. If there is an accident, it will not pay a fine but it will have to compensate for the harm caused by the accident. Given that he it protected with limited liability, the operator will pay γD, however this amount is greater than the fine ($\gamma D > F_0$)

6 For instance, the Canadian Nuclear Safety Commission can in addition to the ability of imposing a administrative monetary penalty, it is also enabled to remove the operation certificate or to undertake a licensed activity and to lay charges against an operator in accordance with the legislation. See http://www.nuclearsafety.gc.ca/eng/acts-and-regulations/compliance-verification-and-enforcement/index.cfm#sec2-8

As mentioned above, nuclear regulators do not exactly know how the operators' safety care level reduces the probability of a serious accident, precisely because both the reactor and the plant are conceived to prevent these events. The design of a nuclear facility is based on the concept of *defense in depth*, whereby if any component fails, a successive chain of back-up systems kicks in to prevent core damage and reduce the risk of releasing radioactive material. This redundancy in the systems as well as the individual characteristics of each operator (i.e. specificities of the site, workers, type of reactor, etc) makes it very difficult for the regulator to identify a single value for β.

For the above, we assume that the regulator does not know the exact value of this parameter, but it does know that it belongs to an interval $\left[\underline{\beta}, \overline{\beta}\right]$, while β is perfectly known by the firm. Both agents know the value of the parameter α. This last part of the model has been introduced in order to study the effect of uncertainty on how safety care reduces the risk of a serious accident in the regulatory policy.

To exemplify our setting, we can consider that the regulatory agency requires that pumps and valves are tested a certain number of times during the year. In this case, the standard s corresponds to the test's frequency, while e is the effective number of tests that the operator carries out during a given year. If the test's frequency is lower than required, it may be less likely to detect failures in the pumps and valves, thus increasing the probability of accident. To check whether an operator has carried out the test as often as required, the regulator must inspect the plant. However, it is difficult for the regulator to quantify how much the probability of an accident will increase if tests are done less frequently.

All of these elements further complicate the problem of setting optimal standards for nuclear safety authorities. On the one hand, authorities need to deal with the moral hazard problem when setting the rules, and on the other, with uncertainty as to how safety care reduces the probability of a serious accident. Taking into account all of these elements, the problem that the regulator has to solve is the following:

$$\begin{aligned} \min_{s,q} \quad & c(e) + (\alpha - \beta_{reg} e)D + (1 - \alpha + \beta_{reg} e)q\left[m + F_0\right] \\ \text{s.t} \quad & e = e(s, q) \end{aligned} \tag{4.3}$$

Where $\beta_{reg} \in \left[\underline{\beta}, \bar{\beta}\right]$ is the interval in which the regulator thinks the true β lies. And $e = e(s, q)$ corresponds to the operator's best response function to a given regulatory policy $\{s, q\}$.

4.2.1 Benchmark: The regulator knows β

As a useful benchmark, we compute the optimal policy assuming that the regulator knows β. We proceed by backward induction. First, we find the optimal response of the firm to a given policy $\{s, q\}$ and then we solve the problem of the regulatory agency.

Given that the penalty F_0 introduces a discontinuity in the expected cost function for all the values that are lower than the standard ($e < s$), intuitively the operator proceeds as follows. First, it solves the problem in Equation (4.4) as if it had decided not to comply. Second, it compares the expected cost of this solution with the cost of complying with the safety standard. Finally, it decides to exert the safety care level that represents the cheapest alternative.

$$\min_{e \geqslant 0} \quad c(e) + (\alpha - \beta e)\gamma D + (1 - \alpha + \beta e)qF_0 \tag{4.4}$$

For a given policy $\{s, q\}$ the firm's best response $e(s, q)$ can be decomposed in three cases. The first one corresponds to the case in which the firm *over-complies* ($e(s, q) > s$). This case arises when the safety standard is so low that the operator prefers to increase its safety care level to minimize the expected costs of an accident. This solution is equivalent to an absence of regulation, therefore the operator will choose e^{ps}, i.e. the private optimal safety care level.

In the second case, the firm *complies* with the standard ($e(s, q) = s$). Here, the safety care level that minimizes the operator's cost is the standard, because the threat of penalties increases the cost of lower safety care levels. The last case corresponds to a situation in which the operator optimally does *not comply* ($e(s, q) < s$). In this scenario, the standard is so costly that the firm prefers to pay the expected fine rather than the cost of the safety care level that the regulator wants to enforce.

Figure 4.1 illustrates these three possible cases taking a numerical example[7]. In each panel the horizontal axis shows the possible values for safety care e and safety standard s. The vertical axis gives the values of the expected cost function. We consider three different safety standards ($s = 0.1$, $s = 0.6$, $s = 0.85$) and the same probability of inspection ($q = 0.5$).

The first panel illustrates the case of *overcompliance*. Here, we assume a low standard (i.e. $s = 0.1$) in which case it is optimal for the firm to choose a higher safety care level. In the second case, (i.e. $s = 0.6$), the threat of a fine is effective to induce compliance,

[7] We considered a quadratic cost function and the following values for the parameters: $D = 2$, $\gamma = 0.6$, $\beta = 0.8$, $\alpha = 1$, $F_0 = 0.2$ and $q = 0.5$

as we can see in the second panel of the figure; all of the safety care levels below the standard have a higher expected cost, thus the standard is the level that minimizes the costs. In the final case, it is too costly for the firm to comply with the standard (i.e. $s = 0.85$). In this case, the firm's best response is to choose a lower level of safety care, denoted by n.

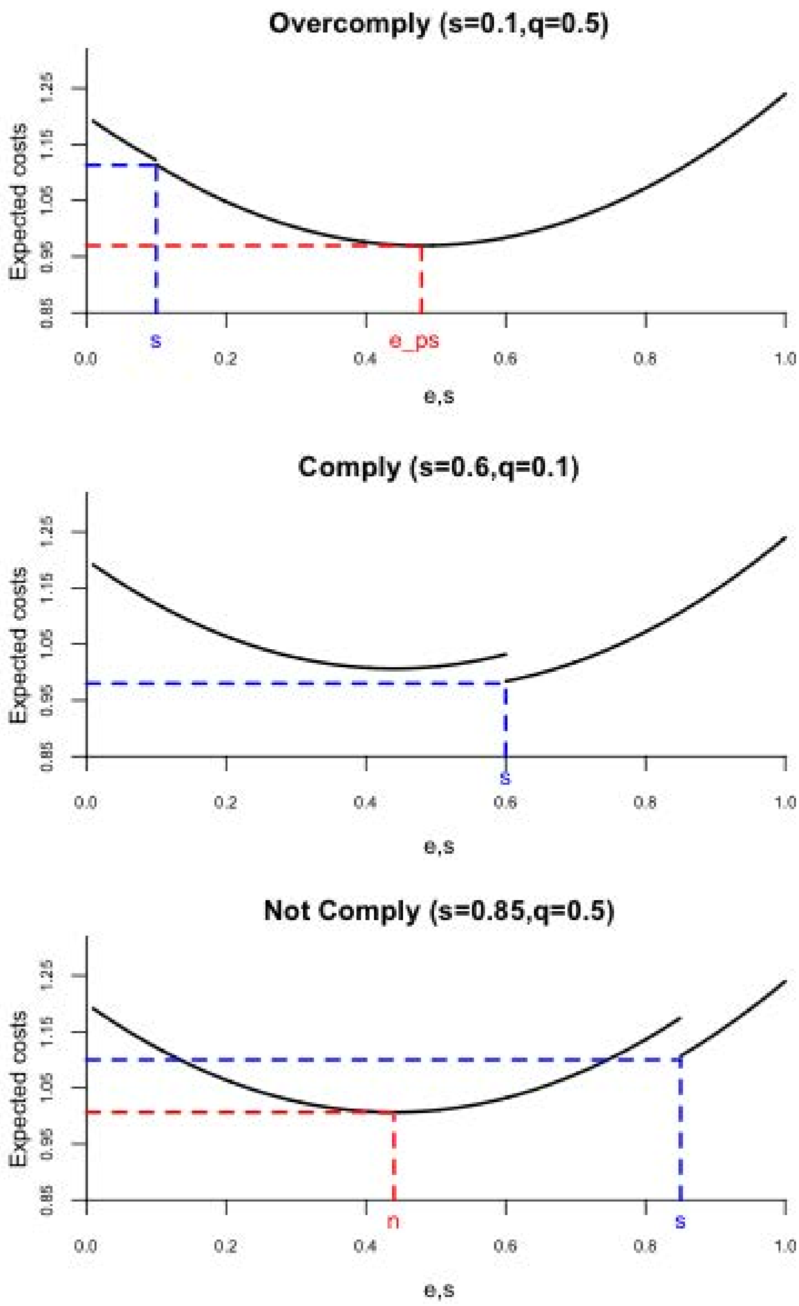

FIGURE 4.1: Operator's best response to different regulatory policies (s,q)

The solution to the firm's problem is summarized in the next proposition, the complete proof is presented in Appendix F.

Proposition 1 *Given the policy $\{s, q\}$, the nuclear operator's optimal response is:*

$$e(s,q) = \begin{cases} e^{ps} & \text{if } c'(s) - \beta\gamma D - \beta q F_0 \leqslant 0 \\ s & \text{if } c'(s) - \beta\gamma D - \beta q F_0 \geqslant 0 \text{ and } c(s) - c(n) - \beta\gamma D(s-n) \geqslant q(1-\alpha+\beta n)F_0 \\ n & \text{if } c'(s) - \beta\gamma D - \beta q F_0 \geqslant 0 \text{ and } c(s) - c(n) - \beta\gamma D(s-n) < q(1-\alpha+\beta n)F_0 \end{cases} \tag{4.5}$$

Where n satisfies the following condition:

$$c'(n) - \beta(\gamma D - qF_0) = 0 \tag{4.6}$$

The previous proposition can be understood as follows. The operator observes the regulatory policy $\{s, q\}$, then it evaluates the first order condition of compliance, with the standard at its inferior limit, to check if it is optimal to reduce safety care marginally. If the operator observes that this optimality condition is negative (first case), it means that the marginal benefit of avoiding an accident is greater than the marginal cost of the standard, and it is preferable to increase safety care. In this case the firm will *over-comply* and exert the private optimal safety effort e_{ps}.

On the contrary, when the first order condition is positive or equal to zero, this means that there is no incentive to marginally increase safety care because it is too costly. In this case, the operator simply compares the total expected cost of complying with that of not complying and then decides. If complying with the standard is more costly, the operator will choose a safety care level n lower than the standard s.

It is important to remark, first, that the safety care level n will be lower than the level which would be chosen in the absence of regulation e^{ps}, due to the fact that the operator may be punished even if no accident is observed, which reduces even further the marginal benefit of avoiding an accident. Second, n depends on the probability of inspection q. If we implicitly differentiate n from Equation (4.6) with respect to this instrument, we get $\frac{\partial n}{\partial q} = \frac{-\beta F_0}{c''(n)} < 0$

This derivative tells us that, conditional on non-compliance, a higher probability of inspection q reduces the gap between the expected costs in case of accident γD and in case of no accident qF_0, hence the level of safety effort n will be lower. Although this effect mat appear as counterintuitive, it is not, if we consider that the overall incentive of a higher q is that it increases the incentives to comply.

Once we have found the optimal response of the firm $e(s, q)$, we proceed to solve the regulator's problem. Here, it is important to mention that the task that society has given to safety regulators is to guarantee that nuclear power plants operate below a maximum accepted risk level, which should be attainable by complying with the safety rules. For this reason, the regulator seeks only to set policies $\{s, q\}$ that induce compliance. This means that the regulatory policy has to ensure that the operator's best response is to comply with the standard (i.e. $e(s,p) = s$). Therefore, the pair $\{s, q\}$ should be such that the expected costs of choosing safety care n are higher than those of complying with s. In general, the problem the safety authority solves is the following:

$$\begin{aligned} \min_{s,q} \quad & c(s) + (\alpha - \beta s)D + q(1 - \alpha + \beta s)m \\ \text{s.t} \quad & q = q_c(s) \end{aligned} \tag{4.7}$$

The objective function corresponds to the expected social cost when the firm complies with the safety standard. To be sure that $e(s,q) = s$ we need to satisfy the conditions of the second case in Equation (4.5). This is captured in the constraint denoted with $q_c(s)$ that defines the equation of the possible monitoring probabilities q that will induce compliance for a given standard s. The values of the pairs $\{s, q\}$ in equation $q_c(s)$ should satisfy the following implicit condition:

$$c(s) - c(n) - \beta\gamma D(s - n) - q(1 - \alpha + \beta n)F_0 = 0 \tag{4.8}$$

Given that monitoring is costly, we discard the policies $\{s, q\}$ that the firm strictly prefers to comply (i.e. Equation (4.8) less than 0) and focus on those that satisfy the last condition with strict equality.

If we differentiate this last constraint with respect to the available tools s and q, we ascertain how the probability of monitoring q should change to induce compliance when standard s is changed. In short we compute $\frac{\partial q}{\partial s} = \frac{c'(s) - \beta\gamma D}{(1-\alpha+\beta n)F_0} > 0$. This last result is quite intuitive; it tells us that higher standards require higher monitoring probabilities to induce compliance, whereas lower standards are easier to enforce, in the sense that they need less frequent inspections.

Now we can proceed to find the optimal policy $\{s^*, q^*\}$ that the regulator will set when it perfectly knows the value of β. The solution is summarized in the next proposition.

Proposition 2 *The optimal policy $\{s^*, q^*\}$ that induces compliance is given by the following conditions:*

$$c'(s^*) - \beta D + \frac{\partial q_c(s^*)}{\partial s}(1 - \alpha + \beta s^*)m + q_c(s^*)\beta m = 0 \tag{4.9}$$

$$q^* = q_c(s^*) \tag{4.10}$$

The solution given in Equations (4.9) and (4.10) shows that the safety level that the regulator can effectively enforce is lower than the first best outcome. The presence of moral hazard imposes the social cost of monitoring in order to enforce a safety standard.

4.3 Imprecise probabilities and robust optimization

In this section, we analyze the properties of an optimal regulatory policy subject to uncertainty about the parameter β. As we mentioned previously, the safety authority does not know the exact value of β, nevertheless, it knows that this parameter belongs to an interval $[\underline{\beta}, \bar{\beta}]$. As a reminder, if the operator knows the value of β, then its best response is still given by Proposition 1. In this situation, the problem for the regulator is the following:

$$\begin{aligned} \min_{s,q} \quad & c(s) + (\alpha - \beta_{reg} s)D + q(1 - \alpha + \beta_{reg} s)m \\ \text{s.t} \quad & q = q_c(s) \end{aligned} \tag{4.11}$$

Where $\beta_{reg} \in \left[\underline{\beta}, \bar{\beta}\right]$.

This problem can be solved using robust optimization techniques. This methodology makes it possible to assess optimization problems in which the data is uncertain and when we only know that the parameters belong to a set. The main purpose is to find a solution that gives an acceptable performance under most realizations of the uncertain parameters. In this paper we use two approaches to solve the problem, i.e. worst-case approach and regret robustness.

4.3.1 Worst-case approach

The objective of the safety regulator in this first case is to find the optimal policy in the worst-case of all possible scenarios. In the economic literature, this optimization criterion can be compared to the maxmin expected utility proposed by Gilboa and Schmeidler (1989).

For our particular problem, the worst case corresponds to a situation in which the regulator considers the value of β_{reg} that leads to the highest total expected cost. Formally, the regulator's problem can be stated as follows:

$$\begin{aligned}
\min_{s,q} \quad \sup_{\beta} \quad & \{c(s) + (\alpha - \beta_{reg}s)D + q(1 - \alpha + \beta_{reg}s)m\} \\
\text{s.t} \quad & q = q_c(s) \\
& \beta_{reg} \in [\underline{\beta}, \bar{\beta}]
\end{aligned} \tag{4.12}$$

Using the expected cost equation, we find that $\frac{\partial EC}{\partial \beta_{reg}} = -s(D - qm)$. Given that we are interested in major nuclear accidents, we can argue that the cost of the damages D is greater than the total cost of inspections qm. For this reason, we claim that this derivate is negative, therefore the social expected costs are inversely related to the value of β.

This means that the highest expected cost (i.e. the worst-case) over the possible values of β_{reg} is attained with the lowest value in the interval, that it is equal to $\underline{\beta}$. The rationale behind this idea is that the worst case that the regulator can envisage is when safety care does not effectively reduce the probability of a major accident. In other words, the regulator thinks that hazards are a result of the design rather than the operator's behavior.

To see how the optimal policy differs from the policy with no uncertainty in the parameter β, we only need to check how the conditions in Equations (4.9) and (4.10) change with respect to this parameter.

Let us first see how the safety standard s changes in the worst-case approach with respect to the benchmark case. We use the first order condition in Equation (4.9) and compute $\frac{\partial s}{\partial \beta}$. We find the following expression:

$$\frac{\partial s}{\partial \beta} = \frac{D - \left[\frac{\partial q_c(s)}{\partial s} s + q\right] m}{c''(s) + m\left[\frac{\partial^2 q_c}{\partial s^2}(1 - \alpha + \beta s) + 2s\frac{\partial q_c}{\partial s}\right] m} > 0 \tag{4.13}$$

This result tells us that the regulator will be cautious when setting the standard taking worst-case approach. We know that the expected social costs will be a function of the lowest possible value of β_{reg}, that is $\underline{\beta}$. Thus the positive derivate in Equation (4.13) means that the safety standard will be the lowest possible when adopting the worst case approach. This corresponds to the least stringent safety standard, denoted by s_{wc}. The overall probability of an accident that the regulator can guarantee is given by $\alpha - \underline{\beta} s_{wc}$.

This conservatism regarding the safety standard is due to the fact that in taking the worst-case approach, the regulator might be underestimating the effect that safety care has in reducing the probability of accident.

We can now consider the probability of an inspection in the worst-case approach, if the regulator would wants to enforce a given fixed safety standard s. This entails computing $\frac{\partial q_c}{\partial \beta}$.

$$\frac{\partial q_c}{\partial \beta} = -\frac{\gamma D(s-n) + qnF_0}{(1-\alpha+\beta n)F_0} < 0 \tag{4.14}$$

This derivate shows how the regulator modifies the probability of inspection when his belief about β changes. This equation shows that the regulator weighs the incentives that he has to give to the operator in order to induce compliance against the potential amount of money that is not being collected through fines. The fact that this derivate is negative indicates that in the worst-case approach, the regulator has to be more vigilant. For instance, to enforce s^* he would have inspected more often than in the benchmark case.

These results are two sides of the same coin. Since the regulator is pessimistic and considers that the operator's safety care is not very effective in reducing the risk of accident (i.e. $\underline{\beta}$), the standard will not be very strict. However, this also implies that it underestimates the operators' incentives to exert safety care, or the operators' marginal benefit of safety care. As a consequence, it will increase the monitoring frequency in order to induce compliance.

However, note that the probability of inspection to induce compliance in the worst-case approach $q_c(s_{wc})$, is also determined by s_{wc} which we know to be lower than in the benchmark case, thus it will also be lower.

The results that we obtain using the worst-case approach explain why some nuclear safety authorities have invested in properly assessing the most effective ways in which a nuclear operator can reduce the probability of nuclear accident. It is likely that with experience[8] regulators have succeeding in gathering better information about β and that they have realized that the operators' safety care levels have an important effect in reducing the likelihood of a serious accident.

A good example of how nuclear regulators have improved their knowledge of how safety care translates into a lower probability of nuclear accident is the continuous improvements in PRA techniques. PRA's have been preformed repeatedly in nuclear facilities in order to identify the main sources of probable equipment failure that can result in core damage. PRA studies have allowed nuclear operators to efficiently allocate their safety investments and therefore effectively reduce the likelihood of a serious accident.

[8] For instance David et al. (1996) showed that thanks to the lessons learnt after the Three Mile Island accident, that the standards and rules set by Nuclear Regulatory Commission led to substantial reductions in the risk of unplanned outages

These improvements have also allowed nuclear regulators to set stricter safety standards because with the PRA updates have revealed that the marginal benefit of safety care is higher than their initial expectations.

4.3.2 Regret robustness approach

The second criterion that we use in this paper is known as the *regret robustness approach* or *min-max regret criterion*. In economic literature, this approach can be compared with that taken byLinhart and Radner (1989).

In our setting, the *min-max regret criterion* means that the regulator's objective is to minimize the maximum difference between the objective function and its best possible value. In other words, the regulator wants to identify the value of β_{reg} for which it can make the largest mistake (in terms of social costs) and then choose the regulatory policy $\{s, q_c(s)\}$ that minimizes the costs on that particular case.

Intuitively, we can say that there are two types of mistake that the regulator will regret. The first type of error arises when it sets a standard higher than the optimal one ($s > s^*$) because it selects a high value of β_{reg}, when the real β is low. In this case, the standard is not only too costly but also ineffective to reduce the probability of accident.

The second type of error arises when the regulator sets a low safety standard. In this case, the regulator selects a low β_{reg}, for instance like in the worst-case approach ($\beta_{reg} = \underline{\beta}$), when in reality safety care can significantly reduce the probability of a serious accident (i.e. high real value of β). In this case, the inefficiency arises because the marginal cost of increasing safety care is lower than the marginal benefit. In addition, society is unnecessarily exposed to a greater risk of major nuclear accident.

To solve this problem, the regulator proceeds in several steps. First, for each $\beta_{reg} \in [\underline{\beta}, \bar{\beta}]$ it determines the optimal policy $\{s^*(\beta_{reg}), q_c(s^*(\beta_{reg}), \beta_{reg})\}$ and then computes $EC^*(\beta_{reg})$, which corresponds to the minimum expected social costs for each β_{reg}. This minimum expected cost function is given by following equation:

$$EC^*(\beta_{reg}) = c\big(s^*(_{\beta_{reg}})\big) + \big(\alpha - \beta_{reg} s^*(_{\beta_{reg}})\big)D + \big(1 - \alpha + \beta_{reg} s^*(_{\beta_{reg}})\big)q_c(s^*(_{\beta_{reg}}), \beta_{reg})m \tag{4.15}$$

Second, it considers all the possible compliance-inducing policies $\{s, q_c(s, \hat{\beta})\}$, for all the possible values of $\hat{\beta}$ that also belongs to $[\underline{\beta}, \bar{\beta}]$. Here it is important to note that the probability of inspection, which induces compliance to a certain standard s, will change according to the value of β that the regulator thinks is the real one. Here we have denoted by $\hat{\beta}$ the value that the regulator uses to compute the compliance-inducing policy, which might differ from the real one. The expected cost function for these compliance-inducing policies is given by:

$$EC(s, q_c(s, \hat{\beta}), \beta_{reg}) = c(s) + (\alpha - \beta_{reg} s)D + (1 - \alpha + \beta_{reg} s) q_c(s, \hat{\beta}) m \tag{4.16}$$

In the next step, the regulator computes the regret function, denoted by $R(s, q_c(s, \hat{\beta}), \beta_{reg})$ to measure the gap between these two last equations and determine the values of β_{reg} and $\hat{\beta}$ that maximize this difference. Finally, it selects the regulatory policy that minimizes the costs in that particular case. The problem that the regulator solves under the *regret robustness* approach is the following:

$$\begin{aligned} &\min_{s} \quad \sup_{\beta_{reg}, \hat{\beta}} \quad && R(s, q_c(s, \hat{\beta}), \beta_{reg}) = EC(s, q_c(s, \hat{\beta}), \beta_{reg}) - EC^*(\beta_{reg}) \\ &\text{s.t} && \beta_{reg}, \hat{\beta} \in \left[\underline{\beta}, \bar{\beta}\right] \end{aligned} \tag{4.17}$$

Note that when $\hat{\beta} = \beta_{reg}$ the regret will be minimized by setting the optimal policy $\{s^*(\beta_{reg}), q_c(s^*(\beta_{reg}), \beta_{reg})\}$ (i.e. the regret will be zero).

If we differentiate the regret function with respect to $\hat{\beta}$ and β_{reg} we obtain the following:

$$\frac{\partial R(s, q_c(s, \hat{\beta}), \beta_{reg}}{\partial \hat{\beta}} = (1 - \alpha + \beta_{reg} s) m \frac{\partial q_c(s, \hat{\beta})}{\partial \hat{\beta}} < 0 \tag{4.18}$$

$$\begin{aligned} \frac{\partial R(s, q_c(s, \hat{\beta}), \beta_{reg})}{\partial \beta_{reg}} =& D[s^*(_{\beta_{reg}}) - s] - m[s^*(\beta_{reg}) q_c(s^*(_{\beta_{reg}}), \beta_{reg}) - s q_c(s, \hat{\beta})] \\ & - (1 - \alpha + \beta_{reg} s^*(_{\beta_{reg}})) m \frac{\partial q_c}{\partial \beta_{reg}} \end{aligned} \tag{4.19}$$

The sign of the derivate with respect to $\hat{\beta}$ is negative and indicates, as we have already seen in the worst-case approach, that the highest expected costs are reached when safety care is not effective in reducing the probability of accident, which means a low value for β. In our case this means that $\hat{\beta} = \underline{\beta}$.

The sign of the derivate of the regret function with respect to β_{reg} will depend on the mistake that the regulator makes. When it is very optimistic and thinks that the real β is very high, the standard it sets may be greater than the optimal one (i.e. error type 1). If this error predominates, the first term will be negative and, given the high magnitude of D, we could argue that the derivative is negative. In that case, the *regret robustness* problem boils down to the worst-case approach because the biggest mistake that the regulator will regret varies inversely with the value of β_{reg}, therefore the value that maximizes the regret will be $\underline{\beta}$.

However, when the regulator wants to avoid setting a standard lower than the optimal one ($s^*(\beta_{reg}) > s$), it will focus on a case in which the derivative in Equation (4.19) is positive. Therefore, when a type 2 error predominates, the mistake that the regulator will regret the most is having set a policy under the assumption that safety care is not effective in reducing the probability of an accident ($\hat{\beta} = \underline{\beta}$), when in reality it is ($\beta_{reg} = \bar{\beta}$).

We now study the regulatory policy that minimizes the regret function in this last scenario, i.e. with values of $\beta_{reg} = \bar{\beta}$ and $\hat{\beta} = \underline{\beta}$. The optimal standard when applying *regret robustness*, is denoted by (s_{rr}) and satisfies the following first order condition:

$$c'(s_{rr}) - \bar{\beta}D + \bar{\beta}q_c(s_{rr}, \underline{\beta})m + (1 - \alpha + \bar{\beta}s_{rr})m\frac{\partial q_c(s_{rr}, \underline{\beta})}{\partial s} = 0 \tag{4.20}$$

In the worst-case approach, the optimal safety standard which we denoted by s_{wc} satisfies the same first order condition given in Equation (4.20), but the regulator does not consider the possibility of error, therefore instead of $\bar{\beta}$ we have $\underline{\beta}$ as follows:

$$c'(s_{wc}) - \underline{\beta}D + \underline{\beta}q_c(s_{wc}, \underline{\beta})m + (1 - \alpha + \underline{\beta}s_{wc})m\frac{\partial q_c(s_{wc}, \underline{\beta})}{\partial s} = 0 \tag{4.21}$$

Taking these two first order conditions, we could conclude that the optimal standard that a safety regulator will set taking a *regret robustness* approach is stricter than the one it would set when adopting a worst-case scenario, but lower than the one that it would set when assuming that it does not make mistakes, i.e. both $\beta_{reg} = \hat{\beta} = \bar{\beta}$. In Figure (4.2), we plot the difference between s_{rr} and s_{wc} as well the standard that the regulator would set under this "best scenario" ($\beta_{reg} = \hat{\beta} = \bar{\beta}$) and is denoted by $s_{\bar{\beta}}$[9].

Although at first glance the regulatory policy under *regret robustness* seems better than the worst-case approach, it is important to point out that this regulatory policy also has its drawbacks. In this case, there is a risk of non-compliance if the real value of β is low enough. Remember that the operator compares the net benefit of complying with the expected penalty if it does not comply but, unlike the regulator, it knows the true value

[9] In this numerical example, we consider again a quadratic cost function and the following value for the parameters: $D = 2$, $\gamma = 0.6$, $\underline{\beta} = 0.8$,$\bar{\beta} = 0.88$, $\alpha = 1$ and $F_0 = 0.2$

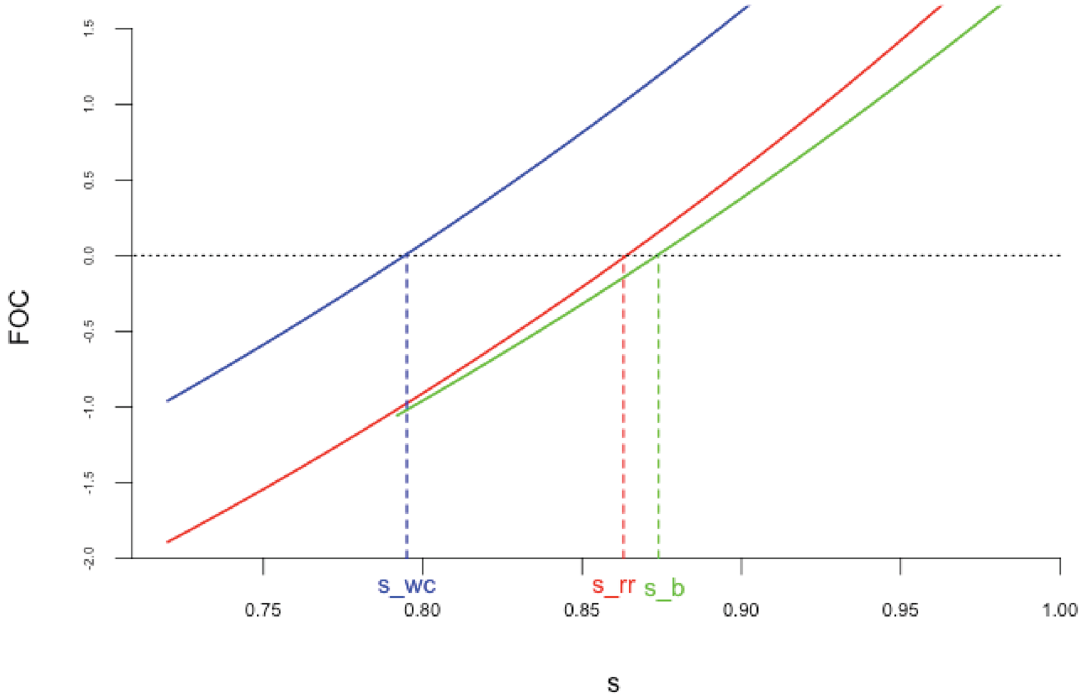

FIGURE 4.2: Difference in the safety standards set taking worst-case and regret robustness approaches

of β. Thus, when the marginal benefit of safety care for the firm is low (i.e. low β) a regulatory policy that entails a high standard makes non-compliance more attractive.

The risk of non-compliance highlights the potential drawbacks that a nuclear safety regulator has to deal with when applying *regret robustness* criterion. This issue becomes more relevant when the interval in which β should lie is wide. Contrary to the worst-case criterion, where only the level of $\underline{\beta}$ is important to define the maximum acceptable probability of an accident, when taking a regret robustness approach, the regulator is concerned with the length of the interval. This is because the wider the interval, the more likely it is that the regulator will set standards that nuclear operators will not comply with. Hence, it is not possible for a regulator to completely ensure that the maximum probability of an accident is $\alpha - \bar{\beta}s_{rr}$.

This latter issue is particularly relevant when the regulator has to set an uniform safety policy for a heterogeneous nuclear fleet. If we consider k nuclear operators, each of which is characterized by a different $\beta_k \in [\underline{\beta}, \bar{\beta}]$. Under the worst-case approach, the regulator can be sure that all operators will comply because the standard is determined by the least efficient operator ($\underline{\beta}$).

With the regulatory policy set under *regret robustness* $\{s_{rr}, q_c(s_{rr})\}$, it is possible to determine a marginal operator which is indifferent to whether it complies with the standard or not. If we denote the efficiency of reducing the probably of an accident by this marginal operator when applying the *regret robustness* with $\hat{\beta}$, we can argue that for the operators that are less efficient than this marginal operator (i.e. $\beta_k < \hat{\beta}$) is optimal not to comply with the standard.

4.4 Conclusion

We have developed a model to study the effect of uncertainty regarding the probability of nuclear accident when a regulator has to set a safety standard subject to both moral hazard and limited liability. Our motivation is to take into account two of the main features that nuclear power safety regulators have to deal with. First, the difficulty of properly identifying how safety care impacts the probability of a major nuclear accident. Second, the fact that nuclear regulators will always want to enforce safety standards that induce compliance.

This last feature steams from the fact that safety regulators have to assure society that nuclear reactors operate below a certain acceptable risk level that should be attainable if the operators comply with safety standards. In addition, we can expect that due to the huge damages that a major accident might provoke, laxity will not only increase the risk of nuclear accident, but will also harm the credibility and reputation of safety agencies, as seen with the latest nuclear accident in Japan.

In our model, the regulator controls the operator's safety care level by imposing a standard. Since it is not able to observe operator's action, the regulator also randomly inspects nuclear facilities and is able to threaten the operator with a fine in case of non-compliance. To deal with the fact that the regulator does not perfectly know how safety care translates into a lower probability of accident, we use an imprecise probability approach. Using this methodology, we assume that the regulator can define an interval within which the parameters that define the probability of accident should lie. We use two robust optimization techniques, i.e. worst-case scenario and regret robustness, to solve the regulator's problem, and compare the results with a benchmark case, in which the regulator is perfectly informed.

In the worst-case scenario, the regulator sets a safety standard under the assumption that operator's safety care is not effective in reducing the probability of an accident. In the terms of our model, this assumption means that the regulator takes the lower bound of the interval to set the regulatory policy, this is represented by $\beta_{reg} = \underline{\beta}$. Because the expected damages of a major nuclear accident are huge, by taking this value the expected social costs reach their maximum value.

Our result suggests that the worst case regulatory policy will imply the enforcement of the less stringent safety standard. In addition, we show that for a given standard the regulator will inspect more often than it should, to induce compliance. These features arise because the regulator believes that operators' behavior is not effective in reducing the probability of accident, thus the safety standard will not be high. Simultaneously, it means that the regulator believes that the expected benefits of safety care are not big enough incentive to deter non-compliance, which is why its optimal solution is to increase the expected penalty by increasing the monitoring probability.

Although, the worst-case safety standard will not be as strict as when the regulator is perfectly informed, this by no means implies that the regulator will be lax. When a regulator believes that the real β is low, some ways it is placing more emphasis on the inherent risk of the technology, that on the hazards that might arise during the operation. In consequence, the regulator could be stricter in ex ante licensing and design rules. In terms of our model, this means that the regulatory emphasis might be done in α rather than in β.

Complementary work and an interesting future research path would be to add a previous stage to this model, in which α is determined by a nuclear vendor and it then it subject to some uncertainty for both the regulator and operator.

In our second approach, known as regret robustness, the regulator seeks to determine a policy that minimizes the largest error that it might make. This means that it attempts to find the value of the unknown parameter that maximizes the difference between the expected social costs and its optimal value. We find that the mistake that the regulator will regret the most arises when it believes that safety care is not effective to reduce the probability of accident ($\hat{\beta} = \underline{\beta}$), but in reality it is. In terms of our model, this means that $\beta_{reg} = \bar{\beta}$.

Taking this approach, the safety standard will be stricter than that of the worst-case standard and lower than the standard the regulator would set in a case in where it does not consider the possibility of being wrong. Although this is an intermediary solution, the drawback of the policy chosen under regret robustness is that it might induce non-compliance for the most inefficient operators (those with a low β). This last result provides yet another warning of once again about the difficulty of enforcing strict safety standards, not only because of moral hazard but also due to technological uncertainty.

We think that it is possible to consider these two approaches as alternatives to achieve a given acceptable risk level goal, usually expressed in terms of the probability of a major nuclear accident. The first way would be to use the worst-case approach to set the safety standard, which, although less stringent, would be easier to enforce (in terms of frequency of inspection). In addition, to ensure that the operators function below the fixed threshold, regulators could require a high ex ante level of safety features (low α), as a condition to granting a license.

The second possibility is to focus in on operation of the reactor. In this case, the regulator can use the regret robustness safety standard, which is more stringent and requires a more frequent inspections, but it allows it to tolerate a lower ex ante safety level (higher α).

In fact, if we look at how nuclear safety has been assessed by regulators, we can compare these two ways of achieving a given acceptable risk with the deterministic and probabilistic safety approaches respectively. In the former, the emphasis is done on the nuclear power plant's design. The deterministic approach's main goal is to ensure that, within the conception of the unit, various situations are considered to be plausible and taken into account to ensure the containment of radioactive materials. In the latter, the emphasis is on the operating stages. The goal of the probabilistic approach is to identify and analyze every possible situation and sequence of events that might result in a major nuclear accident during the operation.

We argue that these two approaches have acted as complements rather than substitutes throughout the history of nuclear power for civil use. In the first stages of development, nuclear regulators' uncertainty was considerable. For this reason, they focused their attention on the design and construction to ensure high ex ante safety levels, but they set conservative safety standards (as in the worst-case approach). As they gained knowledge on how safety care can reduce the probability of accidents, they were able to increase safety standards. In parallel, technological progress has made it possible to achieve better ex ante safety levels, allowed safety regulators to set lower acceptable risk levels and focus their attention on the operator's behavior and setting stricter safety standards (as in the regret robustness approach).

Improvements in PRA techniques provide a good example of how these two approaches have been complementary for nuclear regulators. In our framework, this would be represented by a continuous increase in the lower bound of β. If nuclear regulators set safety standards using a worst-case approach, our model predicts that this improved knowledge of the effectiveness of nuclear operators' behavior in reducing the risk of accident will make it possible to enforce stricter standards. However, although we consider that new designs achieve good ex ante safety levels, it is possible that safety goals in terms of accident probability also become stricter, which makes it more effective for the regulator to turn its attention to the operation of nuclear reactors. This means that it can set stricter safety standards (use regret robustness) to achieve the new acceptable risk levels.

Despite the simplicity of our framework, it highlights the pros and cons of the two main approaches in nuclear power safety regulation and allows us to conclude that regulatory policies subject to uncertainty on how safety care can reduce the probability of a major accident, will always entail a residual risk for society. If a safety regulator adopts a worst-case approach, it will be able to assure that nuclear facilities operate below a certain risk level attainable with the compliance of safety standards. However, the safety standard might not be as strict as it could be, in which case society bears the risk of enforcing low safety standards, when it could be possible to attain a higher level. If on the contrary, the regulator takes a regret robustness approach, standards will be stricter. However it will not be possible to guarantee that all nuclear facilities comply with it. In this case, society has to bear the risks associated with the safety level chosen by operators that decide not yo comply with the safety standards.

Chapter 5

General Conclusion

This PhD thesis analyzed some of the challenges for nuclear power development, that were raised after the latest nuclear accident at Fukushima Dai-ichi power plant. In particular, we have focused our attention on two issues that have a direct impact on nuclear power competitiveness: construction costs and safety regulation. The concerns about the possibility of building a new nuclear power plant at reasonable cost were exacerbated after the accident, inasmuch as it might induce extra costs in new reactors. Additionally, the importance of setting stricter safety standards reemerged after it was knew that the japanese safety regulator had information about the possibility of tsunamis of the magnitude seen on March 2011. The reactions of both nuclear industry and nuclear safety regulators to these issues will determine the future of nuclear power, if these reactions are correct they will allow the materialization of the *nuclear renaissance*, if not, they will prevent an increase of nuclear power share in the world's energy production.

Given this context, the main objective of this dissertation was to provide answers to the following questions: how to properly estimate the probability of a major nuclear accident? which are the main determinants of the construction costs of a new nuclear reactor? and finally, how nuclear regulatory agencies set safety standards given that the link between safety care and the likelihood of a major nuclear accident is uncertain? In this thesis, we have used actual data about the construction costs, lead-times, technological choices and innovation coming from the two largest nuclear fleets in the world: U.S and France. Additionally, we have taken into account in our analysis, the specificities of a major nuclear accident, to be able to give more accurate answers to the previous questions.

Undoubtedly, the development of nuclear power in the world will depend predominantly, on how the industry is able to curb the cost escalation than has been seen as inherent to this technology. In consequence, the results of this dissertation in terms of construction costs will allow us to identify which are the elements that enhance nuclear competitiveness, either because they induce costs reductions, or because they avoid delays during the construction. In addition, they will be useful to explain what we could expect in terms of cost and lead-times from the current reactors under construction, given the technological and industrial choices that have been made. Finally, they will allow us to give some policy recommendations for those countries that have envisioned to construct nuclear reactors in the near future.

In parallel, the further development of nuclear power will also depend on how safety authorities are able to determine an accepted social risk level, without harming the profitability of nuclear operators or jeopardizing the inhabitants surrounding the nuclear facilities. The first step to set this objective is to properly assess the probability of a major nuclear accident. The second step towards this objective is that nuclear regulators set safety standards in a cost-effective way. In particular, nuclear regulators must take into account the uncertainty that exists between safety care and the probability of a major accident. The results of this dissertation in terms of safety regulation will be useful to understand the trade-off underlying different regulatory approaches and determine which is the best way to cope with the uncertainty regarding major nuclear accidents.

The analysis in this PhD thesis is particularly important for those countries that are interested in continuing or embarking upon nuclear power programs. Within the western context, nuclear power is called to play an important role in energy transition to a decarbonized electricity supply and reduce the dependence on fossil fuels. Countries like the United States, the United Kingdom, Poland and France contemplate nuclear power within their future energy mix. Moreover, the most promising region for nuclear power deployment is in the east of the globe. In particular in countries with growing energy demand and ambitious nuclear programs like China, India, Russia and Turkey.

5.1 Conclusion about Construction Costs

Reducing the technological variety of the nuclear fleet by limiting the models that can be installed is key to improve nuclear power competitiveness. Our results showed that the standardization of the French nuclear fleet was successful in curbing the construction costs, contrary to what happened in the construction of the U.S nuclear fleet. We found that building the same type of reactor repeatedly, would allow to reduce the costs of the last units of a given series. According to our model in Chapter 3, we might expect that the costs for the second unit of a reactor model built by the same firm would be reduced in 10% to a 12%.

This first result is particularly important for those countries that have conceived significant additions in nuclear capacity by building a high number of reactors. Given that the construction of a nuclear power plant depends largely on on-site and reactor characteristics, reducing the technological variety and construct multi-unit sites will mean that a new reactor can be built without any design or site modifications and thus, it is possible to avoid the additional costs related with them. In addition, a standardized nuclear fleet might reduce the probability of incidentals during the construction that lead to delays and cost overruns. Finally, building the same type of reactor could induce cost reductions thanks to the possibility of buying components in a larger scale.

In the light of this result, we can expect that Chinese nuclear fleet, that nowadays relies on the construction of several CPR-1000 reactors will be successful in terms of progressively reducing the construction cost of this model. This might be also what we can expect to see in India, where the nuclear fleet that is currently under construction consists in 4 reactors of the same design (i.e. PHWR-700). We can also expect that the costs of the new reactors in South Korea decrease, in particular for the latest APR-1400 reactors that will be built.

In the U.K the situation might be different. The potential cost reductions in the nuclear fleet would be conditional to the result of the first project at Hinkley Point C. We could expect that if this project meet the initial budget and schedule and if it is decided to continue with the EPR at Sizewell C in Suffolk, the costs of these reactors will be less than the previous. However, it is yet to be seen if this first experience with the EPR does not repeat the cost overruns and delays in the construction, as in Finland and France.

The second lesson learnt from the construction of the U.S and French nuclear fleet is that there existed positive and significant economies of scale. This means that constructing larger reactors might be a way to reduce the costs per MWe. The results of Chapter 3 suggested that even if the construction of bigger reactors meant an increase in the construction periods, in average we could expect that an increase of 10% in the capacity installed would reduce construction costs by 4.5%. This result solved the impossibility of testing economies of scale by using only the cost data coming from the French nuclear fleet as we highlighted in Chapter 2.

For countries with growing energy demand, it is possible that constructing large reactors will allow to supply much of the demand, while allowing some cost reductions per MWe installed and without taking a large space (contrary to wind farms, for instance). However, as we have mentioned in Chapter 2, reducing the capacity of nuclear reactors could be one of elements to rethink nuclear industry. In fact, we consider that the development of small modular reactors might foster nuclear development in other countries, that have not yet considered it within their energy agendas, either because they have lower energy demand or because they have restricted budgets. In this sense, smaller reactors could have shorter construction schedules, lower capital costs and the potential of further savings due to off-site module fabrication.

Our third important result highlighted the importance of meeting the construction schedules, as an effective way to curb the cost escalation. Regarding this result, we identified different factors that explain why the construction periods in U.S and France have been so lengthy. The first explanation is linked to changes in the installed technologies. We have found that cumulated experience in other designs had a negative impact on the lead-times that ended up raising the construction costs. This result shows that the experience in the construction of other reactor models is not directly transferable to all the projects, hence it is likely to expect lengthy construction periods when a new design is installed.

We also have found that the increments in the lead-times in the construction of the U.S and French fleet were partially due to the effect of the two major nuclear accidents: Three Mile Island and Chernoblyl. This last result warns of the possible effects that Fukushima Dai-ichi might have had in the reactors under construction. We will have to wait until they are finished to see, if it is possible to link the potential delays during the construction, with a stricter supervision or new safety requirements due to the latest major accident in Japan.

All these factors, that were key to understand the increase in the lead-times in the U.S and France, can also be used to explain why the construction of the EPR in Europe has had continuos delays. Given that the EPR is a new design, a first of a kind, the experience that AREVA or EDF had in the construction of other models is not directly transferable to this new project, therefore it is likely that incidentals during the construction translates into delays. In addition, we may explain the lengthy construction period of the EPR as a result of its capacity (i.e. 1650 MWe). We find that bigger reactors take longer periods to be built, for this reason it is likely to expect that it takes more time to construct this design than its predecessor (N4 model 1500 MWe). The first N4 model constructed in France took approximately 12 years.

Our results also indicated that an homogenous nuclear fleet, besides allowing cost reductions in the long run (i.e. after building repeatedly the same reactor), it might also have some benefits in the short term, through reductions in the lead-time. For this reason, we are convinced that a standardization strategy enhances the competitiveness of nuclear power in two ways. As we mention at the beginning, it allows costs savings through learning by doing at the firm level. But, in addition it tends to reduce the construction lead-times and therefore the construction costs in the short term.

In fact, these results are also helpful to explain the first delays observed in the construction of the AP-1000 and EPR reactors in China. China has based their nuclear program around their CPR-1000 reactor and so far it has a good record in terms of construction lead-times (4 years in average). However, recently they decided to install Generation III+ reactors by building four AP1000 reactors at Sanmen and Haiyang and two EPR at Taishan. Both construction projects have delays, 18-30 months in the former and 13-15 months in the latter[1]. In the light of our results, we can argue that part of the increase in the construction lead-times is a result of a less homogeneous nuclear fleet under construction.

The last and perhaps the most important result in terms of construction costs that we have found is that innovation has not improved nuclear power competitiveness. Technological change in nuclear power has not induced reductions in the amount of capital needed to build a new reactor. On the contrary, we found that it was one of the main drivers of the cost escalation. This result represents a major challenge for nuclear power development, given that it goes in the opposite direction with the pattern observed in other energy technologies, where technical progress has contributed to reduce their investment costs. This trend has been registered in competing carbon-free technologies like wind power and photovoltaics.

This last result might partially be explained by the fact that the requirements of nuclear safety authorities have pushed nuclear vendors to innovate, in order to achieve better safety performance in the existing reactors. In Chapter 2, we found some evidence that suggested that reactors with better safety indicators, in terms of lower unexpected events that might lead to a serious accident, were related with higher construction costs. These results lead us to conclude that the latest reactors, although more expensive, have also embodied safety improvements aiming to reduce risks of major accident.

Taking into account the above, we can argue that one of the possible reasons to explain why the EPR is such expensive is precisely because it embodies some innovations, that allow it to achieve higher safety levels, inter alia. In fact, AREVA promotes this design saying that it is an upgrade in nuclear technology (i.e. Generation III+), precisely due to the level of safety that it guarantees. According to the vendor, the EPR has an expected core melt down frequency less than 1 event each one million reactor years.

The trade-off between the benefits of standardization and those related with technological change is of paramount importance for nuclear power development. We started this section arguing that standardization leads to lower construction costs, hence it is key for nuclear power competitiveness. However, we have also found that new designs have better safety features. This means that to adopt a new technology, it is necessary to do

[1] See Schneider and Froggatt (2014)

a cost benefit analysis to see, whether it is reasonable to invest in a better reactor in terms of a reduced risk of accident, or if instead, the gain in safety does not worth the increase in the costs and therefore, it is better to keep on using the established technology. In this sense, we can conclude that complementarily to a standardization strategy, countries interested in nuclear power have to consider within their programs, which will be the optimal pace of technological change.

After studying the history of the construction of the U.S and French nuclear fleet, we can say that the relation between: the economics of safety and nuclear innovation constitutes the most challenging issue for nuclear power industry. On the one hand, it is desirable to minimize the risk of a nuclear disaster, as much as possible, in particular after seeing the terrible consequences of Fukushima Dai-ichi core melts. But on the other hand, innovations have to be done without threatening nuclear power competitiveness. In summary, we consider that nuclear industry should make innovation efforts not only to increase safety performance, but also in allowing to reduce the capital costs needed to construct a new nuclear reactor.

5.2 Conclusion about Safety Regulation

In terms of safety regulation, our model in Chapter 4 highlighted the trade-off linked with the adoption of both, a deterministic and a probabilistic approach to regulate nuclear facilities. In some sense, the deterministic approach focus in design of the unit, as a way to achieve a given accepted risk level. This alternative can be related to our worst case approach, in which the regulator is not optimistic in how the operator's behavior can reduce the probability of an accident. Under this assumption, the regulator will fix the less stringent safety standard and monitor more often. Given that he believes that safety care is not so effective in reducing the probability of accident, he thinks that expected benefits of safety care are not a enough incentive to deter no compliance, that is the reason why he finds optimal to increase the monitoring probability.

On the contrary, the probabilistic approach focus the regulatory effort on the operator's behavior. Here, the regulator believes that safety care during the operation of the reactor is very effective to reduce the probability of a major nuclear accident. In terms of our model, this approach is similar to the regret robustness criterion. In this case, the regulator seeks to find a policy that minimizes the largest error that he can make. We found that if the safety authority sets the regulatory policy under this approach, the standard will be stricter compared with the the worst case standard, but it will be less strict than the one that the regulator will set in the case in which he does not consider the possibility of being wrong.

Even though, the safety standard obtained under regret robustness is more stringent and might allow to achieve a better safety level, it is important to remark that it might induce no compliance of the less efficient operators. This last result warns, once again, about the difficulty of enforcing strict safety standards, not only due to the problem of moral hazard but also because technological uncertainty.

From an static point of view, the model that we have developed to study how to set safety standards for nuclear operators captures both the pros and cons of the two main approaches that have been used, so far, in the history of nuclear power. The main conclusion is that setting standards, under the uncertainty on how safety care can reduce the probability of major accident, will always entail a residual risk for the society. Under the worst-case approach, the society bears the risk associated with the difference between the less efficient operator and the safety level provided by the standard. If the regulator prefers a regret robustness approach, the standard will be stricter, however it will no be possible to guarantee that all the nuclear facilities comply with it. Here the society has to bear the risk associated with the difference between the safety level chosen by the operators that decide to not comply and the safety standard.

Up to this point, it is important to recognize that our model is very simple and do not pretend to capture all the features that a nuclear regulator has to face when setting safety standards. For instance, we have reduced the operator effort to provide safety to one dimension, when it is multidimensional. In the sense, that nuclear operators perform many tasks to achieve a given safety care level. In addition, we have assume that the regulator can not observe the safety care level selected by the operator, when it might be possible that some of the standards are more easy to verify than others. Given that the multidimensionality and degree of observability of safety care may have an impact on the regulatory policy, these elements could represent possible extensions of our basic model.

Another important caveat of our model is that it is static, therefore we can not conclude anything about the transition of the regulatory process. If this model is extended to introduce dynamics in the way in which nuclear regulator set safety standards, it might be possible to determine when it is optimal to change from a deterministic approach to a probabilistic one. In fact, if we revise the history of nuclear safety regulation, we can claim that roughly, these two approaches have been complements rather than substitutes. The transition of the emphasis given to these approaches have changed, to the extent that the regulator has gained better knowledge about how safety care reduces the probability of an accident.

In the inception of nuclear industry (for civil uses), the uncertainties for regulators were huge. As a result, they focused their attention in establishing safety rules related with the design and construction, but they set conservative standards for the operation (as in the worst case approach). Progressively, they got better knowledge of how safety care affects the probability of nuclear accidents. For instance, after the core melt down in Three Mile island, that was due to a mistake during the operation, the U.S Nuclear Regulatory Commission decided to carry out PRAs in nuclear reactors, in order to detect how nuclear operators could prevent events that lead to a serious accident. The results of the PRAs and their continuous improvements have given to nuclear operators precious information about how to reduce the risk of a major accident. In consequence, they were able to set stricter safety standards.

In parallel, new reactors have been installed. As we have observed in the U.S and French nuclear fleet (Chapters 2 and 3), new reactors have embodied innovations aiming to achieve better safety performance. This means that technological progress made it possible to achieve better ex ante safety levels, allowing safety regulators to set even lower acceptable risk levels and translate their attention to the performance of the nuclear operators, through the adoption of stricter safety standards (as in regret robustness approach).

It is clear that the complementary transition from a worst case to a regret robustness approach is strongly related with technological progress. Once again, the relation between nuclear safety and innovation pops up as a cornerstone for nuclear power. As we mentioned in the previous section, this relation was relevant to understand the cost escalation in the construction both in of U.S and French nuclear fleet. It might be possible that due to the increase on the safety performance of new reactors, nuclear regulators have been able to set stricter safety standards and pursue even lower accepted risks levels. However, the impact of technological progress in nuclear safety regulation was not studied in our model, what makes this subject a potential area for further research.

Appendix A

Cour des Comptes Actual Construction Costs for the French Nuclear Fleet

TABLE A.1: Data from the *Cour des Comptes* report

Pair of units	Capacity MW	Year	Type	Overnight Cost (M€2010/MW)
		Palier 900 MW		
Fessenheim1.2	1780	1978	CP0	0,836
Bugey2.3	1840	1979	CP0	0,886
Bugey4.5	1800	1979	CP0	0,899
Damprierre1.2	1800	1980	CP1	1,217
Gravelines1.2	1840	1980	CP1	0,822
Tricastin1.2	1840	1980	CP1	1,188
Blayais1.2	1830	1982	CP1	1,110
Dampierre3.4	1800	1981	CP1	1,172
Gravelines3.4	1840	1981	CP1	0,856
Tricastin3.4	1840	1981	CP1	1,247
Blayais3.4	1820	1983	CP1	0,890
Gravelines5.6	1820	1985	CP1	1,093
SaintLaurent 1.2	1760	1983	CP2	1,120
Chinon 1.2	1740	1984	CP2	1,148
Cruas1.2	1760	1984	CP2	1,119
Cruas3.4	1760	1984	CP2	1,253
Chinon3.4	1760	1987	CP2	0,978
		Palier 1300 MW		
Paluel1.2	2580	1985	P4	1,531
Paluel3.4	2580	1986	P4	1,157
St Alban1.2	2600	1986	P4	1,129
Flamanville1.2	2580	1987	P4	1,287
Cattenom1.2	2565	1987	P'4	1,358
Belleville1.2	2620	1988	P'4	1,083
Cattenom3.4	2600	1991	P'4	1,149
Nogent1.2	2620	1988	P'4	1,194
Glofech1.2	2620	1992	P'4	1,305
Penly1.2	2660	1991	P'4	1,227
		Palier 1450 MW		
Chooz1.2	2910	2000	N4	1,635
Civaux1.2	2945	2002	N4	1,251

Appendix B

Linear models for the Construction Costs

In this Appendix, we show the estimation results as well as the VIF for different specifications of the linear regression model shown in Equation 1. The models that we have estimated are the following:

- Model 2

$$\ln(C_i) = \alpha_0 + \alpha_1 \ln(Cap_i) + \alpha_2 EXPI_i + \alpha_3 EXPP_i + \alpha_4 EXPT_i + u_i \tag{B.1}$$

- Model 3

$$\ln(C_i) = \gamma_0 + \gamma_1 \ln(Cap_i) + \gamma_2 EXPP_i + \gamma_3 EXPT_i + u_i \tag{B.2}$$

- Model 4

$$\ln(C_i) = \theta_0 + \theta_1 EXPI_i + \theta_2 EXPP_i + \theta_3 EXPT_i + u_i \tag{B.3}$$

Table B.1: Estimates for Model 2

Coefficients	Estimate	Std. Error	t value	Pr($>|t|$)
(Intercept)	5.474	8.444	0.648	0.523
Ln Cap	-0.732	1.125	-0.650	0.522
EXPI	0.013	0.011	1.193	0.245
EXPP	-0.008	0.013	-0.667	0.511
EXPT	-0.003	0.008	-0.386	0.703

Table B.2: VIF for Model 2

Ln Cap	EXPI	EXPP	EXPT
73.161	58.620	20.917	1.794

Table B.3: Estimates for Model 3

Coefficients	Estimate	Std. Error	t value	Pr(> $\|t\|$)	
(Intercept)	-4.502	1.155	-3.896	0.001	***
Ln Cap	0.598	0.148	4.032	0.001	***
EXPP	0.006	0.003	1.661	0.109	
EXPT	-0.007	0.007	-1.027	0.314	

Table B.4: VIF for Model 3

Ln Cap	EXPP	EXPT
1.257	1.692	1.429

Table B.5: Estimates for Model 4

Coefficients	Estimate	Std. Error	t value	Pr(> $\|t\|$)	
(Intercept)	-0.017	0.060	-0.291	0.773	
EXPI	0.006	0.001	4.236	2e-04	***
EXPP	-0.001	0.003	-0.152	0.880	
EXPT	-0.005	0.007	-0.768	0.449	

Table B.6: VIF for Model 4

EXPI	EXPP	EXPT
1.003	1.432	1.432

Appendix C

Alternative model specifications

Table C.1: Alternative model specifications

	Model 5		Model 6	
	Cost	Lead-time	Cost	Lead-time
HHI.Mo	1.249 **	-0.400 ***	0.247	-0.444 **
	(0.490)	(0.141)	(0.481)	(0.185)
ln *ExpArqMo*	-0.153 ***	0.005		
	(0.041)	(0.011)		
ln *ExpArqNoMo*	0.028	0.024 **		
	(0.035)	(0.009)		
ln *ExpNoArqMo*	0.0461	0.014		
	(0.041)	(0.011)		
ln *ExpNoArqNoMo*	-0.095	0.152 ***		
	(0.103)	(0.017)		
Inv.ExpArqMo			0.335 ***	-0.025
			(0.067)	(0.027)
Inv.ExpArqNoMo			-0.097	-0.007
			(0.080)	(0.032)
Inv.ExpNoArqMo			-0.150 *	-0.016
			(0.079)	(0.032)
Inv.ExpNoArqNoMo			0.181	-0.337 ***
			(0.245)	(0.076)
ln *Know*			1.291 **	
			(0.598)	
ln *Cap*	-0.839 ***	0.117 **	-0.609 ***	0.174 ***
	(0.221)	(0.050)	(0.182)	(0.061)
ln *NPP.UC*	0.498 ***	-0.101 **	0.318 ***	-0.040
	(0.182)	(0.043)	(0.105)	(0.040)
Arq.Utility	-0.255 ***	-0.008	-0.292 ***	0.024
	(0.096)	(0.027)	(0.087)	(0.034)
ln *EDem*		-1.202 ***		-1.467 ***
		(0.108)		(0.125)
ln *LT*	2.270 ***		1.133 *	
	(0.820)		(0.686)	
ln *Cement*	0.392		0.003	
	(0.538)		(0.359)	
ln *Labour*	-2.020		-0.710	
	(1.365)		(0.808)	
Tmi.US	-0.055	0.292 ***	0.075	0.300 ***
	(0.197)	(0.041)	(0.177)	(0.049)
Tmi.FR	-0.001	-0.053	-0.184	-0.004
	(0.252)	(0.071)	(0.223)	(0.089)
CH	-0.107	0.053 *	-0.051	0.053
	(0.140)	(0.030)	(0.122)	(0.036)
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

Appendix D

Alternative model specifications for lead-time

Table D.1: Alternative model specifications for lead-time in OECD countries

Variables	(1) ($\ln LT$)		(2) ($\ln LT$)	
$HHI.Mo$	-0.509	***	-0.458	**
	(0.189)		(0.200)	
$\ln Cap$	0.225	***	0.240	***
	(0.051)		(0.052)	
$\ln ExpArqMo$	-0.010			
	(0.031)			
$\ln ExpArqNoMo$	0.0411	***		
	(0.013)			
$\ln ExpNoArqMo$	0.0141			
	(0.018)			
$\ln ExpNoArqNoMo$	0.080	*		
	(0.041)			
$Inv.ExpArqMo$			0.0514	
			(0.111)	
$Inv.ExpArqNoMo$			0.003	
			(0.032)	
$Inv.ExpNoArqMo$			0.009	
			(0.048)	
$Inv.ExpNoArqNoMo$			-0.238	
			(0.163)	
$\ln EDem$	-17.010	***	-21.240	***
	(3.857)		(3.387)	
$Tmi.Abroad$	0.126	*	0.124	*
	(0.066)		(0.069)	
$Tmi.US$	0.432	***	0.448	***
	(0.060)		(0.062)	
CH	0.214	***	0.214	***
	(0.029)		(0.027)	
$Constant$	2.111	***	2.542	***
	(0.450)		(0.576)	
Country FE	Yes		Yes	
Time FE	Yes		Yes	
Obs.	286		286	
Adj. R^2	0.876		0.872	

Note: Robust standard errors in parentheses

Appendix E

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

Table E.1: List of nuclear reactor models by manufacturer in France and the US

Model	Manufacturer	Number of 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

Appendix F

Operator's best response

Proof of proposition 1. The Lagrangian for the operator as long as $e \geqslant s$ is given by $L(e, \lambda) = c(e) + (\alpha - \beta e)\gamma D + \lambda(e - s)$ and the Kuhn Tucker first order conditions are the following:

$$c'(e) - \beta\gamma D + \lambda = 0 \tag{F.1}$$

$$\lambda(e - s) \geqslant 0; (e - s) \geqslant 0; \lambda \geqslant 0 \tag{F.2}$$

In case that $\lambda = 0$, then the firm *overcomplies* and $e > s$ and the best response of the firm in this case satisfies:

$$c'(e^{ps}) - \beta\gamma D = 0$$

In case that, $\lambda = 0$, thus $e = s$. The first order condition is $c'(s) - \beta\gamma D \leqslant 0$.

The Lagrangian for the operator when $e \leqslant s$ is given by $L(e, \mu) = c(e) + (\alpha - \beta e)\gamma D + (1 - \alpha + \beta e)qF_0 + \mu(s - e)$ and the Kuhn Tucker first order conditions are the following:

$$c'(e) - \beta\gamma D + \beta qF_0 - \mu = 0 \tag{F.3}$$

$$\mu(s - e) \geqslant 0; (s - e) \geqslant 0; \mu \geqslant 0 \tag{F.4}$$

In case that $\mu \geqslant 0$, then the $e = s$ and the best response of the firm in this case is to *comply* with the standards and satisfies the following condition:

$$\mu = c'(s) - \beta\gamma D + \beta q F_0 \geqslant 0$$

Finally, if $\mu = 0$, then the firm *do not comply* $e < s$ and the best response of the firm in this case satisfies:

$$c'(n) - \beta\gamma D + \beta q F_0 = 0$$

As long as $c(s) + (\alpha - \beta s)\gamma D > c(n) + (\alpha - \beta n)\gamma D + (1 - \alpha + \beta n) q F_0$.

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L’Économie de l’Énergie Nucléaire : Coûts des Construction et Régulation de la Sûreté

RESUME : Cette thèse étudie le rôle des coûts de construction et de réglementation de la sécurité sur la compétitivité de l'énergie nucléaire. L'analyse des coûts de construction est basée sur l'utilisation de données réelles provenant des parcs nucléaires français et américains. En particulier, nous étudions différents canaux à partir de laquelle des réductions de coûts pourraient survenir. Nous montrons que la normalisation est un critère crucial pour la compétitivité économique de l'énergie nucléaire, d'abord parce que les effets d'apprentissage positifs sont conditionnels à la technologie, ce qui signifie que les réductions de coûts ne peuvent venir que si le même type de réacteur est construit à plusieurs reprises, mais aussi parce qu'elle permet de réduire le coût indirectement par l'intermédiaire courts délais de construction. Dans l'analyse du rôle de réglementation de la sécurité, nous évaluons d'abord l'effet de la dernière accident nucléaire majeur (c.-à Fukushima Dai-ichi) de la probabilité de survenance d'un tel événement, puis les effets de l'incertitude concernant la façon dont les soins de la sécurité à réduire le probabilité d'un accident nucléaire dans l'établissement de normes de sécurité en vertu de l'aléa moral et responsabilité limitée. Nous constatons que la norme sera la moins stricte lorsque le régulateur adopte une approche pire des cas, et plus stricte lorsque le régulateur adopte l'approche de la robustesse de regret et il est optimiste quant à l'efficacité des soins de la sécurité pour réduire le risque d'accident. Toutefois, cette norme pourrait induire le non-respect par les opérateurs les moins efficaces.

Mots clés : Énergie nucléaire, coûts de construction, effets d'apprentissage, régulation de la sûreté, risque moral, optimisation robuste

Economics of Nuclear Power : Construction Costs and Safety Regulation

ABSTRACT : This thesis studies the role of construction costs and safety regulation on nuclear power's competitiveness. The analysis of construction costs is based on the use of actual data coming from the American and French nuclear fleets. In particular, we study different channels from which cost reductions might arise. We show that standardization is a crucial criterion for the economic competitiveness of nuclear power, first because the positive learning effects are conditional to the technology, this means that cost reductions will arise only if the same type of reactor is built several times, but also because it allows to reduce the cost indirectly through shorter construction lead-times. In the analysis of the role of safety regulation, we first assess the effect of the latest major nuclear accident (i.e Fukushima Dai-ichi) in the probability of occurrence of such an event and then the effects of the uncertainty regarding how safety care reduce the probability of a nuclear accident in setting safety standards under moral hazard and limited liability. We find that the standard will be the less strict when the regulator adopt a worst-case approach, and stricter when the regulator adopts the regret robustness approach and it is optimistic about safety care effectiveness to reduce the risk of an accident. However, this standard might induce non-compliance by the least efficient operators.

Keywords : Nuclear power, construction costs, learning effects, safety regulation, moral hazard, robust optimization

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