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Michel Berthélemy

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Michel Berthélemy

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Cerna, Centre d'économie industrielle
MINES ParisTech
60, boulevard Saint Michel
75272 Paris Cedex 06 – France
Tél. : 33 (1) 40 51 90 00

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What drives innovation in nuclear reactors technologies?

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Michel Berthélemy[1]

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Abstract

This paper examines the evolution of innovation in nuclear power reactors between 1974 and 2008 in twelve OECD countries and assesses to what extent nuclear innovation has been driven by economic incentives, political decisions and safety regulation considerations. We use priority patent applications related to Nuclear Power Plants (NPPs) as a proxy for innovating activity. Our results highlight that nuclear innovation is partly driven by the conventional paradigm where both demand-pull, measured by NPPs constructions in the innovating country and in the rest of the world, and technology-push, measured by Research and Development (R&D) expenditures specific to NPPs, have a positive and significant impact on innovation. Our results also evidence that the impact of public R&D expenditures and national NPPs construction on innovation is stronger when the quality of innovation, measured by forward patent citations, is taken into account, and have a long run positive impact on innovation through the stock of knowledge available to innovators. In contrast, we show that political decisions following the Three Miles Island and Chernobyl nuclear accidents, measured by NPPs cancellations, have a negative impact on nuclear innovation. Finally, we find that the nuclear safety authority has an ambivalent effect on innovation. On one hand, regulatory inspections have a positive impact on innovation, one the other hand, regulatory decisions to temporarily close a NPP have an adverse impact on innovation.

JEL Classification: 031, Q40, Q48, L50

Keywords: Innovation, nuclear reactors, nuclear safety regulation, nuclear development

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[1] CERNA, Mines ParisTech, 60 boulevard Saint-Michel, 75006 Paris, France,
Email: michel.berthelemy@ensmp.fr

1. Introduction

Empirical economic literature on the determinants of technological change in clean technologies, and in particular energy technologies, has been growing rapidly for the last two decades. Considering the importance of energy saving and alternative forms of energy to foster climate change mitigation, and the role of technological change to reduce mitigation cost, this literature has studied how economic and regulatory incentives have an impact on the pace and direction of innovation.

The aim of this paper is to assess how nuclear innovation has evolved and has been induced by government-led incentives and the characteristics of nuclear industry, through for instance political shocks and nuclear safety authority stringency, since nuclear reactor technologies entered the commercial stage. Very little attention has been devoted to the innovation taking place in nuclear reactors technologies despite the facts that nuclear power generation encompasses a significant share of the electricity mix of developed countries and plays a key role in climate change mitigation scenarios. In 2010[2], nuclear power provides 13.5% of the world's electricity consumption, 24% of electricity consumption in OECD countries, and 34% in the European Union. In the 2010 IEA Blue Scenario, nuclear power generation is expected to become the first electricity source by 2050 with 24 % of worldwide electricity consumption, contributing to 7 % of the climate change mitigation effort to curb emission by 50 % compared to 2007 (IEA, 2010).

Similarly, innovation in this energy field has significant importance both for the competiveness and the safety margins of Nuclear Power Plants (NPPs). The OECD Nuclear Energy Agency (OECD/NEA, 2007) highlights, using country case studies, how important innovations in nuclear reactors since the first commercial reactors in the 1960s have improved the competitiveness of NPPs through, for instance, an increase in operation and maintenance efficiency (e.g., nuclear fuel rode reliability), more standardized design or an increase in the NPPs lifetime. Innovation in nuclear reactor technology has also enabled improvements in NPPs safety margins both in terms of the expected probability of a major accident (e.g., automatic scrams in case of technical failure) and the potential impact outside the NPP in the event of a major accident (e.g., core catcher). Needless to say, the recent Fukushima nuclear accident has called for a revision of NPPS safety margins. While some safety margins improvements will originate from organizational changes within the nuclear industry which will learn from this accident (David et ali., 1996), and from changes about the international framework on nuclear safety regulation (Berthélemy and Lévêque, 2011), one can expect that technological change will also have to play a key role.

Furthermore, it is worth recalling that the nuclear innovation system has experienced important structural changes since the early day of the nuclear programs. In particular, if the US nuclear program *Atom for Peace* is generally pictured has a by-product of the US navy nuclear military program

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[2] World Nuclear Association (November 2011), see: http://world-nuclear.org/info/inf16.html

(Cowan, 1990), with high government control over R&D activities in most countries (DeLeon, 1979), this government and military controls over nuclear technologies have been gradually eluded in OECD countries as civil nuclear programs have reached the commercial stage. For instance, the then US Atomic Energy Commission (AEC) had transferred most of its intellectual property rights to the US firms Westinghouse and General Electric by the early 1960s (DeLeon, 1979).

This paper follows the empirical body of literature on the determinants of innovation in energy technologies and the role of environmental regulation as a channel for environmental innovation. In energy technologies, Newell et ali. (1999) and Popp (2002) show respectively that the direction and the pace of innovation in energy saving technologies has been induced by changes in energy prices and is also impacted by the quality of the stock of knowledge available to innovators. Johnstone et ali. (2008) evidence that the policy instruments supporting the diffusion of renewable energy sources (e.g., feed-in tariffs, obligation or green certificates) play a significant role in spurring innovation in these technologies. Nemet (2009) highlights that uncertainty about government incentives in favor of wind power can have negative impacts on innovation in wind power technologies. More recently, Dechezleprêtre and Glachant (2011) study the determinants of innovation in the wind industry through a panel approach and show that innovators don't only respond positively to national incentives in terms of public R&D spending and new installed capacities in their home country but also to incentives from foreign countries through the increase in installed capacities in the rest of the world.

In parallel, numerous authors have attempted to explore the link between environmental regulation and innovation. In particular, Porter and Van der Lindle (1995) argue that compliance to environmental regulation may be a key channel for spurring new innovation and in turn for improving firms' competitiveness. For example, Jaffe and Palmer (1997) find that Pollution Abatement and Control Expenditures (PACE) have a positive impact on US firms R&D expenditures but have no incidence on patent application. Brunnermeirer and Cohen (2003) argue that environmental innovation in the United-States manufacturing industry is induced by the level of PACE and regulatory enforcement but only find a positive effect for the former. In parallel, based on survey data and a discrete choice approach, Horbach (2008) finds evidence that environmental innovation in German firms is induced by environmental regulation.

Following the aforementioned literature, we measure innovation effort in nuclear reactors through priority patent applications in twelve OECD countries with commercial NPPs between 1974 and 2008 using the European Patent Office (EPO) Patstat database. These specifications of the panel dimensions allow us to focus solely on the commercial area of the civil nuclear industry as well as on the stage of the nuclear fuel cycle where innovation results essentially from the industry. For example, we do not consider innovation in fast breeding reactors where innovation essentially originates from public research centers and has not reached the commercial stage yet. However, our analysis differs from the existing literature to the extent that we also attempt to explore how different measures of innovation impact the significance and the magnitude of our explanatory variables. In particular, we measure innovation both in terms of the row count of priority patent applications and in terms of these priority patents weighted by the number of forward citations these patents receive[3]. This second measure of innovation is commonly used in the innovation literature (OECD, 2009) to capture the value of the patents studied.

We show that the positive impacts of public R&D expenditures and national NPPs constructions on nuclear innovation are found to be larger when priority patents are weighted by foreign citations, indicating that these incentives are channels which induce more valuable innovation. Another important finding of our analysis refers to the importance of the stock of knowledge, measured by the discounted stock of previously patented innovation for current innovation. In other words, policies supporting nuclear innovation have a long run positive impact on nuclear reactors innovation and there exists a strong first mover advantage for innovating countries in nuclear reactor technologies. In contrast, political decisions, measured by the decision to cancel NPPs construction, are found to have negative impacts on innovation in nuclear reactors. Finally we find that the nuclear safety authority has an ambivalent impact on innovation. On the one hands, the level of monitoring, measured in terms of the average number of inspections per NPP, has a positive effect on nuclear reactor innovation. On the other hands, the decision to temporarily close NPPs because the nuclear operator is not complying with the safety regulation has a negative effect on innovation. This can be explained by the fact that non-compliance may originate from a lack of resources which will in turn have a negative impact on innovation.

The next sections of this paper are organized as follow. In section 2, we provide a descriptive overview of the evaluation of the innovation system for nuclear reactors since the early days of the civil nuclear programs and show how the control over nuclear reactor technologies has gradually been passed to the private sector. In section 3, we present the different dataset used for our analysis and address the methodological approach used to measure innovation. Section 4 presents a descriptive overview of the trend of innovation in nuclear reactor and the distribution of this innovation among the main players of the nuclear industry. Section 5 is devoted to the description of our empirical model and presents our results. Finally section 6 reviews the conclusions of our empirical analysis and suggests paths for future research.

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[3] Patent laws require patent applications to make reference to the prior patents in order to delimit the scope of the property right associated with the patent.

2. The evolution of the nuclear innovation system

The early days of the nuclear technology innovation system can be best pictured as a technology sector which originated under strict government control and planning along with highly centralized research and development centers and a strong culture of secrecy (Cowan, 1990). For instance, in the US, the creation of the Atomic Energy Commission (AEC), in charge of both military and civil research for nuclear technology, was a direct extension of the World War II *Manhattan Project* and shared much in common with this war project in terms of military control and secrecy culture (Lowen, 1987). However, by the mid-1950s and with the prospect of the development of civil applications for nuclear energy, with for instance the *Atom for Peace* program in the US, involvements of private corporations have been rapidly growing with the notable predominance of the US firms Westinghouse and General Electric for the development of NPPs designs (Joint Congressional Committee on Atomic Energy, 1952).

The rapid involvement of private corporations has not been the sole attribute of the US nuclear industry and in fact private corporations have been later involved in the commercialization of NPPs in most of the western European countries (DeLeon, 1979), either through public-private partnerships (e.g., Framatome[4]) and/or international cooperations (e.g., Euratom). This involvement of the private sector, which initially took place at the construction stage of the first generation of NPPs, rapidly shifted toward the development of nuclear reactor design technologies especially as NPPs designs evolved toward more standardized technologies (e.g., Light Water Reactors (LWRs)) by the late 1960s (OECD/NEA, 2007).

The commercial stage of nuclear energy has also been characterized by the importance of international technological transfers, originating essentially from the US toward a large number of countries (e.g., France, Germany, Japan, and Korea) to the notable exception of the United-Kingdom (UK). A number of countries have then adapted and improved the design of these NPPs to create their national design of nuclear reactors (e.g., the APR1400 Korean reactor is based on a design initially transferred by the US firm Combustion Engineering).

It is thus important to stress that the innovation system for nuclear reactors has evolved from a high government control framework toward a system where most of the incremental innovation originates from the private sector. However, if this postulate is essentially true for nuclear reactor technologies, government control and leadership remains strong at other stages of the nuclear fuel cycle and in particular at the back-end stage (e.g., waste treatment and long term storage), for technologies facing high proliferation risk (e.g., isotope enrichment technologies) or with long term deployment horizon

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[4] Framatome is now part of the French nuclear firm Areva. In fact, it has also at the beginning an international joint venture between the French Commissariat à l'Energie Atomique (CEA) and the US firm Westinghouse.

(e.g., fast breeding reactors). In that respect, the scope of our analysis is limited to the conventional nuclear reactors technologies in market economies between 1974 and 2008[5] in order to focus on the nuclear technologies and on the period where private corporations have been the most involved in the innovation stage. This limit to the scope of our analysis is especially important in order to limit endogeneity biases in our empirical analysis between public R&D expenditures and innovation.

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

3. Data

3.1. Atomic energy patents

Patent data are extensively used by economists as a way to track the innovative activity of an industry or a sector. Their advantages and limitations have been equally discussed in the economic literature (OECD, 2009). First, the main attribute of patent data over other data sources, such as R&D expenditures, is that patents are *ex post* indicators of the innovation effort. Second, patent are available at a very disaggregated level and, thanks to improvements in patent databases, it is now possible to track where and when patents originated at the firm level and in most of the countries in the world. In addition, patents follow an international patent classification which allows linking a specific patent to its relevant technological field. Third, patent analysis can be refined through the use of indicators. For instance, it is possible to build indicators about the value of a patent, either through the use of forward patent citations made to a specific patent, the size of patent family or patent renewal information (Van Zeebroeck, 2010).

The use of patents as indicators has a number of limitations. Patents are only one of the alternatives for innovators to protect their innovations. In particular, patents grant a temporary exclusion right over a specific innovation in exchange of the public disclosure of this innovation. Consequently, innovators may prefer to keep this innovation secret. Innovators may also aim at protecting their innovation through product complexity or know-how. The propensity to patent innovation may also vary among technological sectors, countries and over time. Whilst this effect does constitute an important bias

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[5] This choice of period is also driven by data constraints as data on public R&D expenditures are only available from 1974 and because patent data are available up to 2008 in our Patstat 2010 edition.

when presenting descriptive statistics about patents, the use of country and time fixed effects, along with focusing on only one technological sector, can mitigate this problem in econometric analysis.

More importantly to our analysis, atomic energy patents have received a specific treatment compared to the rest of the intellectual property right system. Atomic energy patents encompass the unique attribute, along with defense related technologies, that an innovation patented can be classified and remain *de facto* secret for a period of time. In addition, some atomic energy patents legislations do allow the preemption of firms' patent rights to the benefit of government agencies, through compulsory licensing, if the innovation is thought to benefit to the general interest[6].

If the impacts of these specific legislations on the incentives to patent and to innovate have been extensively pointed out by legal scholars (Newman and Miller, 1947; Joint Congressional Committee on Atomic Energy, 1959), it is generally recognized that these features of atomic patents have progressively faded away as private enterprises become largely involved in the development of nuclear technologies and needed intellectual property rights to secure the economic benefits of their innovation effort (Hamann, 1962), all the more when countries started to export their nuclear technologies. It is reasonable to argue that patent secrecy is not a problem for our analysis which goes back to 1974 where many reactor technologies had already been transferred to other countries.

When using patent to measure innovation, one needs to be able to assess which patent classification classes are relevant to the analysis. In that respect, our empirical work has largely benefited from the creation by the EPO of a new classification specific to climate change related technologies which includes a technology class specific to nuclear fission reactors "Y02E30"[7].

In parallel, we retrieve atomic energy patents applications between 1938[8] and 2008 in the 12 countries studied in our analysis using the EPO / OECD World Patent Statistical Database[9] (Patstat) in order to build our innovation dependent variables, knowledge stock based on previously patented innovation and the forward citations made to these patents. In the end, our dependent variable includes 7,999 priority[10] patent applications between 1974 and 2008.

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[6] For instance, this provision is present in the US 1954 Atomic Energy Act.

[7] See : http://worldwide.espacenet.com/eclasrch?classification=ecla&locale=en_EP&ECLA=y02e30

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

[9] Available at: http://www.epo.org/searching/subscription/raw/product-14-24.html

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

3.2. Data on nuclear power plants construction and cancellation

Data on nuclear power plant construction are retrieved from the International Atomic Energy Agency (IAEA) Power Reactor Information System (PRIS) database[11]. This database includes general information about all the NPPs in the world since 1970 and in particular information about the date when the construction of one NPP starts, finishes and/or is cancelled in every country in the world. It also includes information about NPPs' energy capacity and their characteristics in terms of design and reactor supplier. Moreover, the PRIS database provides detailed information about the operation of NPPs and in particular about outages causes and durations at the NPP level.

Using this database we retrieved information about the dates when the construction of NPPs started and about their capacity (in MWe) in the twelve countries studied in our panel model and in the rest of the world since 1974. We also collect data on the date of NPPs construction cancellation, i.e., NPPs whose construction started but were not finished because of government or utility decisions. At the end, our dataset includes 237 NPPs whose construction started in the twelve market economies studied in our econometric model between 1974 and 2008 with a total capacity of 241 GWe. In parallel 141 NPPs construction started during this same period in the rest of the world, with a total capacity of 116 GWe. These NPPs constructions in the rest of the world have essentially taken place in Russia (25 NPPs), China (22 NPPs), Ukraine (21 NPPs) and India (16 NPPs). Finally, out of the 237 NPPs whose construction started in the countries studied, 51 have been cancelled during the construction stage, representing a total capacity of 51 GWe. These NPPs cancellations took place in the US (41 NPPs) and Germany (6 NPPs) and Spain (4 NPPs).

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

In parallel, we also use the PRIS database to collect data on NPPs outages, their characteristics and occurrences. Outages are available in the PRIS database at the NPP and year level and include information on their causes (e.g., refueling, inspection, technical failures), the systems impacted (e.g., steam generator, turbine), the total duration and the electricity generation loss resulting from these outages. More specifically, we are interested in NPPs outages resulting from inspections made by the nuclear safety authority or from the nuclear safety authority decision to temporarily close a NPP because of non-compliance with the safety standards. These two kinds of outages are thought to capture two distinct attributes of the nuclear safety regulation and have been used by economists to capture the role of nuclear safety regulation (Feinstein, 1989). The number of inspections (Brunnermeier and Cohen, 2003) and non-compliances events (Muehlenbachs et ali., 2011) at industrial installations are a common proxy to measure regulation stringency. Outages resulting from

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[11] Available at :http://prisweb.iaea.org (access restricted)

inspections are used a proxy for nuclear safety monitoring while outages resulting from non-compliance with the safety regulation are used to capture nuclear operators non-compliance with safety standards. However, this latter variable should be interpreted cautiously as it may also reflect increases in the rate of non-compliance detection or increases in nuclear safety standards stringency (Feinstein, 1989).

These two variables are expressed in each country in terms of the annual average number of outages per reactor for both kinds of outages. Clearly, taking into account the duration or the energy loss resulting from these outages would have been preferable. However, this measure would have been biased as, for instance, nuclear operators take advantage of the inspections to undertake refueling and maintenance work. In the end, our dataset includes 11,034 outages resulting from inspections and 484 outages resulting from nuclear safety regulators decisions between 1974 and 2008 in the twelve countries studied in our panel model.

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

Data on public R&D expenditures were collected from the International Energy Agency (IEA) energy technology R&D database[12]. These data are available since 1974, with few missing years for some countries which have not been reported to the IAE, for all the IAE member states and include disaggregated information about R&D expenditures for nuclear fission. In particular, we were able to extract information specific to nuclear reactors public R&D expenditures, and exclude expenditures covering other stages of the nuclear fuel cycle[13].

We also collect data on countries annual GDP between 1974 and 2008 using the World Bank database[14], measured in 2010 US dollar current price and adjusted for purchasing power parity.

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[12] Available at: http://wds.iea.org.

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

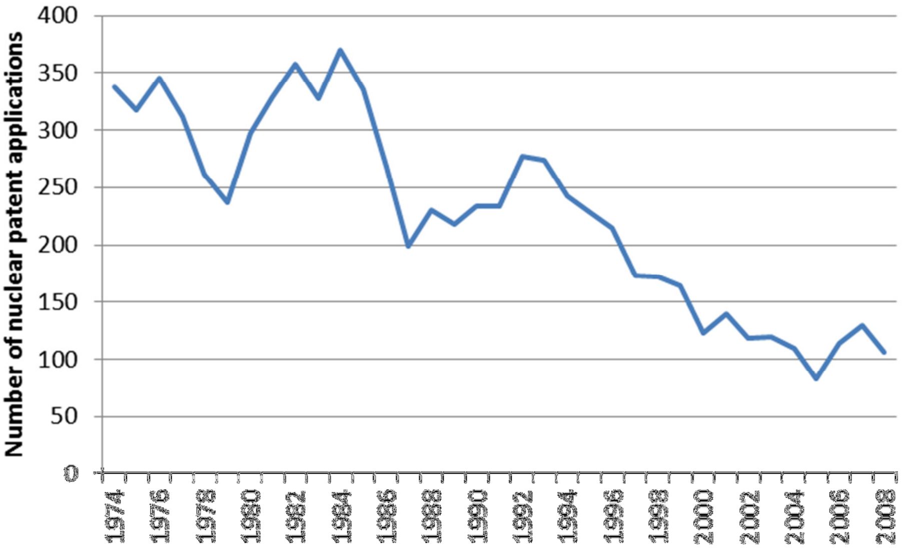
[14] Available at: http://data.worldbank.org/.

4. Innovation and diffusion of nuclear reactor technologies

4.1. Distribution of nuclear reactor patents

This section presents the distribution of nuclear patents specific to nuclear reactors between 1974 and 2008. Figure 1 and 2 present respectively the trend in priority patent applications between 1974 and 2008 and their distribution among the twelve countries[15] studied in our empirical model. The choice of country studied is based on a number of criteria and constraints. First, data on R&D expenditures in nuclear reactor technologies are only available for OECD countries. Second, we are only interested in countries with active and commercial NPPs. Third, in order to provide meaningful results we need to study countries with intellectually property law system in place throughout the period[16]. As Figure 1 highlights, patent applications in the field of nuclear reactors have experienced a decreasing trend over the period studied, in particular since 1984, ranging from 371 patent applications in 1984 and 82 in 2005. It is worth noting that this trend may be reversing at the end of the period with a 40 % increase in patent application between 2005 and 2008. The distribution of these patents among countries shows that innovation essentially took place in the United-States, France, Japan and Germany, these four countries representing 90 % of our sample. Note that this trend is opposite to what is happening in other technological sectors such as electronic or ICT or pharmaceutical.

Figure 1: Trend in patent applications in nuclear reactor technologies (1974 – 2008)



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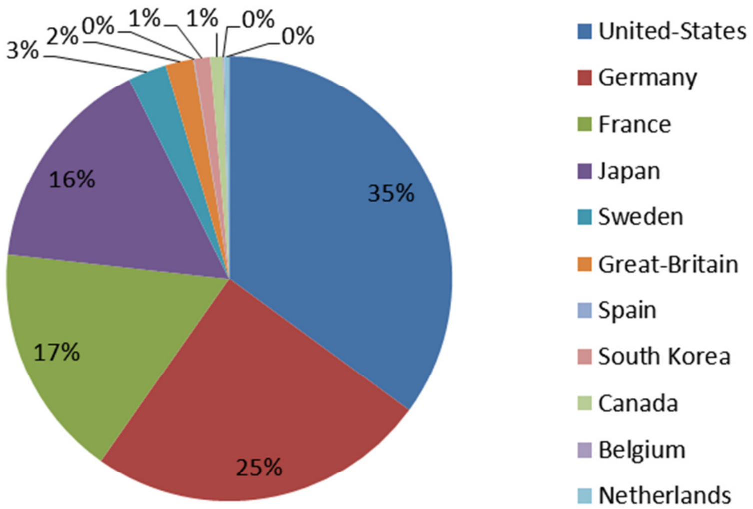
[15] Namely: Belgium, France, Great Britain, Japan, South Korea, the Netherland, Spain, Sweden, Switzerland, Canada, Germany and the United-States.

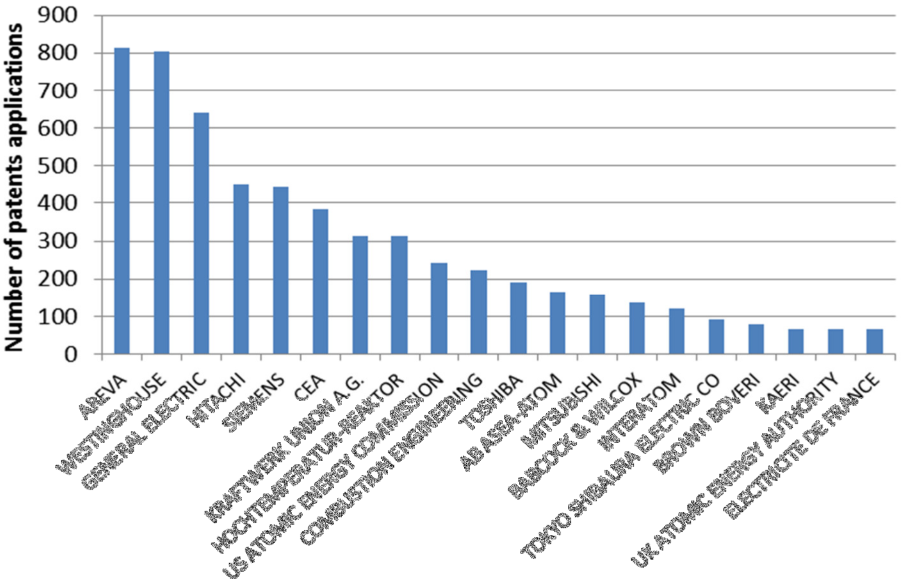
[16] For instance, even if we would have access to public R&D expenditures in Russia or China, we would not keep them in our panel study as the notion of property has historically been very distinct in these countries compared to the Western Europe countries or to the United-States.

Figure 2: Distribution of patent applications among countries (1974 – 2008)



If we now focus on the main firms and public research organizations[17] applying for patent protection in nuclear reactors technologies, we observe that firms represent the vast majority of innovators in this field which is also characterized by few large organizations. Figure 3 presents the top-20 of innovating organizations in our sample and shows that the nuclear innovation system between 1974 and 2008 in the twelve countries studied is highly concentrated as the top-20 organizations represent 70 % of our dataset with 5771 patent applications. In particular, AREVA, Westinghouse and General Electric represent more than 25 % of all the innovating organizations. Moreover, private firms represent 88 % of these 20 organizations and more than 90 % of all the organizations.

Figure 3: Top-20 of innovating organizations in nuclear reactors (1974 – 2008)



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

Finally, innovation in nuclear reactor technologies is also characterized by the importance of foreign patenting. In other words, innovators do not only seek patent protection in their home country but will also extend these patents abroad[18], suggesting that foreign markets opportunities are an important to nuclear reactor innovators. In particular, between 1974 and 2008 in the twelve countries studied, international inventions, i.e., innovations that have been extended in at least one other country (Dechezleprêtre et ali., 2011), account for about two thirds of all the nuclear reactors patents and are patented, on average, in 4.8 countries. As Table 1 shows, this propensity to seek patent protection is a feature of most of the countries studied and this flow of patent export is directed both toward OECD and non-OECD countries.

This propensity to export patent does vary between countries as, for instance, Spain exports only 3.7% of its patents abroad while Sweden exports 98.7% of its patents. Moreover, countries tend to export their patents more toward other OECD countries than non-OECD countries. For example, South Korea exports 93.5 % of its patents toward OECD countries but only 30.4 % toward non-OECD countries. However, patent exports toward non-OECD countries remains an important feature of nuclear reactor patents as on average 38.2 % of the patents are exported toward these countries, implying that market opportunities are not only soughed in OECD countries but also in the rest of the world. In particular, the top four non-OECD countries where patent protection have been sought by innovators in the countries studied are China, South-Africa, Russia and Brazil. The fact that patent applicants seek patent protection in these countries is not without importance for our empirical analysis as it supports the hypothesis that nuclear developments in these non-OECD countries matters for nuclear innovators.

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

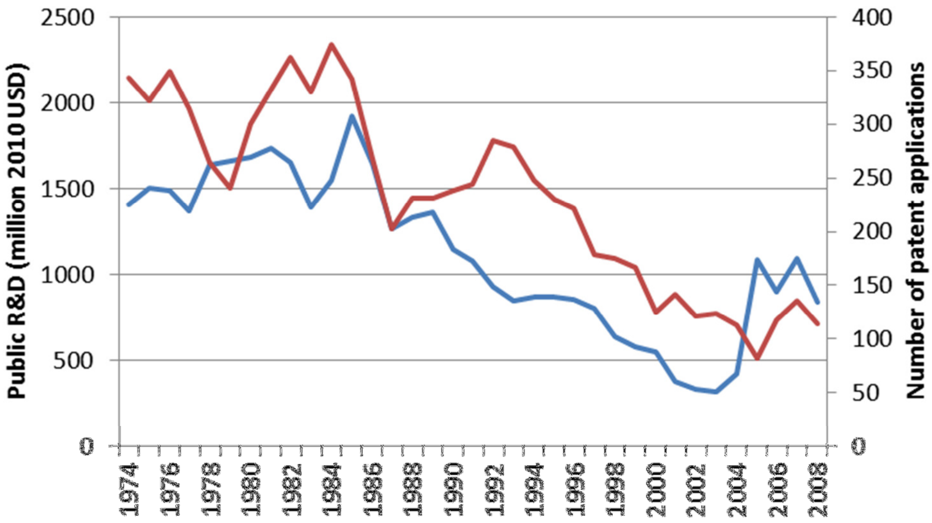
Table 1: Patent export rate for the twelve OECD countries between 1974 – 2008

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

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

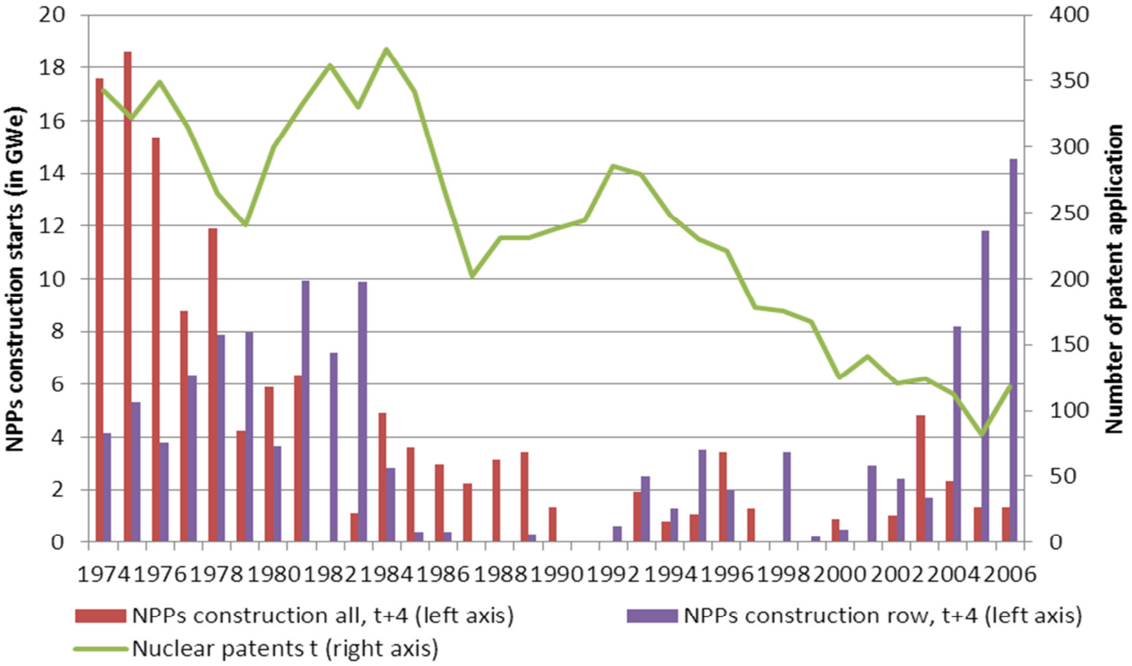
Turning to the influence of public R&D expenditures and NPPs constructions on nuclear reactor innovation, a descriptive overview highlights that those variables are highly correlated. In particular, Figure 4 and 5 highlights the trend and correlation between innovation and respectively public R&D expenditures and NPPs construction in the innovating countries and in the rest of the world. As Figure 4 shows, public R&D expenditures specific to nuclear reactors have experienced a decreasing trend over the 1974 – 2008 period in the 12 countries studied with a maximum of nearly 2 billion USD in 1985 and a minimum of 300 million USD in 2003. Alike nuclear innovation, the trend has been increasing during the last few years with an increase of 63 % between 2003 and 2008 and both variable are highly correlated with a correlation coefficient of 78 % between public R&D expenditures and innovation.

Figure 4: Nuclear patent applications and public R&D expenditures for nuclear reactors



Similarly, as Figure 5 shows, nuclear reactor innovation and NPPs constructions in the innovating countries and in the rest of the world, aggregated among countries, are also correlated with respectively a correlation coefficient of 32 and 40 % when a four years lag is taken for NPPs constructions. More importantly, we observe that during the beginning of the period, the decrease in NPPs in the innovating countries has been substituted by an increase in NPPs construction in the rest of the world which could be interpreted as a factor explaining why, during this period, innovation continued to increase slowly in the innovating countries.

Figure 5: Nuclear patent applications and NPPs construction



5. Empirical model and results

5.1. Main hypotheses and variables specifications

Descriptive insights from section 4 suggest that innovation in nuclear reactors has been induced by technology-push (i.e., public R&D expenditures) and demand-pull (i.e., NPPs construction) incentives. When we consider NPPs constructions in the innovating countries and in the rest of the world, we observe that both are correlated with the innovation activity and may have contributed at different moments to support innovation.

As aforementioned in section 3, patent data can be used in a number of ways as a measure of innovation. In that respect, a common measure of patent is to consider the row count of priority patent applications in one country at time t. However, thanks to the Patstat database, we are able to introduce a second measure of innovation which takes into account the quality of the patent through the count of forward citations[19] received by these patents within the next five years (van Zeebroeck, 2010) such as:

$$Weighted_{patent_{i,t,T}} = \sum_{s=t}^{t+T} \sum_{j \in J(s)} C_{j,i} \qquad (1)$$

Weighted_patent$_{i,T}$ is the number of forward citations received by patent filed by innovators in country i published in year t within T years from its publication. $C_{j,i}$ is a dummy variable which is equal to 1 if application j is citing application i, and 0 otherwise. $J(s)$ is the set of all applications published in year s. We set a value of $T = 5$, a value commonly used in the literature, to treat application years in a consistent manner and the last four years of our sample are censored to avoid truncation bias. Moreover, the use of time and country fixed effects in our sample allows controlling for unobservable changes in the propensity to patent over time and among countries. Using these two measures of innovation we are able to assess the extent to which our results will be impacted when the quality of innovation is introduced and whether some explanatory variables induce not only more innovation but also more valuable innovation.

Public R&D expenditures $RD_{i,t}$ are used to capture technology-push incentives. Similarly to Popp (2002) or Dechezleprêtre and Glachant (2011) we use current expenditures at time t to explain innovating activity at the same period. While the presence of public organization in our patent dataset could create an endogeneity problem, we do not consider that this should be regarded as an important bias in our analysis as most of the public organizations in the nuclear industry do in fact generate a large proportion of their revenue from public-private partnerships. This feature of public organizations is especially strong for nuclear reactors technology development (OECD/NEA, 2007).

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

In parallel, NPPs constructions in the innovating country $cap_{i,t+4}$ and in the rest of the world (row) $cap_{row,t+4}$, measured in MWe, are used to capture demand-pull incentives. Unlike Dechezleprêtre and Glachant (2011) we do not consider that this variable captures only the expectations about government support for demand, but the expectations about the market size for NPPs[20]. The construction of NPPs in the rest of the world, with respect to each country i, is used to capture the spillovers that foreign nuclear programs can have on national innovation. Indeed, as shown in Table 1, innovators tend to file international patents in both OECD and non-OECD countries, which highlights that international market opportunities matter for national innovators. Moreover, it is important to take into account the long term planning process which takes place before the construction of a NPP and the fact that the construction time of a nuclear reactor can vary extensively between 5 and 10 years. In that respect, it is necessary to consider the date when the construction of the NPP starts and not the date when the construction finishes. While little empirical evidences exist about the lag between the innovation and diffusion of nuclear reactors technologies, Lor (2008) shows a four years delay between patent applications and technology transfer agreements for the CEA nuclear patents. Based on these evidences, we decide to take a four years lag for our demand-push variables. We also decide not to build a model about innovators' expectations and measure these demand-pull variables in terms of the NPPs capacity (in MWe) as the long term planning process implies that the nuclear industry has usually a good foresight about future constructions.

One may also expect that, given the eventful history of nuclear power development, political decisions, and in particular political decisions to revisit NPPs construction programs, can adversely impact innovation activity as innovators expect a lower return on their investment in innovating technologies. In practice, these political events have emerged largely as consequences of the Three Miles Island (TMI) and Chernobyl accidents (in Ukraine) in the United-States and Germany respectively. We attempt to measure this impact of political decisions through the number of NPPs whose constructions started but were never completed (in MWe) at time t ($cancelled_{i,t}$). While this measure could be an imperfect measure of political decisions since the decision not to finish NPPs construction can originate both from the government and the utilities, Delmas and Heiman (2001) show that US utilities decisions not to finish NPPs constructions following the TMI accident were directly influenced by the changes in the US government attitude toward nuclear power. Moreover, we argue that this measure of a political shock is a better proxy than using dummy variables for the TMI and Chernobyl accidents as it captures the propagation of these accidents within the nuclear industry over time.

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[20] The reason is that if wind power generation is not competitive without public support schemes such as feed-in tariffs or green certificates, NPPs have been commercialized without *direct* subsidies. However, one may argue that NPPs constructions have benefited from *indirect* subsidies through, for instance, limited liability schemes in case of nuclear accidents.

Nuclear safety regulation is also a key characteristic of the nuclear industry. Finding a suitable proxy for nuclear safety stringency is a difficult task since nuclear safety regulation includes many dimensions (OECD/NEA, 2008). As aforementioned, our approach to nuclear safety is to consider that it is constituted of two components: i) NPPs monitoring activity and ii) NPPs outages resulting from the nuclear operator failure to comply with safety standards. Nuclear safety monitoring, measured by the annual average number of regulatory inspections per reactor in one country $inspection_{i,t}$, is used to capture nuclear safety regulation stringency. This approach of nuclear safety regulation is similar to the measure of environmental regulation developed by Brunnermeier and Cohen (2003) and is based on the argument that *ex ante* stricter monitoring of NPPs increases the incentive for nuclear operators to comply with nuclear safety standards. The second component, aims at capturing the effect of *ex post* regulatory action if the nuclear operator does not comply with the safety standards. As aforementioned, it is measured by the annual average number of outages per reactor in one country resulting from a decision made by the nuclear safety authority $regulatory\_outage_{i,t}$. In contrast with nuclear inspections, we do not expect regulatory outages to necessarily have of positive impact on innovation. Indeed, while non-compliance with safety standards may spur new innovation to comply with regulation, it may also reflect a lack of resources from nuclear operators which, in turn, may lead to less innovation. Note that this hypothesis about resources constraints would be consistence with the fact that non-compliance events could also reflect increases in the rate of non-compliance detection or more stringent nuclear safety standards.

Finally, we take into account the stock of knowledge available to inventors in country *i* at time *t*. This capture the *"building on giant's shoulders"* effect, in other words todays' innovation is based on the stock of previous innovation. This effect is important from a policy perspective as it indicates that policy incentives do not only induce current innovation but also have long run impacts and may induce a first-mover advantage in the sense that countries with early nuclear programs may maintain a comparative advantages in nuclear innovators compared to late comers. It is measured through the discounted stock of previously patents since 1939 in country *i* and a discount factor δ captures the fact that innovation from the period *t-1* would be more useful to todays' innovation that innovation from *t-2*. Similarly to equation (1), we build two distinct variables. Equation (2) is a simple discounted stock of knowledge and equation (3) is a discounted stock of knowledge weighted by forward patent citations made with a five years window to take into account the quality of the knowledge $CIT_{i,T,t-k}$ available to innovators as defined in equation (1). We take a 10 % discount factor to reflect the empirical literature evidences about knowledge depreciation (Peri, 2005).

$$K_{i,t} = \sum_{k=1}^{\infty}(1-\delta)^k N_{i,t-k} \tag{2}$$

$$Weighted\_K_{i,t} = \sum_{k=1}^{\infty}(1-\delta)^k \, CIT_{i,T,t-k} \tag{3}$$

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

5.2. Empirical framework

Our empirical approach follows a simple panel data approach where fixed effects are introduced for the time and country dimensions of the panel. Because patent data have over-dispersed distribution and arise from counting the number of patents, OLS estimators are biased and it is necessary to use a count data model. We use a Poisson regression[21] to capture this specificity of our data and because, unlike Negative Binomial regressions, Poisson regressions for panel data with Stata[22] allow to control for heteroskedasticity as well as to cluster the standard error at the country level and lead to more robust estimator (Cameron and Trivedi, 2010). This model is estimated using maximum likelihood. We estimate two models, one where the row number of patent applications is used as the explanatory variables and the other one where patent applications are weighted by patent citations as defined in equation (1). We apply a log-linear transformation[23] to the right side of our equations such as:

$$Patent_{i,t} = \alpha_1 \log\_Know_{i,t} + \alpha_2 \log\_RD_{i,t} + \alpha_3 \log\_cap_{i,t+4} + \alpha_4 \log\_cap_{row,t+4} + \alpha_5 \log\_cancelled_{i,t} + \alpha_6 \log\_inspection_{i,t} + \alpha_7 \log\_regulatory\_outage_{i,t} + \alpha_8 \log\_GDP_{i,t} + \eta_{i+}\theta_t + \varepsilon_{i,t} \qquad (4)$$

$$Weighted\_patent_{i,t} = \alpha_1 \log\_Weighted\_Know_{i,t} + \alpha_2 \log\_RD_{i,t} + \alpha_3 \log\_cap_{i,t+4} + \alpha_4 \log\_cap_{row,t+4} + \alpha_5 \log\_cancelled_{i,t} + \alpha_6 \log\_inspection_{i,t} + \alpha_7 \log\_regulatory\_outage_{i,t} + \alpha_8 \log\_GDP_{i,t} + \eta_{i+}\theta_t + \varepsilon_{i,t} \qquad (5)$$

Where, η_i and θ_t are respectively country specific and time specific fixed effects[24]. Similarly, $log\_GDP_{i,t}$ is used to control for countries' economic activity. The explanatory variables follow the notation presented in section 5.2. The panel model is unbalanced as public R&D expenditures data are not available for all the period in some countries (41 observations out of 408 are missing). However, this feature of our data is mitigated by the use of country and time fixed-effect and we have no reason to expect the missing variables to be correlated with the error term $\varepsilon_{i,t}$. Descriptive statistics for the panel data are presented in Table 2.

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

[22] We use Stata 11.1. Cluster-robust standard errors for panel Poisson estimators is a new feature of Stata 11.

[23] We take log(1+X) in order to compute the logarithm when our variables have a value of zero. Robustness checks with log(X) are performed in the Appendix.

[24] We perform the Hausman test for model specification a rejected the null hypothesis that unobserved heterogeneity has uncorrelated with the explanatory variables, hence supporting the choice of country fixed effects over random effects.

As aforementioned, the aim of this empirical framework is twofold: i) Assess the relative importance of our explanatory variables and ii) understand how the magnitude of our explanatory variables is affected when one takes into account the quality of the knowledge available to inventors and the quality of the innovation.

Table 2: Descriptive statistics

Variable	Mean	Std. Dev.	Min	Max
$Patent_{i,t}$	21.1	32.0	0	151
$Weighted\_patent_{i,t}$	34.2	69.9	0	410
$Know_{i,t}$	219.7	261.9	0	902.4
$Weighted\_Know_{i,t}$	321.2	543.7	0	2525.6
$RD_{i,t}$	105.1	147.8	0	681.6
$Cap_{i,t+4}$	381.1	1462.9	0	19256
$Cap_{row,t+4}$	8354.7	8207.5	0	39426
$Cancelled_{i,t}$	139.5	999.4	0	13189
$Regulatory\_outage_{i,t}$	0.033	0.079	0	0.66
$Inspection_{i,t}$	1.06	0.448	0	4
$GDP_{i,t}$	1613.6	2329.1	130.7	11670.8

5.3. Empirical results

Estimation results of equations (4) and (5) are presented in Table 3[25]. We used a Poisson panel data estimator with country fixed-effects and robust-clustered standard errors at the country level. Robustness checks are provided in the Appendix and show that our results are robust when a Negative Binomial estimator and different specifications of our explanatory variables are used and when the panel is restricted to fewer countries.

Estimations from models (1) and (2) show that innovation in nuclear reactors are driven both by technology-push (public R&D expenditures) and demand-pull (NPPs construction) incentives. As these models follow a log-linear transformation, coefficients can be directly interpreted as elasticities. Our results show that public R&D expenditures are the main policy driver of innovation in nuclear reactors as, for instance in model (1), a 10 % increase in public R&D expenditures is estimated to lead to a 0.7 % increase in innovation in nuclear reactors. Similarly, the results for national and foreign demand-pulls confirm the insights from Figure 5: NPPs construction abroad have been a substitute to national NPPs construction program for spurring innovation in nuclear reactors. Moreover, our

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[25] We also estimate model (1) with $log\_weighted\_know_{i,t}$ instead of $log\_know_{i,t}$ as explanatory variable. This does not alter the magnitude of our explanatory variables.

estimates indicate that NPPs construction abroad have a higher impact on innovation than national NPPs construction. This result may arise from the fact that innovators have a higher propensity to patent innovation induced by foreign demand-pull as patent protection may be more important for an innovator to diffuse its innovation abroad compared to its home country.

Table 3: Estimated coefficients of the Poisson fixed-effect regressions

	Model (1)	**Model (2)**
Dependent variable	$Patent_{i,t}$	$Weighted\_patent_{i,t}$
$log\_know_{i,t}$	0.423 **	-
	(0.207)	
$log\_weighted\_know_{i,t}$	-	0.274 **
		(0.134)
$log\_RD_{i,t}$	0.072 **	0.125 ***
	(0,030)	(0,025)
$log\_Cap_{i,t+4}$	0.059 ***	0.078 ***
	(0.012)	(0.014)
$log\_Cap_{row,t+4}$	0.122 ***	0.143 ***
	(0.023)	(0.004)
$log\_cancelled_{i,t}$	-0.056 ***	-0.042 *
	(0.019)	(0.023)
$log\_regulatory\_outage_{i,t}$	-0.612 ***	-0.341
	(0.149)	(0.240)
$log\_inspection_{i,t}$	0.463 **	-0.253 *
	(0.182)	(0.153)
Observation	309	309
Control for GDP	Yes	Yes
Country FE	Yes	Yes
Time FE	Yes	Yes

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

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

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

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

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

Our results also provide important insights about the role of nuclear safety regulation on innovation. In particular, they show that nuclear safety standards monitoring, measured by the average number of inspections per reactor, has a strong positive impact on innovation. This confirms the fact that the level of monitoring increases the incentives for firms to comply with nuclear safety standards which in turn spur innovation in nuclear reactors. In contrast, we find that *ex post* outages resulting from non-compliance of nuclear operators with nuclear safety standards has a negative impact on innovation. We do not argue though that this result should be interpreted as the sign that nuclear safety regulation has some negative effects on innovation. Rather, it underlines that the nuclear operator did not comply with the safety standards which can arise because some lack of resources resulting in less innovation. One may also argue that these events may lead to some eviction effects as companies delegate more resources for compliance with the safety standards to the detriment of innovating activities. The fact that non-compliance events have no incidence on patents weighted by citations in model (2) is also consistent with this hypothesis: with fewer resources, nuclear innovators decide not to patent the least valuable innovations, but will still patent the most valuable innovations which receive more forward citations.

6. Conclusions and policy implications

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

We show that nuclear reactors innovation has been, on average, relatively stable up to the mid-1980s and has since followed a decreasing trend. It is worth noting that this trend may have been reversed since the early 2000s, in line with the perception of a nuclear renaissance. Moreover, this innovation is essentially concentrated in the countries where NPPs constructions at home and NPPs exports have been the most active: the United-States, Germany, France and Japan, account for 90 % of the patents studied.

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

Third, our results provide evidence about the role of nuclear safety regulation on innovation. We find that the level of monitoring (measured by the average number of inspections per reactor) has a positive impact on innovation. This result can be interpreted as the positive effect that regulatory enforcement has on the incentive to innovate in order to comply with safety standards. We find that when nuclear operators do not comply with safety standards and has its NPPs temporarily closed by the safety authority, the impact on innovation is negative. We argue that this result may reflect the fact that nuclear operators do not comply with safety standards because of some lack of resources which may directly, or through an eviction effect, lead to less innovation.

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

In light of the recent Fukushima nuclear accident in Japan, it is worth noting that our results have potentially important policy implications. Similarly to the TMI and the Chernobyl accidents, it can be anticipated that the Fukushima accident will not only lead to a revision of NPPs orders around the world, but may also lead to a reduction of innovation effort in nuclear reactor technologies. In turn, this effect may lead to less improvement in technologies in favor of the competitiveness and safety margins of NPPs. This last point remains speculative though since the links between innovation and improved competitiveness and safety for NPPs is only drawn from evidences on case studies (OECD/NEA, 2007) and has not been empirically measured yet.

In that respect, these results do call for future research on the interplays between innovation in nuclear reactors and the performances of both existing and future reactors. For instance, do these innovations lead to spillover effects in existing reactors or do they only influence future reactors performances? Furthermore, our empirical analysis studies jointly innovation aimed toward more competitive and towards safer NPPs and only addresses one of the dimension of nuclear safety regulation. For instance, one could argue that the NPPs licensing process has important incidences on the nuclear industry incentives to innovate as new innovations may have to undertake long and uncertain regulatory reviews before being embodied into nuclear reactors (Cohen, 1979). This calls for future research on both the measure of safety regulation and the direction of nuclear innovation as one may argue that safety regulation could play a role on both the pace and the direction of innovation, for instance by increasing the research effort to improve NPPs safety margins. In particular, it stresses the need to dismantle innovations in nuclear reactors between those in favor of more competitive reactors and those in favor of an increase in NPPs safety margins. Key word searches based on patent abstracts could be a way to address this issue.

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Appendix: robustness checks

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

1. Use of a Negative Binomial estimator, as this estimator is more suited to handle over-dispersion of our dependent variable (Table 4);

2. Drop of Belgium, the Netherlands and Spain as these three countries have very few patent filed in nuclear reactor technologies (Table 5);

3. Alternative value of the discount factor δ used to build the knowledge stocks and drop of the NPPs built by Russia (within or outside the former USSR) for the foreign demand-pull as one may argue that these NPPs constructions were a captive market for the Russian nuclear industry (Table 6).

Table 4: Estimated coefficients of the Negative Binomial fixed-effect regressions

	Model (1)	**Model (2)**
Dependent variable	$Patent_{i,t}$	$Weighted\_patent_{i,t}$
$log\_know_{i,t}$	0.815 *** (0.114)	-
$log\_weighted\_know_{i,t}$	-	0.571 *** (0.070)
$log\_RD_{i,t}$	0.052 ** (0,022)	0.093 *** (0,021)
$log\_Cap_{i,t+4}$	0.036 *** (0.013)	0.062 *** (0.014)
$log\_Cap_{row,t+4}$	0.122 ** (0.057)	0.116 (0.073)
$log\_cancelled_{i,t}$	-0.041 ** (0.016)	-0.033 ** (0.013)
$log\_regulatory\_outage_{i,t}$	-0.106 (0.368)	-0.392 (0.351)
$log\_inspection_{i,t}$	0.594 *** (0.167)	0.263 (0.183)
Observation	309	309
Control for GDP	Yes	Yes
Country FE	Yes	Yes
Time FE	Yes	Yes

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

Table 5: Estimated coefficients of the Poisson fixed-effect regressions (Excluding Belgium, the Netherlands and Spain)

	Model (1)	**Model (2)**
Dependent variable	$Patent_{i,t}$	$Weighted\_patent_{i,t}$
$log\_know_{i,t}$	0.380 *	-
	(0.210)	
$log\_weighted\_know_{i,t}$	-	0.328 **
		(0.142)
$log\_RD_{i,t}$	0.076 ***	0.117 ***
	(0.029)	(0.016)
$log\_Cap_{i,t+4}$	0.058 ***	0.080 ***
	(0.012)	(0.012)
$log\_Cap_{row,t+4}$	0.120 **	0.138 ***
	(0.023)	(0.033)
$log\_cancelled_{i,t}$	-0.056 ***	-0.046 **
	(0.020)	(0.023)
$log\_regulatory\_outage_{i,t}$	-0.631 ***	-0.642 ***
	(0.152)	(0.035)
$log\_inspection_{i,t}$	0.370 ***	-0.035
	(0.152)	(0.165)
Observation	235	235
Control for GDP	Yes	Yes
Country FE	Yes	Yes
Time FE	Yes	Yes

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

Table 5: Alternative specifications of the explanatory variables

	No Russian built NPPs (1)	**No Russian built NPPs (2)**	**δ = 0.2 (3)**	**δ = 0.2 (4)**
Dependent variable	$Patent_{i,t}$	$Weighted\_patent_{i,t}$	$Patent_{i,}$	$Weighted\_patent_{i,}$
$log\_know_{i,t}$	0. 416 **	-	0. 593 ***	-
	(0.208)		(0.154)	
$log\_weighted\_know_{i,t}$	-	0.269 **	-	0.392 ***
		(0.136)		(0.087)
$log\_RD_{i,t}$	0072**	0.125 ***	0.044	0.125 ***
	(0.03)	(0.026)	(0.030)	(0.026)
$log\_Cap_{i,t+4}$	0.059 ***	0.079 ***	0.046 ***	0.060 ***
	(0.013)	(0.014)	(0.010)	(0.014)
$log\_Cap_{row,t+4}$	0.114 ***	0.132 ***	0.097 ***	0.119 ***
	(0.024)	(0.020)	(0.026)	(0.026)
$log\_cancelled_{i,t}$	-0.056 ***	-0.042 *	-0.046 ***	-0.029
	(0.020)	(0.023)	(0.016)	(0.020)
$log\_regulatory\_outage_{i,t}$	-0.613 ***	-0.342	-0.430 ***	-0.130
	(0.153)	(0.246)	(0.149)	(0.196)
$log\_inspection_{i,t}$	0.459 **	0.251 *	0.487 ***	0.192 *
	(0.182)	(0.152)	(0.157)	(0.132)
Observation	309	309	309	309
Control for GDP	Yes	Yes	Yes	Yes
Country FE	Yes	Yes	Yes	Yes
Time FE	Yes	Yes	Yes	Yes

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