Policy-induced low-carbon innovations for buildings: A room for standards? Evidence from France

Valentin Laprie

2024-17 Document de Travail/ Working Paper

EconomiX - UMR 7235 Bâtiment Maurice Allais
Université Paris Nanterre 200, Avenue de la République
92001 Nanterre Cedex

Site Web : economix.fr
Contact : secreteriat@economix.fr
Twitter : @EconomixU

Policy-induced low-carbon innovations for buildings: A room for standards? Evidence from France

Valentin Laprie[1]

EconomiX (UMR 7235) – University Paris X Nanterre, Nanterre, France

Climate Economics Chair, Paris, France

Technical and Scientific Center for Buildings, Champs-sur-Marne, France

April 18, 2023

Abstract

Low-carbon technical change in the building sector is a promising solution to address the challenges of climate change, energy security, and public health. We aim to investigate the effects of various environmental policies on low-carbon innovation in the building sector where strong investment barriers transpire, focusing on France as a case study. Pollution taxes, subsidies, standards, which induce more low-carbon innovation? Using a quality index for patents and a Polynomial Distributed Lag Model, our results suggest a limited impact of a carbon tax on promoting low-carbon innovation within the building sector in France. Moreover, our findings indicate that subsidies targeting less polluting technologies emerge as a primary driver of qualitative innovation. Additionally, our study reveals that energy standards for buildings exert a significant albeit temporary influence on the number of patents in relevant technological domains.

Keywords: Environmental Policy, Technical Change, Patents, Energy Efficiency, Buildings

JEL Codes : O33, O34, O38, Q54, Q55, Q58

---

[1] Contact for corresponding author: valentin.laprie@chaireeconomieduclimat.org

1. Introduction

Although neglected in the literature on induced innovation, low-carbon technical change in the buildings sector presents some interesting features. On the one hand, the sector is a major contributor to current pollution levels. According to the latest Intergovernmental Panel on Climate Change (IPCC) report, CO2 emissions from buildings have grown by 50% since 1990. In 2022, 21% of the world's final energy consumption and 10% of global CO2 emissions are attributable to the residential sector (IEA, 2023). It is therefore essential to cut the GHG emissions associated with final energy consumption in buildings if we are to stay below the 2°C target set by the Paris Agreement. On the other hand, as highlighted by Ürge-Vorsatz et al. (2016), low-carbon solutions for buildings generate benefits that overlap beyond economic and environmental issues. Other co-benefits include improved welfare and health standards in housing, increased 'green' jobs and reduced employment in the fossil fuel sector, increased household disposable income, and increased energy security and sovereignty. Thus, low-carbon technical change for buildings brings environmental, economic, social, health, and geopolitical benefits and should be on the agenda of public authorities.

However, it is well established that technical change is not directed towards clean technologies under natural market conditions. The unpriced nature of polluting activities and the existing positive knowledge spillovers do not provide sufficient incentives for firms to innovate in low-carbon technologies. Moreover, Acemoglu et al. (2012) have highlighted the existence of path dependencies toward polluting technologies when a country has historically invested in this sector and accumulated a stock of knowledge making R&D in polluting technologies more productive. All these market failures call for public action to redirect technical change towards low-carbon technologies.

Hicks was the first to posit the hypothesis that an increase in the relative price of a production factor would drive innovation towards the economy of that factor (Hicks, 1932). Since then, many economists have attempted to measure the impact of environmental policies aimed at increasing the cost of pollution on technological change towards decarbonized technologies in energy production and demand (Popp, 2002), transportation (Aghion *et al.*, 2016), or industrial sectors (Brunnermeier and Cohen, 2003). Yet, despite the role that buildings have to play in reducing greenhouse gas emissions, few studies have focused on the building sector.

The main objective of this paper is to investigate the effects on low-carbon innovation of different environmental policies in the context of investment barriers by differentiating between market-based instruments such as a carbon tax or subsidies and command-and-control instruments such as energy standards. We are focusing on France as a study case since it has a range of environmental policies for buildings and is a trendsetter in terms of energy standards. To our knowledge, such a study applied to the case of France has never been conducted and is innovative in this respect.

As a measure of innovation, we use the count of patents granted in France by national and EP route from 1970 to 2017 in three technological classes of interest, namely (i) the introduction of renewable energies in buildings, (ii) Heating, Ventilation and Air Conditioning (HVAC) Systems and (iii) building and architectural elements. Yet, one of our contributions is to introduce an original measure of patent quality based on their ability to stand out from past knowledge and to shape future knowledge. Therefore, the effects are differentiated between regular innovation and innovation with a strong impact on GHG emissions abatement where the literature on induced innovation is purely interested in simple counting of patents (Girod et al., 2017; Jaffe & Palmer, 1997; Noailly, 2012, among others). We estimate the effects of environmental policies on the different patent counts using a Polynomial Distributed Lag Model to capture the non-linearity of the effects over time.

The paper is organized as follows. In Part 2, we review the literature on induced innovation and environmental policies, establishing our hypotheses. Part 3 outlines our methodology, defining measures for patent quality, relevant environmental policies, and data used. In Part 4, we present our Polynomial Distributed Lag Model. The subsequent section, Part 5, unveils the results, and we conclude in Part 6 with policy implications.

2. Induced low-carbon innovation for buildings: Background and Hypothesis

Public authorities can boost low-carbon innovations in the building sector by increasing pollution costs for households and enhancing the financial attractiveness of green technologies. This, in turn, stimulates demand and incentivizes firms to invest in R&D, resulting in more patent applications—a phenomenon known as the demand-pull effect, well-documented in prior research (Popp, 2019).

While a substantial body of literature like Popp (2002) or Aghion et al. (2016) find higher energy prices (a proxy for carbon tax) correlate with more energy-saving and clean technology patents, Noailly (2012) observes an exception in the buildings sector. This discrepancy can be attributed to sector-specific barriers, including split incentives, information gaps, financial constraints, uncertainty, and retrofit quality concerns.

These barriers are used to explain the Energy Efficiency Gap, the mismatch between financially and socially optimal adoption levels of energy efficient technologies (Jaffe and Stavins, 1994; Linares and Labandeira, 2010; Giraudet, 2011; Gillingham and Palmer, 2014). A study by the French Treasury Department assessed the level of cost-effective energy-saving pools. They found that at least 61TWh of energy could be saved at a negative cost. By introducing a level of hidden cost at 50% of the initial cost, they found that only 50TWh could be saved. If we take into account the irrationality of agents, profitable energy savings could be reduced by 40% (Camilier-Cortial *et al.*, 2017). However, the study lacks a comprehensive approach to all these barriers taken together.

Given the limited buildings-related research on the demand-pull effect from carbon tax (apart from Noailly's study), we maintain the following hypothesis:

H1: *An increase in energy prices induces energy-related patents for buildings*

Alongside carbon taxes, public authorities can trigger the demand-pull mechanism by introducing technology-specific subsidies for consumers to curtail the life-cycle costs of green products. While subsidies' positive influence on technology adoption is well-documented (Hassett and Metcalf, 1995; Jaffe and Stavins, 1995; Gillingham and Palmery, 2014; Hughes and Podolefsky, 2015; Hesselink and Chappin, 2019), their ultimate impact on low-carbon innovation remains understudied.

Yet, (Barradale, 2010) argues that policies subject to implementation uncertainties, such as tax credits, could potentially induce an investment downturn and Johnstone et al. (2010) find no discernible impact of tax credits on the number of green patents but using only dummy variables in their regressions. In contrast, recent research by Gerarden (2023) demonstrates a significant and positive effect of consumer subsidies on long-term advancements in solar panel innovation on top of a higher adoption rate. Given the efficiency of subsidies in driving higher adoption rates for energy efficient products and the lack of clear evidence regarding their link to innovation, we mean to test the following hypothesis:

H2: *Technology-specific subsidies for consumers induce patents in the targeted technologies for buildings*

Beyond market-driven financial incentives, another demand-pull policy with the potential to influence low-carbon innovation in buildings is the establishment of energy or environmental standards, mandating specific energy consumption, insulation, equipment efficiency, or pollutant emissions levels for households' dwellings. Such command-and-control instruments could drive demand, providing incentives for firms in related technology fields to innovate further (Tassey, 1991; Gann, Wang and Hawkins, 1998).

The connection between regulatory environmental standards and innovation has been relatively underexplored in previous literature, primarily due to their heterogeneous nature, which makes them challenging to include in empirical analyses. Nevertheless, some notable findings, such as those by Noailly (2012) and Kim & Brown (2019), highlight a significant association between regulatory energy standards and energy-efficiency-related patents. The same goes for European CO2 emission standards and environmental automotive patents (Barbieri, 2015). In contrast, Girod et al. (2017) find no discernible effect of appliance and building standards but rely solely on undifferentiated energy efficiency patents and binary variables for standards in their analysis.

The first French energy standard for buildings appeared in 1974 as a maximum heat loss coefficient after the first oil crisis, to support the country's energy independence. It was subsequently revised five times, with more stringent coefficients, moving from building insulation to overall energy consumption, to renewable energies, summer comfort, and design requirements. This wide range of requirements is what we expect to lead to low-carbon patents. With that knowledge in mind, we will test the following hypothesis:

H3a: *New building energy standards induce energy-related patents for buildings*

It is noteworthy that standards represent static incentives, locking both targeted actors and related technologies into specific paths once the energy requirements are met and the new technologies are developed, offering limited incentives for further innovation compared to an emission tax (Jaffe and Stavins, 1994; Gann, Wang and Hawkins, 1998; Johnstone, Haščič and Kalamova, 2010). Hence, we will also test the following hypothesis:

H3b: *The initial surge in patent activity following the introduction of a new standard fades over time.*

Also, a distinction is often made between prescriptive technology-based standards and performance standards. The former stipulates the use of specific technologies (e.g., condensing gas boilers or photovoltaic panels), while the latter defines an ultimate level of final energy consumption or emission levels for a dwelling, allowing flexibility in technology choice. In line with the narrow version of Porter's hypothesis, performance-based standards may be more effective in stimulating innovation compared to technology-based prescriptive standards (Jaffe and Palmer, 1997). However, the distinction blurs in the building sector due to potential overlaps or standards existing between these types (see Section 3.2.3). For instance, a building energy standard could set a final maximum energy consumption level for a dwelling along with the mandatory use of specific heating systems. Thus, we refrain from testing specific hypotheses related to the type of standard.

Finally, we indicate that, while not the focus of this study, other energy efficiency policies may significantly impact low-carbon innovation for buildings. For instance, information programs such as consumption feedback, energy and firm labels or *in situ* energy audits proved to be effective in developing energy efficiency (B. Howarth, Haddad and Paton, 2000; Stavins, 2002; Delmas, Fischlein and Asensio, 2013; Newell and Siikamäki, 2014). To address the lack of liquidity for household investments, discounted-interest eco loan programs are also used, although their impacts are ambiguous and often overlooked in the literature (Berry, 1984; Eryzhenskiy, Giraudet and Segú, 2023). White certificate schemes have demonstrated effectiveness in enhancing energy efficiency investment at a negative social cost (Bertoldi *et al.*, 2010; Giraudet, Bodineau and Finon, 2012). Besides inducing green innovation through the demand-pull mechanism, public authorities can directly subsidize low-carbon R&D. Although, in theory, such R&D subsidies are necessary to deviate from pollution knowledge path dependency (Acemoglu et al., 2012), empirical evidence suggests they are less effective than demand-pull mechanisms (Noailly, 2012; Nesta, Vona and Nicolli, 2014; Aghion *et al.*, 2016; Costantini, Crespi and Palma, 2017).

3. Data

In this section, we present both the quality-weighted patent data used to capture low-carbon innovation for buildings in France, and the national environmental policies expected to induce these patents, based on the assumptions described above.

3.1. Patents as a quantitative and qualitative measure of low-carbon innovation

The very ambitious 2 ° C target set by the Paris Agreement (not to mention the 1.5 ° C target) and the delay of most countries in reaching this target call for the future emergence of game-changing low-carbon technologies to drastically sharp future emissions. As is often the case in literature, we define this type of innovation as both a major discontinuity with past knowledge while having a major impact on future knowledge and we take patents to measure it. To identify these high-quality patents, we must therefore identify those that are highly novel (i.e. those that mark a break with the past knowledge flow) and those that have a significant impact (i.e. those on which future knowledge will be based). We start from class Y02B of the Cooperative Patent Classification (CPC), which includes all "Climate change mitigation technologies related to buildings" in the Worldwide Patent Statistical Database (PATSTAT). More precisely, we are interested in technologies for which households can make a choice at the time of construction or during the lifetime of the dwelling to be able to estimate a *demand-pull* effect of environmental policies. We select three sub-classes, sub-class: Y02B 10/00 for "Integration of renewable energy sources in buildings", sub-class Y02B 30/00 for "Energy efficient heating, ventilation or air conditioning (HVAC)" technologies and sub-class Y02B 80/00 for "Architectural or constructional elements improving the thermal performance of buildings". Details of the three technology sub-classes are given in **Table 1**. Patents of interest are all patents belonging to these technological sub-classes granted at the INPI (French Patent and Trademark Office) between 1970 and 2017 by national or EP procedure.

Table 1: *Description of technology classes of interest: Y02B 10/00, Y02B 30/00 and Y02B 80/00*

CPC CODE	Technological content
10/00 Integration of renewable energy sources in buildings}	• Photovoltaic • Solar thermal • Wind • Geothermal heat-pumps • Hydropower in dwellings • Hydropower in dwellings
30/00 Energy efficient heating, ventilation or air conditioning	• Hot water central heating systems using heat pumps • Hot air central heating systems using heat pumps • District heating • Domestic hot-water supply systems using recuperated or waste heat • Heat recovery pumps • Free-cooling systems • Free-cooling systems • Absorption based systems • Efficient control or regulation technologies • Passive houses; Double facade technology
80/00 Architectural or constructional elements improving the thermal performance of buildings	• Insulation • Glazing • Roof garden systems

3.1.1. Patent Novelty

We construct a new novelty indicator where patent documents are represented by a vector of technological classes with the idea that what defines an invention is the intelligent and innovative combination of sub-technology. For example, patent number FR2950988 concerns a “Device for passively tracking the movement of the sun” and is defined by the IPC subclasses F24S50/20 for “Arrangements for controlling solar heat collectors (for tracking)” and G05D3/00 for “Control of position or direction”. The technology covered by the patent is therefore described by the following sub-technology vector:

$$PAT_{FR2950988} = \{F24S50/20\ ;\ G05D3/00\}$$

By doing so for our whole set of patents we can build a Patent - Technology Matrix (PTM) where the number of rows is equal to the number of patents and the number of columns is equal to the number of sub-technologies covered by our patent pool. In this PTM the cell $Tech_{i,k}$ takes the value of 1 if the technological subclass k appears in the patent i and takes the value 0 otherwise. In total, our patent pool covers 2,358 full-digit IPC technology sub-classes (for computation convenience we have excluded all the technological classes that appear less than 5 times over the whole period since even if they can represent a novelty, they have no impact on the knowledge flow). The use of the full-digit IPC sub-classes allows for a higher technological granularity than using 3 or 4-digit classes. From the example of the FR2950988 patent, the 4-digit classes that describe the technology are F24S for "Solar heat collectors, Solar heat systems" and G05D for "Systems for controlling or regulating non-electric variables", a combination that only vaguely describes the technology embedded in the patent. A problem is that the number of subclasses defining a patent is highly variable (on average 3 classes per patent with a variance of 6) and we cannot know how well a given class defines the patent technology without diving into the technical content. However, we can approximate the importance of a class to a patent by looking at how much it relies on it. Thus, the more a technology class defining a patent is present in its backward citations (the citations to previous patents made by patent i), the more likely it is to describe the patent. In our PTM, we weight the occurrence of a class k in a patent i by the total number of classes M and adjust it by the frequency of this class among all its backward citation’s classes BM with $BTech_{i,l}$ the number of times class l appears backward:

$$Tech\,Weight_{i,k} = \frac{Tech_{i,k}}{\sum_{k=1}^{M} Tech_{i,k}} + \frac{BTech_{i,l=k}}{\sum_{l=1}^{BM} BTech_{i,l}}$$

By comparing one by one the technological vectors of the patents we can say how far a patent is technologically from one another but we cannot say to what extent the use of a technology class represents a novelty at time t. We then introduce the temporal character to highlight the yearly evolution of the use of technological classes as the inverted log-frequency of patents containing the class k at year t:

$$Backward\ Inverse\ Patent\ Frequency_{k,t} = \log\left(\frac{\#\ of\ patents\ prior\ t}{\#\ of\ patents\ prior\ t\ with\ Tech_k + 1}\right)$$

The less a class k used by the patent i has been used by previous patents, the more the patent i will be considered novel. It follows that if subsequent patents use the same class k they will reach a lower score which is a problem for us because they may be considered as different from i even though they embed the same technology but in a less novel way. To correct this, we will always use the Backward Inverse Patent Frequency of the first patent using the class k. Finally, we weigh our TPM as the following product:

$$\underbrace{Tech\ Weight_{i,k}}_{\text{class k importance in patent i}} \times \underbrace{Backward\ Inverse\ Patent\ Frequency_{k,t}}_{\text{class k novelty at time t}} \quad ; \quad t = \min t\ with\ k$$

Then we compute the Euclidean distance between each patent defined by its technology vector in the PTM and introduce our novelty score as the average distance between the patent i filed in year t and the patents filed x years prior to t:

$$Novelty_i = \frac{\sum_{j \in \wp_x^i} dist(i,j)}{\#\ of\ patents\ in\ \wp_x^i}$$

with $\wp_x^i$ the patent pool applied x years before the application year of patent i (we take $x =$ 5 years as the baseline but past patent pools of 3 and 10 years are also considered for robustness).

3.1.2. Patent Impact

The impact of a patent is essentially its influence on the path of knowledge. In other words, an impactful patent should be at the root of a large number of subsequent patents and should be found in their backward citations. Although the use of citations has limitations such as the arbitrary nature of the examiner's decision to include certain citations, the variability of their numbers according to the time horizon considered or the discrete mode of their accounting, they remain an unequaled measure of the impact that a patent will have on the technological path. Thus, we use a standard count of the number of citations each patent receives, called forward citations. However, a patent may be cited by multiple patents protecting the same technology but in different countries for example. These patents can be gathered under the same patent family called simple family or EPO worldwide bibliographic data (DOCDB) family. To avoid double counting the same technology citing the focal patent, we count the number of distinct DOCDB families a patent is citing by (those with distinct DOCDB family ID). So, the impact of a patent is defined by:

$$Impact \equiv \# \; of \; patents \; in \; \mathrm{C}_x^i$$

where, C_x^i is the set of patents citing the patent i at most x years after its publication date. The number of citations a patent will receive depends on its publication date since more recent patents have potentially received fewer citations than older ones. The distribution of citations over time is therefore truncated. In addition, Hall et al. (2001) highlight another phenomenon, that by which the distribution of forward citations of older patents is flatter than that of the most recent patents (a median lag of 10 years for the 1975 patents versus 5 years for the 1990 cohort), suggesting a structural change in the propensity to cite patents. Thus, we consider only citations having occurred within five years since the publication date of the focal patent (although 3 and 10-year forward citations will be used for robustness). Furthermore, while the above novelty indicator is somewhat normally distributed, the number of forward citations is a skewed indicator: the bulk of patents are cited rarely or not at all, while a minority receive numerous citations. Such a feature of citation counts will have to be reflected in the definition of the quality of a patent.

3.1.3. High-Quality Patents

As we said earlier, high-quality patents are those that are both at the rupture with the past technological flow and the root of new technological paths. For novel patents to become breakthrough innovations, they must be developed and implemented in a way that creates value for society. Thus, we identify the quality of a patent i using the following product:

$$Quality_i = Novelty_i \times Impact_i$$

According to our definition of quality, patents that receive no citation get a score of 0 since they will have no impact on the technological flow. On the other hand, a patent can be regarded as qualitative if it is very distinct from the technological flow while having a low impact on future knowledge. The most qualitative patents will be those that are both highly novel and highly impactful. We use a 5-year backward horizon for the novelty indicator and a 5-year forward horizon for the number of citations.

Table 2: Top-5 high-quality patents for buildings in the 3 CPC technological classes. *The novelty and impact scores are evaluated with a 5-year backward and forward horizon, respectively.*

Patent N°	Application year	Applicant	Novelty score	Impact score	Quality score
Renewable Energy					
EP2092631	2006	SOLAREDGE	2.72	36	97.74
EP1719910	2004	MITSUBISHI	2.88	32	92.15
EP2374190	2008	SOLAREDGE	2.36	39	92.15
EP1623495	2003	ENECSYS	2.12	40	84.74
WO9604123	1994	W. BARTHLOTT	1.80	46	82.60
HVAC					
EP2096203	2009	V-ZUG	4.80	18	86.46
WO9913562	1997	BOREALIS	2.88	30	86.32
EP2206824	2010	V-ZUG	3.30	21	69.20
EP2322072	2011	V-ZUG	3.34	19	63.42
FR2935468	2009	COOLTECH	3.14	19	59.66
Construction					
EP2357544	2009	VKR HOLDING	1.30	50	64.82
EP0645516	1993	SAINT GOBAIN	1.22	23	27.99
EP1988228	2007	R. MATTHIAS	0.94	11	10.34
EP0480119	1990	WAREMA	1.64	5	8.20
FR2929632	2008	LE PRIEURE	1.50	5	7.50

Table 2 exhibits the 5 most qualitative patents in renewable energy, HVAC, and construction elements. Patent N° *EP2092631* is a clear illustration of the effectiveness of our method for tracking cutting-edge technologies. This patent describes an innovation in solar energy harvesting systems, focusing on the sustainability and maintenance of inverters that convert direct current from PV panels into usable alternating current. The invention introduces an inverter with a removable cartridge containing electrical components, allowing for the easy replacement of faulty components without replacing the entire inverter. This approach aims to extend the inverter's lifespan (the main reason for PV panel breakdowns after 5 to 10 years) while reducing maintenance costs by avoiding expensive whole-unit replacements. This patent is both novel as few prior patents focused on this technical issue and very impactful since it has been subsequently cited by 36 patents between 2006 and 2011.

In the following, we consider as qualitative the patents having a quality score above the 75% quantile[2].

---

[2] To account for the heterogeneity of citations as well as for the number of patents in time, the quantiles are evaluated for each 10 years from 1970 and then introduced as a 10-year moving average.

3.2. Environmental Policies at Stake

As described in Section 2, the need for new technologies to tackle climate change requires demand pull instruments to redirect investment towards low-carbon R&D. In this section, we present the French policies used to test the previously set out hypothesis: a carbon tax, consumer subsidies, and building energy standards.

3.2.1. Incentivise the adoption of low-carbon technologies with a standard Pigouvian tax

In France, the carbon tax is an independent component of energy taxes, but was only introduced in 2014 at a price of €$7/tCO_2$ and then increased annually until reaching €$44.6/tCO_2$ in 2018, the year in which the Yellow Vest protests forced the government to suspend the hike. It has not been increased since then and is therefore a poor source of data for investigating its impact on low-carbon innovation.

Although energy prices are frequently utilized as a proxy for examining induced innovation, careful consideration is warranted. Firstly, a price increase often results in reduced energy consumption rather than an immediate uptick in investment in energy efficiency (Gillingham, Newell and Palmer, 2009). The primary focus of our investigation is the demand-pull effect, wherein consumers exhibit increased demand for energy-efficient goods. However, it seems more plausible that consumers respond to a rise in their energy bills rather than directly to fluctuations in energy prices. Notably, consumers may lack awareness of specific electricity or gas prices. To maintain alignment with the demand-pull hypothesis, we argue for the pertinence of studying the impact of the energy bill rather than focusing solely on energy prices. Additionally, the market price of energy may not consistently reflect the final consumer price due to factors such as taxes and fixed-price contracts offered by energy providers. To ensure the robustness of our analysis, we will conduct supplementary tests incorporating energy prices.

Figure 2 shows the degree to which household energy bills are dependent on energy prices, especially following the oil shocks of the 1970s. However, there are differences in dynamics, for instance between 2000 and 2012 the price of oil increased by more than 150%, whereas the energy bill of French households only increased by 36%. Such a difference can be explained by several factors such as the dynamics of energy taxes, France's relative independence from oil thanks to nuclear energy, or the decrease in the energy intensity of dwellings (-15% between 2000 and 2012[3]).

---

[3] SDES, Bilan énergétique de la France

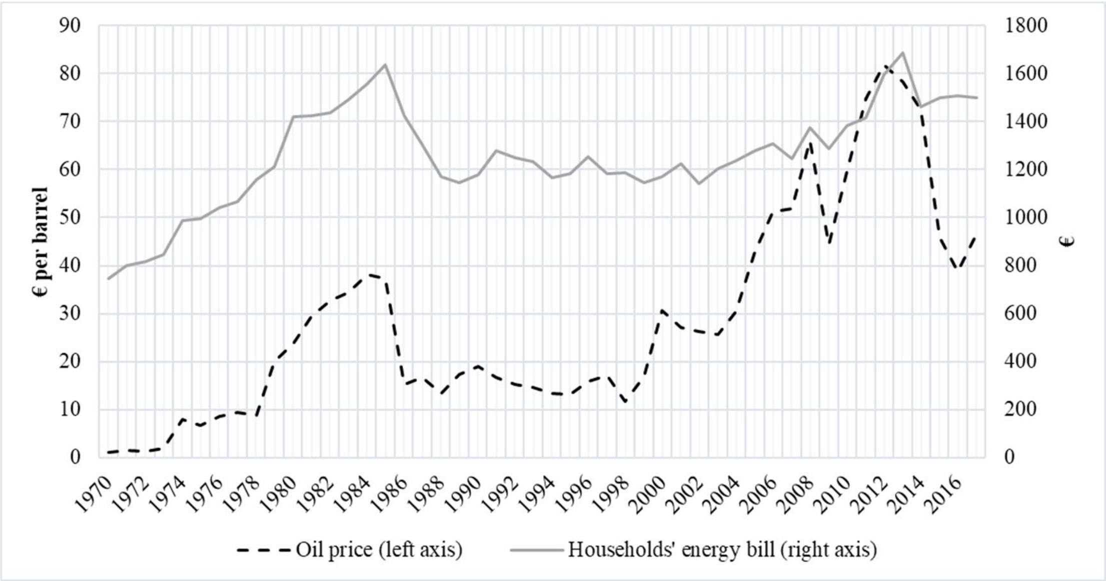


Figure 1: Oil Price VS Annual Household's Energy Bill time series. *The annual energy bill is the total household expenditures for energy in dwellings in billions of euros (source: SDES, Bilan énergétique de la France) divided by the number of principal residences at time. The oil prices are the average spot prices of Brent, Dubai, and West Texas Intermediate, equally weighed (source: World Bank).*

3.2.2. Capital subsidies to give impetus to low-carbon investment

Subsidies for investment in low-carbon technologies for buildings were introduced in France in 2005 and take the form of tax credits. These are available for principal residences without means testing, although the amount depends on income. The tax credit rates have evolved. First differentiated by the type of work and constant regardless of the number of works carried out until 2012, then, to promote global retrofit actions having a real impact on the energy consumption of dwellings, the rates were increased in the case of work packages. In 2014, a simplification of the scheme resulted in a single rate of 30% covering all types of eligible work.

Figure 2 shows the different rates applied to the three work categories of interest: renewable energy (REN), Heating Ventilation, and Air Conditioning (HVAC), and building and architectural elements (CONSTR). Renewable energy technologies were financed at very high rates until 2010. Photovoltaic panels, for instance, were refunded at a rate of 50% until 2010, when their financing decreased to the point where they were removed from the eligible works in 2014.

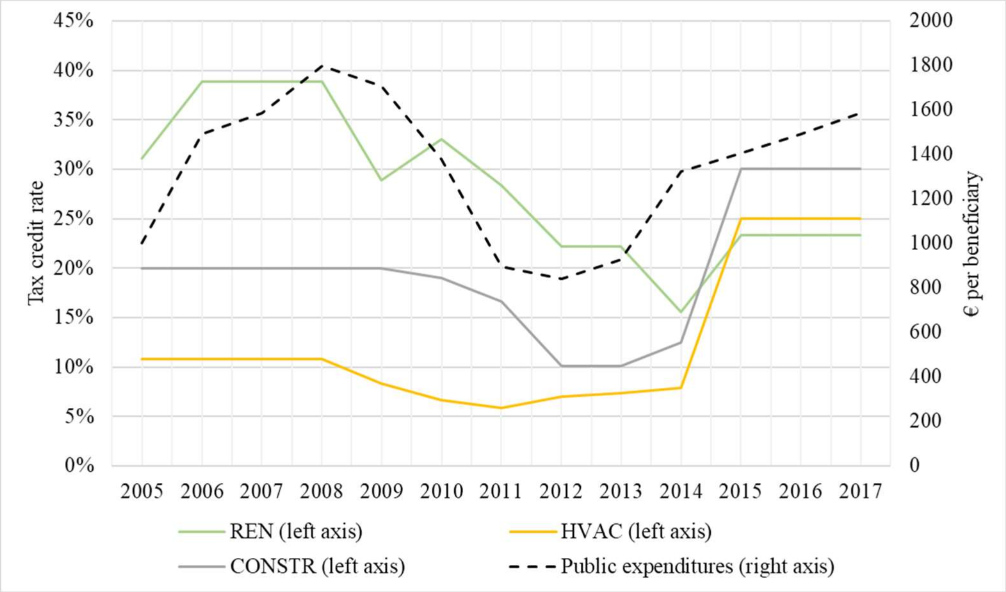


Figure 2: Tax credit rates for the three technology classes and the amount of public expenditure per beneficiary (author's calculation). *The rate for each technological class is the average rate for eligible work each year reorganized to correspond to the technologies included in CPC classes Y02B 10/00, Y02B 30/00, and Y02B 80/00. The eligibility of some technologies has evolved, which is why the average rates do not reach 30% from 2014 onwards. The amounts per beneficiary are projected linearly from 2015 onwards based on the average annual growth rate of the scheme cost since 2012.*

The barriers to investment are evidenced in the figures for tax credit beneficiaries. In 2015, 94% of the declared amounts for subsidies were claimed by owner-occupiers, while the share of rented dwellings was 39.5%, underlining a weak incentive for landlords to undertake retrofits. Also in 2015, 87.9% of the eligible amounts went to individual dwellings while they represented only 66.1% of the building stock, emphasizing here the difficulty of undertaking works when the decision is collective (Inspection Générale des Finances and Conseil Général de l'Environnement et du Développement Durable, 2017).

3.2.3. France, a forerunner in energy standards for buildings

In France, building energy standards are referred to as "Réglementation Thermique" (Thermal Regulation). They are enshrined by law in the building code, and have historically applied only to new buildings, although recent regulations also apply to existing buildings, such as the prohibition from January 2023 on renting out housing with energy labels G or F. The successive thermal regulations and their principal features are presented in **Table 3**.

First introduced in 1974 in reaction to the first oil crisis, these standards were initially based on a maximum heat loss coefficient denoted coefficient G. This coefficient, computed as the ratio between the building's heat loss and habitable volume, set a minimum insulation requirement for new buildings that never existed before.

A significant shift occurred in 1982 when the standards were revised to incorporate free heat gains. This revision introduced a new coefficient, B, which was defined as a function of the original heat loss coefficient, solar radiation, and internal use of the building. Notably, this marked a transition from a focus on heat loss to a broader consideration of the energy needs of the building.

In 1988, France took a pioneering step by introducing a comprehensive energy performance coefficient, emphasizing both heating and hot water performance. This marked a significant milestone as it was the first time that the heating system was explicitly taken into account in the regulations. This innovative approach granted building contractors the flexibility to comply with predefined technologies, meet a heat loss coefficient G, an energy needs coefficient B, or a global energy performance coefficient C. The coefficient C reflects the overall building performance, encompassing heating, domestic hot water, and auxiliary consumptions.

In 2000 the 1988 regulation was revised and France adopted the coefficient C method exclusively. In this approach, the energy consumption of a building should not exceed the coefficient C of a reference building. Furthermore, this regulation introduced considerations for summer comfort inside buildings.

The 2005 regulations that followed were the first to introduce renewable energies such as photovoltaic panels, integrating them as a bonus into the overall energy performance coefficient C. The regulations also encouraged the concept of “bioclimatic design”. This design philosophy favors compact buildings to limit heat loss, optimal orientation to harness exposure to the sun in winter, and measures to cut dependence on cooling in summer. In addition, the 2005 thermal regulation introduced a "Bâtiment Basse Consommation" label for new residential buildings whose coefficient C is less than or equal to 50 $kWh/m^2/year$ (depending on the climatic zone and altitude). Although this is purely a label, France was well ahead of the 2010 Energy Performance of Buildings Directive (EPBD) recast and the ambition to make all new buildings Near Zero Energy Buildings (NZEB) by December 31, 2020.

In 2012, a new thermal regulation revised the 2005 regulation. From now on, the “bioclimatic design” of a building, previously defined, must not exceed the Bbio coefficient, an extension of the coefficient B, which defines the overall energy efficiency of the building. It encompasses architectural design, building form, glazing, amount of natural lighting, insulation, solar heating, and other factors. In addition, the use of a renewable energy source was prescribed among a solar water heater, a thermodynamic water heater, a micro-cogeneration boiler, a connection to the district heating network, or proof of a renewable energy contribution greater than 5 $kWh/m^2/year$ in coefficient C. Apart from renewable energy technologies, the new regulation also prescribed the use of systems for measuring or estimating energy consumption, and the use of presence detectors for lighting. Lastly, the 2012 regulation introduced a stricter coefficient C, making the “Bâtiment Basse Consommation” label compulsory for all new residential buildings. The upper limit of 50 $kWh/m^2/year$ was adjustable based on geographical location and the GHG content of the energies involved. This achievement aligned with the 2010 EPBD's targets concerning Nearly Zero Energy Buildings (NZEBs), positioning France as a front-runner (D’Agostino *et al.*, 2016).

Table 3: *French Thermal Regulations and their main features*

Name	Date	Scope	New Features
RT74	1974	Insulation	• Coefficient G for maximum thermal heat loss with reference levels depending on climatic zone. $G = \frac{HL}{V_h * \Delta T}$ in $W/m^3.K$ where HL are the building’s heat losses in W, V_h the habitable volume in m^3, and ΔT the indoor – outdoor temperature difference.
RT82	1982	Energy needs Insulation	• Coefficient B taking into account free heat supply as internal human activities or the dwelling sunshine with more stringent levels of coefficient G. $B = (1 - F)G$ in $W/m^3.K$ where F is the coefficient of free heat supply from solar radiation and internal use of the building.
RT88	1988	Overall energy consumption	• Coefficient C for minimum global energy performance of the dwelling taking into account stricter coefficients B and G for energy needs, DHW needs, auxiliary needs, and efficiency of equipments: $C = C_{heat} + C_{DHW} + C_{aux} = \frac{B_{heat} * I}{R_{heat}} + \frac{B_{DHW}}{R_{DHW}} + C_{aux}$ in kWh, where C_{heat}, C_{DHW} and C_{aux} are the energy consumptions for heating, DWH, and auxiliaries (flat-rate assessed for ventilation, pumps…), respectively, B_{heat} and B_{DHW} are the energy needs for heating and DHW, respectively, R_{heat} and R_{DHW} are system efficiencies for heating and DHW, respectively and I the intermittence factor (working time, night, holidays).
RT2000	2000	Overall energy consumption Summer comfort	• Coefficient C exclusively with more stringent levels. • The indoor temperature during summer for non-air-conditioned dwellings must be lower than the reference temperature. • Performance standards for insulation, heating, DHW, ventilation, air conditioning, and lighting equipment.

RT2005	2006	Overall energy consumption Renewable energy Bio-climatic design	- The coefficient C is stricter and augmented by the on-site electricity production (Renewable Energy). $C = C_{heat} + C_{cool} + C_{DHW} + C_{light} + C_{vent} + C_{aux} - \boldsymbol{E_{REN}}$ in $kWh/m^2/year$ where some elements are added to the global consumption level of the building such as C_{cool}, C_{light}, and C_{vent}, the energy consumption for cooling, lighting, and ventilation, respectively, and E_{REN} the amount of renewable energy generated. - Bioclimatic design with natural ventilation and lighting. - Introduction of a "Bâtiment Basse Consommation" label for building's consumptions under 50 $kWh/m^2/year$.
RT2012	2012	Overall energy consumption Bio-climatic design Renewable Energy GHG emissions	- Coefficient C at the level of the "Bâtiment Basse Consommation" label: **50** $\boldsymbol{kWh/m^2/year}$ adjustable depending both on the geographic location and the GHG content. - The use of coefficient Bbio for the bioclimatic needs of the building: $\boldsymbol{Bbio = \alpha_1 * B_{heat} + \alpha_2 * B_{cool} + \beta * B_{light}}$ in points where $\boldsymbol{\alpha_1}$, $\boldsymbol{\alpha_2}$, and $\boldsymbol{\beta}$ are specific predefined constants, $\boldsymbol{B_{heat}}$, $\boldsymbol{B_{cool}}$, and $\boldsymbol{B_{light}}$ are the building's needs for heating, cooling, and lighting, respectively. - Prescriptive use of renewable energy technologies, smart meters, and presence detectors for lighting.

France's first-mover status vis-à-vis other European countries and the Union itself makes it a particularly interesting case to study. Indeed, by its demarcation, the country's energy standards policy could have been able to induce environmental innovations that would not have been differentiated from the effects of European policies if other European countries had been studied. In Porter's words: "firms can actually benefit from properly crafted environmental regulations that are more stringent (or are imposed earlier) than those faced by their competitors in other countries" (Porter and van der Linde, 1995).

3.3. Control variables and Summary statistics

All variables used for estimation are summarized in **Table 4**. We use tax credit rates for subsidies distributed to households. For thermal regulations, it would be too simplistic to use a single indicator such as maximum energy consumption in $kWh/m^2/an$, as each regulation is distinct and the scope of requirements increases over time. We therefore prefer to use dichotomous variables to capture the full effect of the policy.

Figure 3 illustrates the trends in the number of general and qualitative patents filed in France, in correlation with the thermal regulations in place at the time. It reveals the surge in innovative activity following these regulations. This is the case, for instance, for renewable energy patents with the RT74, the RT2005, and the RT2012, and HVAC patents with the RT74, the RT88, and the RT2005. The trend in patents for construction elements is more limited, mainly due to the small number of patents filed. Yet the significance of these effects will have to be confirmed by econometric estimation.

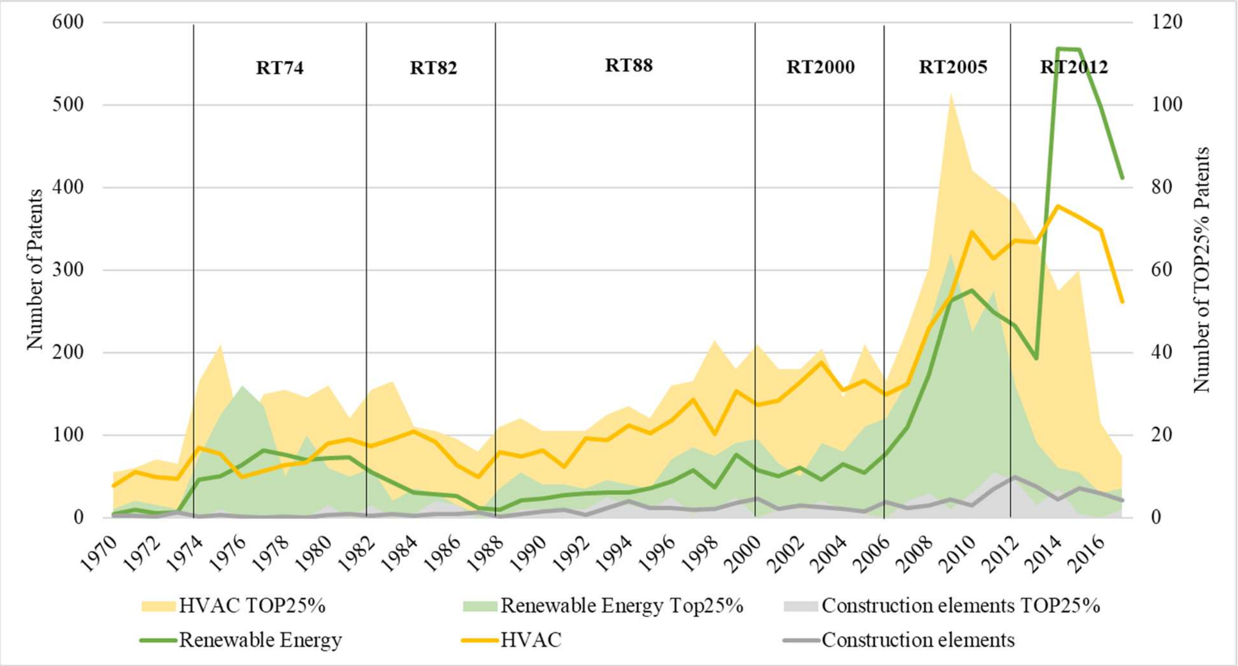


Figure 3: *Number of general and qualitative patents applied in or designating France VS Thermal regulations*

We also define control variables likely to influence the patenting trend of firms. Firstly, the stock of knowledge in each of the three technological classes is defined as the cumulative stock of patents per 1000 inhabitants with one year of lag, computed following the perpetual inventory method:

$$KS_t \;=\; PAT_t \;+ (1-\delta)KS_{t-1}$$

with KS_t the stock of patents of year t and δ a depreciation coefficient for past knowledge of 15% as it is often used in the literature, a value for which we will test the robustness. In addition, we use the growth in energy production from renewables and nuclear power, as well as GDP per capita.

Table 4: *Descriptive Statistics*

Statistic	N	Mean	St. Dev.	Min	Max	Sources
Dependant variables (Number of Patents)						
Renewable Energy	48	106.52	141.54	4	568	PATSTAT
Renewable Energy Top-25%	48	16.17	13.90	1	64	PATSTAT
HVAC	48	144.00	99.08	39	377	PATSTAT
HVAC Top-25%	48	35.23	20.13	11	103	PATSTAT
Construction Elements	48	11.48	11.22	0	49	PATSTAT
Construction Elements Top-25%	48	2.33	2.46	0	11	PATSTAT
Independent variables						
Buildings Energy Bill (in €)	48	1,255.50	213.13	745.32	1,685.46	SDES[4]
Subsidies Renewable Energy (in %)	48	7.67	13.27	0	38.89	IGF[5]
Subsidies HVAC (in %)	48	3.36	6.71	0	25.00	IGF
Subsidies Construction Elements (in %)	48	5.38	9.57	0	30.00	IGF
RT74	48	0.17	0.38	0	1	-
RT82	48	0.12	0.33	0	1	-
RT88	48	0.25	0.44	0	1	-
RT2000	48	0.10	0.31	0	1	-
RT2005	48	0.15	0.36	0	1	-
RT2012	48	0.12	0.33	0	1	-
Control variables						
Knowledge stock Renewable Energy in $t-1$ (per 1000 inhabitants)	48	0.01	0.005	0.0002	0.02	PATSTAT
Knowledge stock HVAC in $t-1$ (per 1000 inhabitants)	48	0.01	0.01	0.005	0.03	PATSTAT
Knowledge stock Construction Elements in $t-1$ (per 1000 inhabitants)	48	0.001	0.001	0.0002	0.003	PATSTAT
Growth Renewable Energy production	48	0.01	0.15	-0.40	0.55	IEA[6]
Growth Nuclear Energy production	48	0.10	0.20	-0.19	0.74	IEA
GDP/capita (in constant €)	48	27,056.44	5,800.94	16,243.46	35,171.30	World Bank

4. Estimation Method

4.1. Polynomial Distributed Lag Model

In estimating the effects of environmental policies on breakthrough low-carbon innovations we believe that a policy will not only produce a single effect with a given lag but should rather have a distributed effect over time, mainly because filing a patent is the final step in a lengthy process of research and development. Addressing the temporal pattern of effects could uncover valuable insights for the design of environmental policies that would be lost with

---

[4] SDES: Service des Données et Etudes Statistique

[5] IGF: Inspection Générale des Finances

[6] IEA: International Energy Agency

one-time effect estimates. Since our dependent variable is the number of patents, which are non-negative integers, we employ a count data model. Thus, we begin with the following simple unconstrained distributed lag model where PAT_t is the number of patents at year t and $POL_{i,t-\ell}$ is the level of a policy i with ℓ year lags:

$$log\left(E\left(PAT_t \mid POL_{i,t\to t-\ell}\right)\right) = \alpha + \sum_{\ell=0}^{L} \beta_{i,\ell} POL_{i,t-\ell} \qquad (1)$$

Because multi-collinearity problems appear when estimating such an equation, we reduce the number of parameters to be estimated by using a polynomial distributed lag model (Almon, 1965) where β's are polynomial functions of the lag of degree p (with $p \in [0, P]$, P sufficiently low and $P < L$) and γ's are parameter to be estimated:

$$\beta_{i,\ell} = f(\ell) = \sum_{p=0}^{P} \gamma_p \ell^p \qquad (2)$$

By introducing *Eq. 2* into *Eq. 1* we obtain the following *Eq. 3* where the number of parameters to be estimated is reduced from $L + 2$ to $P + 2$ and where z's are the linear combinations of the levels of policy from $t - L$ to t:

$$log\left(E\left(PAT_t \mid POL_{i,t\to t-\ell}\right)\right) = \alpha + \sum_{p=0}^{P} \gamma_p z_p \quad with \quad z_p = \sum_{\ell=0}^{L} \ell^p POL_{t-\ell} \qquad (3)$$

The γ parameters estimated from *Eq. 3* are then fed back into equation *Eq. 2* to recover the β values. To assess the significance of the coefficients, other statistics are of particular interest as the variance of the βs:

$$Var\left(\beta_{i,\ell}\right) = \boldsymbol{\ell}\, Var(\widehat{\boldsymbol{\gamma}})\, \boldsymbol{\ell}' \qquad (4)$$

where ℓ is the $P + 1$ dimensional vector of the lag ℓ raised at each degree p and $\widehat{\boldsymbol{\gamma}}$ the vector of the $P + 1$ estimated parameters. We can also derive the cumulative effect of the policy over time along with its variance:

$$S_{\beta_i} = \sum_{\ell} \beta_{i,\ell} \quad \text{and} \quad Var\left(S_{\beta_i}\right) = \boldsymbol{S_L}\, Var(\hat{\boldsymbol{\gamma}})\, \boldsymbol{S_L}' \tag{5}$$

where S_{β_i} is the cumulative effect of policy i on innovation and $\boldsymbol{S_L}$ is the $P + 1$-dimensional vector of the sum of lags ℓ raised at each degree p.

4.2. Specification

To capture enough heterogeneity in the effects of environmental policies on low-carbon innovation without adding too much complexity and too many parameters to estimate, we take 3-degree polynomials for the $\beta_{i,\ell}$ functions. We decide on the number of lags for energy bill and subsidies variables by minimizing the Akaike information criterion between 3 and 8 year-lag[7]. The number of lags used for the successive standards is the number of years the standard is in place before the next one.

Historical patent counts often exhibit overdispersion due to a significant increase in patent filings in the last decade. After testing for overdispersion in our data, we cannot maintain the assumption that the variance and mean are equivalent. Therefore, we employ a negative binomial distribution, introducing a dispersion parameter to adjust for variance. However, our results are robust to a Poisson regression, although they tend to be less conservative. In the analysis of qualitative patents related to construction and architecture elements exclusively, we apply an Ordinary Least Squares (OLS) model with a moving average. This choice is motivated by the limited number of patents, rendering a count data model impractical. The results of these regressions are presented in the next section.

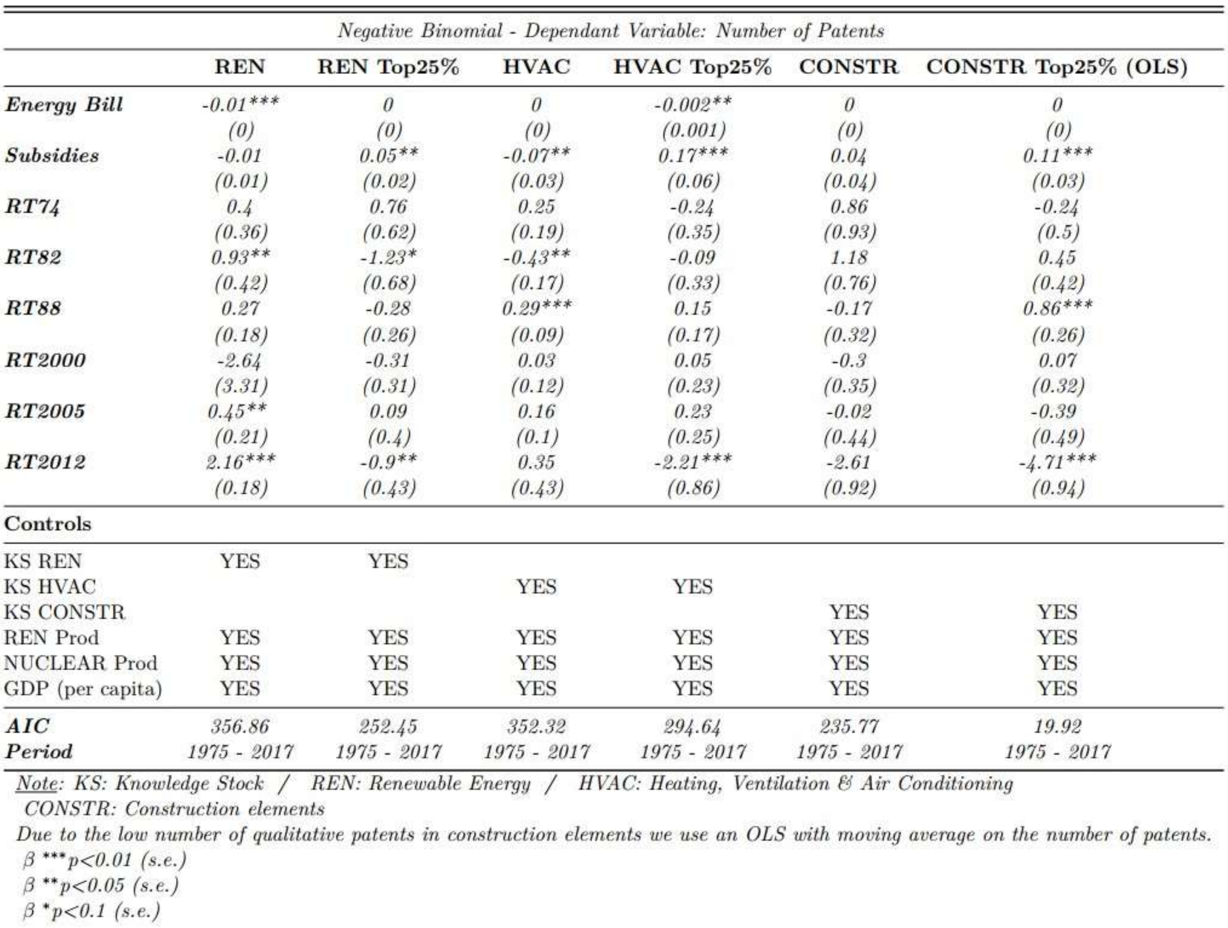
---

[7] Beyond 8 years we lose too much data especially the occurrence of the first energy standard in 1974.

5. Results

In this section, we present the regression results that readers can find in **Table 5**.

Table 5: *Cumulative effects for the three technological classes, differentiating between general and qualitative patents*



Negative Binomial - Dependant Variable: Number of Patents

	REN	REN Top25%	HVAC	HVAC Top25%	CONSTR	CONSTR Top25% (OLS)
Energy Bill	*-0.01****	*0*	*0*	*-0.002***	*0*	*0*
	(0)	*(0)*	*(0)*	*(0.001)*	*(0)*	*(0)*
Subsidies	*-0.01*	*0.05***	*-0.07***	*0.17****	*0.04*	*0.11****
	(0.01)	*(0.02)*	*(0.03)*	*(0.06)*	*(0.04)*	*(0.03)*
RT74	*0.4*	*0.76*	*0.25*	*-0.24*	*0.86*	*-0.24*
	(0.36)	*(0.62)*	*(0.19)*	*(0.35)*	*(0.93)*	*(0.5)*
RT82	*0.93***	*-1.23**	*-0.43***	*-0.09*	*1.18*	*0.45*
	(0.42)	*(0.68)*	*(0.17)*	*(0.33)*	*(0.76)*	*(0.42)*
RT88	*0.27*	*-0.28*	*0.29****	*0.15*	*-0.17*	*0.86****
	(0.18)	*(0.26)*	*(0.09)*	*(0.17)*	*(0.32)*	*(0.26)*
RT2000	*-2.64*	*-0.31*	*0.03*	*0.05*	*-0.3*	*0.07*
	(3.31)	*(0.31)*	*(0.12)*	*(0.23)*	*(0.35)*	*(0.32)*
RT2005	*0.45***	*0.09*	*0.16*	*0.23*	*-0.02*	*-0.39*
	(0.21)	*(0.4)*	*(0.1)*	*(0.25)*	*(0.44)*	*(0.49)*
RT2012	*2.16****	*-0.9***	*0.35*	*-2.21****	*-2.61*	*-4.71****
	(0.18)	*(0.43)*	*(0.43)*	*(0.86)*	*(0.92)*	*(0.94)*
Controls						
KS REN	YES	YES				
KS HVAC			YES	YES		
KS CONSTR					YES	YES
REN Prod	YES	YES	YES	YES	YES	YES
NUCLEAR Prod	YES	YES	YES	YES	YES	YES
GDP (per capita)	YES	YES	YES	YES	YES	YES
AIC	*356.86*	*252.45*	*352.32*	*294.64*	*235.77*	*19.92*
Period	*1975 - 2017*	*1975 - 2017*	*1975 - 2017*	*1975 - 2017*	*1975 - 2017*	*1975 - 2017*

Note: KS: Knowledge Stock / REN: Renewable Energy / HVAC: Heating, Ventilation & Air Conditioning
CONSTR: Construction elements
Due to the low number of qualitative patents in construction elements we use an OLS with moving average on the number of patents.
*β ***p<0.01 (s.e.)*
*β **p<0.05 (s.e.)*
*β *p<0.1 (s.e.)*

5.1. On Market-based instruments: carrot rather than stick

Our first finding is that the higher cost of energy for households (which approximates the effect of a carbon tax) did not have a significant effect on low-carbon innovation, regardless of considering different technological classes or different levels of patent quality. Such a result differs from studies on induced innovation in other sectors (Popp, 2002; Aghion *et al.*, 2016) but is still consistent with the results of Noailly (2012) for the building sector in different European countries. The fact that the increase in energy prices has failed in France to generate incentives to innovate is attributable to the presence of investment barriers discussed above. Lack of information or liquidity, for example, are market failures that could mitigate the demand-pull effect of the Pigouvian internalization of the environmental externality. With such high costs for these technologies, higher energy bills could translate into lower purchasing power and reduced demand. This may explain the negative relationship between renewable and HVAC patents (top 25%).

In contrast, we find a positive and significant effect of low-carbon technology subsidies on the number of high-quality patents in the three technological classes of interest. All else being equal, a 1-point increase in the average rebate rate for equipment costs produced a cumulative increase in the number of qualitative patents of 5 for renewable energy, 11 for building and architectural elements, and 17 for HVAC systems after four to six years. On the one hand, even if the subsidy consists of decreasing the relative cost of clean technologies vis-a`-vis polluting technologies in the fashion of a tax, by focusing on the fixed costs of capital and installation rather than on the operating costs of the technology as a carbon tax would do, the subsidy additionally contributes to mitigating situations of uncertainty on the expected profitability of the equipment depending on future energy prices. On the other hand, a subsidy contributes to lowering other barriers to investment by reducing the need for liquidity to acquire equipment (Gillingham et al., 2009) and by sending an informational signal to households about existing technologies. By reducing the financial and non-financial costs associated with investment, the demand for low-carbon technologies increases and provides market incentives for firms to innovate. It has to be noted that the positive effects only cover high-quality low-carbon innovations[8] according to our indicator. The fact that capital subsidies provide more incentives than taxes is in line with the seminal work of Jaffe & Stavins (1995) and the results from Gerarden (2023) and Girod et al. (2017).

5.2. On Command-and-Control instruments: a diminishing catalyzing effect

Another important result must be noted concerning energy standards. We find that energy standards introducing requirements in new technological classes have a significant positive effect on low-carbon innovation. For example, **Figure 4** and **Figure 5** show that, all else being equal, the 2005 and 2012 standards introducing renewable energy in the calculation of the building's final energy consumption are associated with 45 and 216 additional patents before the implementation of the next standard, respectively. Similarly, we find that the 1988 standard, which introduced the elements of heating and DHW systems through the

---

[8] Except for HVAC for which a 10-point increase in the subsidy rate decreases the number of patents, a result that we cannot explain.

coefficient C generated 29 additional patents (**Figure 6**). The following standard of 2000 did not have a significant impact. Yet a deeper analysis of the temporal profiles of the standards' impact seems to indicate a loss of vigor in the effect of the regulation over time (the last part of cumulative effect curves). This suggests that energy standards have an important short-term effect but that without follow-on regulation the catalyzing impact wanes to the point of creating a perverse effect on innovation by locking the market into existing technological solutions. This is very much in line with the idea that under a standards regime, firms are not incentivized to innovate beyond the targets set (Jaffe, Newell and Stavins, 2002; Fischer, 2003).

Concerning patents for construction and architectural elements we do not detect any significant effects from the first standards setting minimum insulation requirements for buildings (1974 and 1982). However, we observe a positive effect from the RT88, which broadened the perspective on energy needs to encompass the overall energy consumption of the building. We find a negative effect of the RT2012 on high-quality innovation related to construction and architectural elements. It should be noted that the 2012 standards have also had a negative impact on high-quality innovation in renewable energy and HVAC systems. The negative impact of the 2012 standards on most technological classes remains a surprising result. A plausible reason is that this latest standard seeks to reinforce the requirements of past standards, with a maximum heating need coefficient, a maximum energy consumption coefficient, and a summer comfort coefficient, rather than introducing requirements for additional technological classes, as did the 2005 standards for renewable energy and the 1988 standards for heating systems. Therefore the 2012 standard's requirements can be satisfied with already existing products and do not generate incentives to innovate (see again Fischer (2003) and Jaffe et al. (2002)).

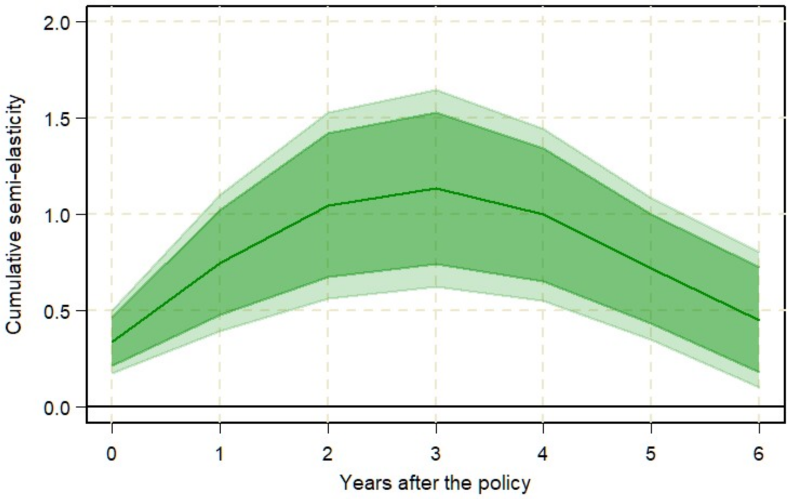


Figure 4: *Cumulative effects of the RT2005 on the number of Renewable Energy patents (the line represents the estimates, the deep green area is the 90% confidence interval and the light green is the 95% confidence interval).*

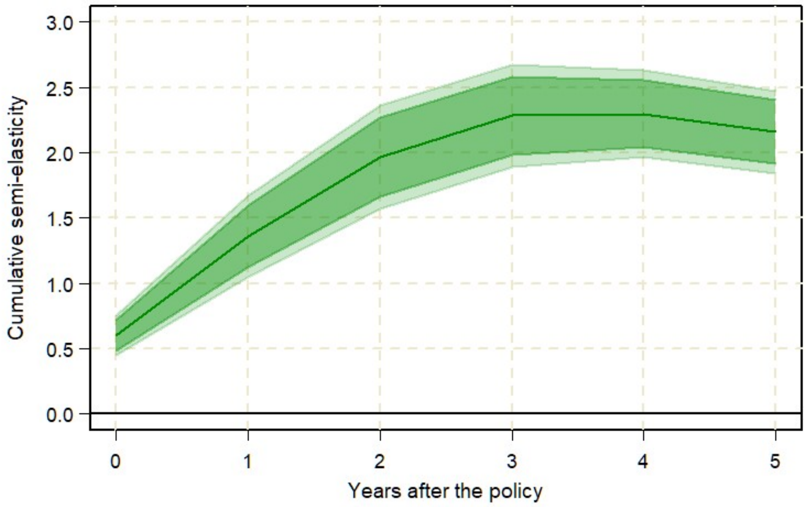


Figure 5: *Cumulative effects of the RT2012 on the number of Renewable Energy patents (the line represents the estimates, the deep yellow area is the 90% confidence interval, and the light yellow is the 95% confidence interval).*

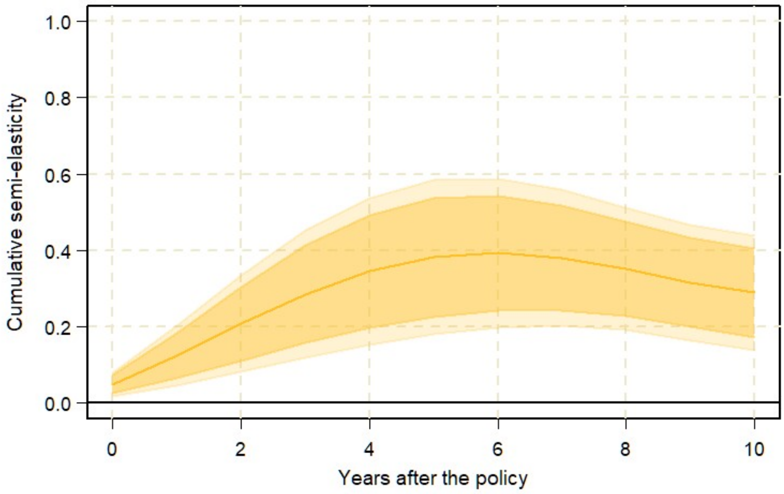
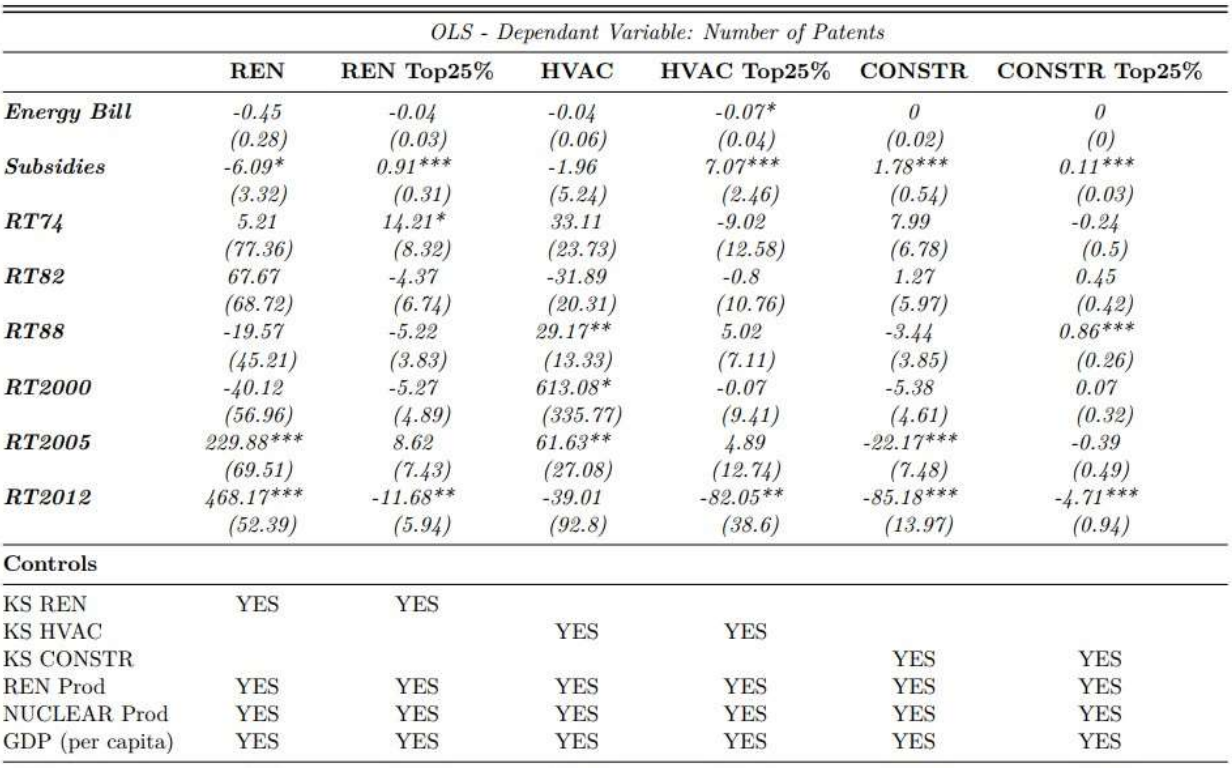


Figure 6: *Cumulative effects of the RT88 on the number of HVAC patents (the line represents the estimates, the deep yellow area is the 90% confidence interval, and the light yellow is the 95% confidence interval).*

5.3. Robustness

All our results are robust to various specifications, including a patent quality level evaluated at the 90th percentile, a Poisson distribution for regressions, and classical Ordinary Least Squares, as shown in **Table 6.** The robustness is also confirmed by depreciation rates of knowledge stock at 10% and 20%, and using the price of oil instead of household energy bills, as demonstrated in **Table 7**. When considering the price of oil, some effects disappear; the RT88 no longer explains the number of patents in HVAC, and subsidies no longer explain high-quality patents, although we attribute this lack of effect to the presence of collinearity between these two variables, confirmed by a Pearson test showing a correlation of 0.76 (t = 7.93, df = 46, p-value = 3.72e-10) with oil prices while only 0.44 with household energy bills (t = 3.29, df = 46, p-value = 0.002). The price of oil is not significant, and the RT2005 and the RT2012 still have a very significant effect on the number of patents in renewable energy, confirming the positive effect of standards as opposed to tax.

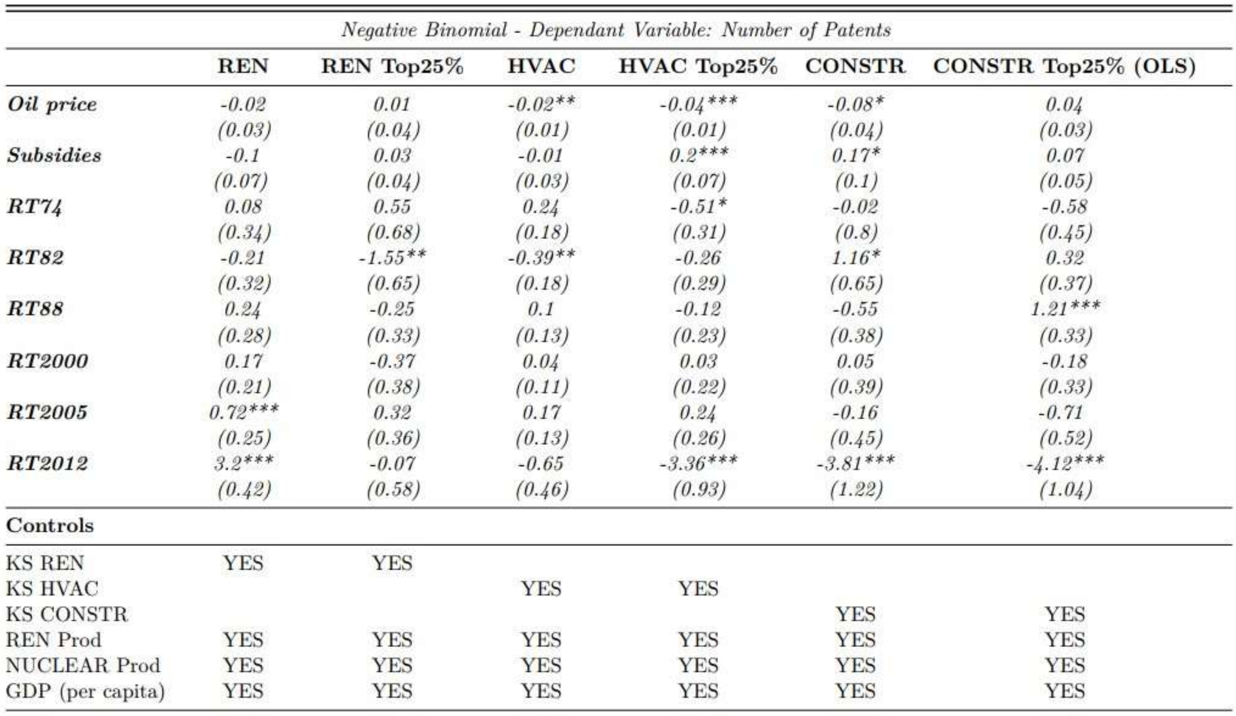
***Table 6**: Cumulative effects with Ordinary Least Square*



OLS - Dependant Variable: Number of Patents

	REN	REN Top25%	HVAC	HVAC Top25%	CONSTR	CONSTR Top25%
Energy Bill	*-0.45*	*-0.04*	*-0.04*	*-0.07**	*0*	*0*
	(0.28)	*(0.03)*	*(0.06)*	*(0.04)*	*(0.02)*	*(0)*
Subsidies	*-6.09**	*0.91****	*-1.96*	*7.07****	*1.78****	*0.11****
	(3.32)	*(0.31)*	*(5.24)*	*(2.46)*	*(0.54)*	*(0.03)*
RT74	*5.21*	*14.21**	*33.11*	*-9.02*	*7.99*	*-0.24*
	(77.36)	*(8.32)*	*(23.73)*	*(12.58)*	*(6.78)*	*(0.5)*
RT82	*67.67*	*-4.37*	*-31.89*	*-0.8*	*1.27*	*0.45*
	(68.72)	*(6.74)*	*(20.31)*	*(10.76)*	*(5.97)*	*(0.42)*
RT88	*-19.57*	*-5.22*	*29.17***	*5.02*	*-3.44*	*0.86****
	(45.21)	*(3.83)*	*(13.33)*	*(7.11)*	*(3.85)*	*(0.26)*
RT2000	*-40.12*	*-5.27*	*613.08**	*-0.07*	*-5.38*	*0.07*
	(56.96)	*(4.89)*	*(335.77)*	*(9.41)*	*(4.61)*	*(0.32)*
RT2005	*229.88****	*8.62*	*61.63***	*4.89*	*-22.17****	*-0.39*
	(69.51)	*(7.43)*	*(27.08)*	*(12.74)*	*(7.48)*	*(0.49)*
RT2012	*468.17****	*-11.68***	*-39.01*	*-82.05***	*-85.18****	*-4.71****
	(52.39)	*(5.94)*	*(92.8)*	*(38.6)*	*(13.97)*	*(0.94)*
Controls						
KS REN	YES	YES				
KS HVAC			YES	YES		
KS CONSTR					YES	YES
REN Prod	YES	YES	YES	YES	YES	YES
NUCLEAR Prod	YES	YES	YES	YES	YES	YES
GDP (per capita)	YES	YES	YES	YES	YES	YES

Table 7: *Cumulative effects with Oil price instead of Energy bill (the oil prices are average spot prices of Brent, Dubai, and West Texas Intermediate, equally weighed (source: World Bank).*



Negative Binomial - Dependant Variable: Number of Patents

	REN	REN Top25%	HVAC	HVAC Top25%	CONSTR	CONSTR Top25% (OLS)
Oil price	*-0.02*	*0.01*	*-0.02***	*-0.04****	*-0.08**	*0.04*
	(0.03)	*(0.04)*	*(0.01)*	*(0.01)*	*(0.04)*	*(0.03)*
Subsidies	*-0.1*	*0.03*	*-0.01*	*0.2****	*0.17**	*0.07*
	(0.07)	*(0.04)*	*(0.03)*	*(0.07)*	*(0.1)*	*(0.05)*
RT74	*0.08*	*0.55*	*0.24*	*-0.51**	*-0.02*	*-0.58*
	(0.34)	*(0.68)*	*(0.18)*	*(0.31)*	*(0.8)*	*(0.45)*
RT82	*-0.21*	*-1.55***	*-0.39***	*-0.26*	*1.16**	*0.32*
	(0.32)	*(0.65)*	*(0.18)*	*(0.29)*	*(0.65)*	*(0.37)*
RT88	*0.24*	*-0.25*	*0.1*	*-0.12*	*-0.55*	*1.21****
	(0.28)	*(0.33)*	*(0.13)*	*(0.23)*	*(0.38)*	*(0.33)*
RT2000	*0.17*	*-0.37*	*0.04*	*0.03*	*0.05*	*-0.18*
	(0.21)	*(0.38)*	*(0.11)*	*(0.22)*	*(0.39)*	*(0.33)*
RT2005	*0.72****	*0.32*	*0.17*	*0.24*	*-0.16*	*-0.71*
	(0.25)	*(0.36)*	*(0.13)*	*(0.26)*	*(0.45)*	*(0.52)*
RT2012	*3.2****	*-0.07*	*-0.65*	*-3.36****	*-3.81****	*-4.12****
	(0.42)	*(0.58)*	*(0.46)*	*(0.93)*	*(1.22)*	*(1.04)*
Controls						
KS REN	YES	YES				
KS HVAC			YES	YES		
KS CONSTR					YES	YES
REN Prod	YES	YES	YES	YES	YES	YES
NUCLEAR Prod	YES	YES	YES	YES	YES	YES
GDP (per capita)	YES	YES	YES	YES	YES	YES

6. Identified limitations

As mentioned in Section 2, the first limitation of this study is the omission of other policies, such as public R&D spending in the relevant technology area. However, we have found only limited data on French R&D spending covering a short period. We tried to incorporate them using instrumental variables to disentangle endogeneity with energy prices, but the results were inconclusive. A second limitation relates to the sample size. Although 48 years is a greater period than is generally considered in the literature, we focus solely on France as a case study. The same analysis could be carried out by examining energy standards and market-based policies in other countries. Thirdly, using PATSTAT's predefined Y02 technological classes is a simplistic representation of low-carbon innovations, as we do not have much detail on the content of patents and there may be errors or misclassifications. A famous example is patents related to two different technologies, namely 4G and 5G, which are classified under the same IPC H04W.

7. Conclusion and policy implications

The purpose of this paper is to investigate the effects on low-carbon innovation of m*arket-based* policies such as taxes and subsidies and of command-and-control instruments such as energy standards in the presence of serious market failures in the building sector, with France as a study case. This dichotomy is particularly worth studying in a market context where failures and obstacles are barriers that tend to undermine the demand-pull mechanisms.

We are only concerned with innovations that have a real impact on the fight against global warming and that are related to technologies for which households have decision-making power. We use patents related to renewable energies in buildings, HVAC systems as well as building and architectural elements granted in France from 1970 to 2017. Next, we define high-quality patents as those that are highly distinguishable from past knowledge while influencing future knowledge. For the *market-based* policies, we use the household energy bill as a proxy for a carbon tax and the tax credit rates associated with investment in the three technological classes considered. For command-and-control policies, we use the occurrence of successive energy standards that have been introduced in France. We estimate the effects of the different public policies through a polynomial distributed lags model.

The findings of this study highlight the nuanced effectiveness of various policy instruments in promoting low-carbon innovation within the building sector. While the implementation of a carbon tax-type instrument shows a systematic absence of significant effects on household energy bills, suggesting limitations in generating demand for clean technologies and incentivizing firms to innovate, subsidies emerge as a more promising approach. Subsidies demonstrate a positive impact on the number of high-quality patents, indicating their potential to lower barriers to investment such as uncertainty and lack of information, thus fostering innovation among firms.

Regarding Command-and-Control policies, specifically energy standards, our results challenge neoclassical assumptions by revealing a strong positive effect on innovation, albeit with a short-term impact that diminishes over time. This underscores the importance of periodically renewing standards to sustain innovation momentum and prevent technological lock-in. Recent policy initiatives, such as the 2021 French standards and the 2023 EPBD revision, which integrate life cycle assessments to evaluate buildings' carbon footprint, signify steps in the right direction by broadening the technological scope and addressing environmental concerns.

The presented results are readily generalizable to other regions of the world where the building sector is a significant energy consumer, and market barriers impede the adoption of new low-carbon technologies. Moreover, it is important to note that the effectiveness of a single policy instrument is never guaranteed, and the complexity of the innovation process and environmental issues necessitates the application of a mix of instruments. For example, information policies to alert households about energy savings will have positive interaction effects with the implementation of energy standards (Jaffe, Newell and Stavins, 1999).

Some elements of the paper should be further explored in future work. Firstly, a broader analysis of the effects of energy standards introduced in other European countries could confirm the results of the study. Secondly, it would be worth testing the effect of the R&D public funding as a way out of the path of dependency as argued by Acemoglu et al. (2012). Thirdly, advances in topic modeling could, if applied to patent studies, be a useful way of tracking intrinsic technological frontier shifts as a result of various types of policy. Yet, we argue that when induced innovation is the object of study, regardless of the area, estimation methods that consider time lags simultaneously should be applied to shed light on the temporal profile of heterogeneous effects.

Acknowledgment

This study was undertaken with the help of the Scientific and Technical Centre for Buildings and the Climate Economics Chair. Helpful suggestions were made by Prof. Marc Baudry and Prof. Béatrice Dumont. Good comments were made by Dr. Thomas Chuffart and Prof. Nadine Levratto. We would also like to thank the anonymous reviewers for their feedback and comments.

References

Acemoglu, D. *et al.* (2012) 'The environment and directed technical change', *American economic review*, 102(1), pp. 131–166. Available at: https://www.aeaweb.org/articles?id=10.1257/aer.102.1.131 (Accessed: 15 November 2023).

Aghion, P. *et al.* (2016) 'Carbon taxes, path dependency, and directed technical change: Evidence from the auto industry', *Journal of Political Economy* [Preprint]. Available at: https://doi.org/10.1086/684581.

Almon, S. (1965) 'The Distributed Lag Between Capital Appropriations and Expenditures', *Econometrica*, 33(1), pp. 178–196. Available at: https://doi.org/10.2307/1911894.

B. Howarth, R., Haddad, B.M. and Paton, B. (2000) ‘The economics of energy efficiency: insights from voluntary participation programs’, *Energy Policy*, 28(6), pp. 477–486. Available at: https://doi.org/10.1016/S0301-4215(00)00026-4.

Barbieri, N. (2015) ‘Investigating the impacts of technological position and European environmental regulation on green automotive patent activity’, *Ecological Economics*, 117, pp. 140–152. Available at: https://doi.org/10.1016/j.ecolecon.2015.06.017.

Barradale, M.J. (2010) ‘Impact of public policy uncertainty on renewable energy investment: Wind power and the production tax credit’, *Energy Policy* [Preprint]. Available at: https://doi.org/10.1016/j.enpol.2010.08.021.

Berry, L. (1984) ‘The role of financial incentives in utility-sponsored residential conservation programs: A review of customer surveys’, *Evaluation and Program Planning*, 7(2), pp. 131–141. Available at: https://doi.org/10.1016/0149-7189(84)90039-9.

Bertoldi, P. *et al.* (2010) ‘Energy supplier obligations and white certificate schemes: Comparative analysis of experiences in the European Union’, *Energy Policy*, 38(3), pp. 1455–1469. Available at: https://doi.org/10.1016/j.enpol.2009.11.027.

Brunnermeier, S.B. and Cohen, M.A. (2003) ‘Determinants of environmental innovation in US manufacturing industries’, *Journal of Environmental Economics and Management*, 45(2), pp. 278–293. Available at: https://doi.org/10.1016/S0095-0696(02)00058-X.

Camilier-Cortial *et al.* (2017) ‘Barrières à l’investissement dans l’efficacité énergétique : quels outils pour quelles économies ?’ Available at: https://www.tresor.economie.gouv.fr/Articles/efb651d9-8d37-4baa-8c2b-ad5805b1889a/files/ce2838f1-6a60-433b-a30d-09321a9ffa50.

Costantini, V., Crespi, F. and Palma, A. (2017) ‘Characterizing the policy mix and its impact on eco-innovation: A patent analysis of energy-efficient technologies’, *Research Policy*, 46(4), pp. 799–819. Available at: https://doi.org/10.1016/j.respol.2017.02.004.

D’Agostino, D. *et al.* (2016) ‘Synthesis report on the national plans for nearly zero energy buildings (NZEBs)’, *Joint Research Center (JRC) publications* [Preprint]. Available at: https://publications.jrc.ec.europa.eu/repository/bitstream/JRC97408/reqno_jrc97408_online%20nzeb%20report(1).pdf (Accessed: 22 November 2023).

Delmas, M.A., Fischlein, M. and Asensio, O.I. (2013) ‘Information strategies and energy conservation behavior: A meta-analysis of experimental studies from 1975 to 2012’, *Energy Policy*, 61, pp. 729–739. Available at: https://doi.org/10.1016/j.enpol.2013.05.109.

Eryzhenskiy, I., Giraudet, L.-G. and Segú, M. (2023) ‘Zero-Interest Green Loans and Home Energy Retrofits: Evidence from France’. Available at: https://doi.org/10/document.

Fischer, C. (2003) ‘Climate change policy choices and technical innovation’, *Minerals & Energy - Raw Materials Report*, 18(2), pp. 7–15. Available at: https://doi.org/10.1080/14041040310019093.

Gann, D.M., Wang, Y. and Hawkins, R. (1998) ‘Do regulations encourage innovation? - the case of energy efficiency in housing’, *Building Research & Information*, 26(5), pp. 280–296. Available at: https://doi.org/10.1080/096132198369760.

Gerarden, T.D. (2023) ‘Demanding Innovation: The Impact of Consumer Subsidies on Solar Panel Production Costs’, *Management Science* [Preprint]. Available at: https://doi.org/10.1287/mnsc.2022.4662.

Gillingham, K., Newell, R.G. and Palmer, K. (2009) ‘Energy Efficiency Economics and Policy’, *Annual Review of Resource Economics*, 1(1), pp. 597–620. Available at: https://doi.org/10.1146/annurev.resource.102308.124234.

Gillingham, K. and Palmery, K. (2014) ‘Bridging the energy efficiency gap: Policy insights from economic theory and empirical evidence’, *Review of Environmental Economics and Policy* [Preprint]. Available at: https://doi.org/10.1093/reep/ret021.

Giraudet, L.-G., Bodineau, L. and Finon, D. (2012) ‘The costs and benefits of white certificates schemes’, *Energy Efficiency*, 5(2), pp. 179–199. Available at: https://doi.org/10.1007/s12053-011-9134-6.

Girod, B., Stucki, T. and Woerter, M. (2017) ‘How do policies for efficient energy use in the household sector induce energy-efficiency innovation? An evaluation of European countries’, *Energy Policy*, 103, pp. 223–237. Available at: https://doi.org/10.1016/j.enpol.2016.12.054.

Hassett, K.A. and Metcalf, G.E. (1995) ‘Energy tax credits and residential conservation investment: Evidence from panel data’, *Journal of Public Economics* [Preprint]. Available at: https://doi.org/10.1016/0047-2727(94)01452-T.

Hesselink, L.X.W. and Chappin, E.J.L. (2019) ‘Adoption of energy efficient technologies by households – Barriers, policies and agent-based modelling studies’, *Renewable and Sustainable Energy Reviews* [Preprint]. Available at: https://doi.org/10.1016/j.rser.2018.09.031.

Hicks, J.R. (1932) *The Theory of Wages*.

Hughes, J.E. and Podolefsky, M. (2015) ‘Getting green with solar subsidies: Evidence from the california solar initiative’, *Journal of the Association of Environmental and Resource Economists* [Preprint]. Available at: https://doi.org/10.1086/681131.

IEA (2023) *Tracking Clean Energy Progress 2023 – Analysis*, *IEA*. Available at: https://www.iea.org/reports/tracking-clean-energy-progress-2023 (Accessed: 29 November 2023).

Inspection Générale des Finances and Conseil Général de l’Environnement et du Développement Durable (2017) ‘AIDES A LA RENOVATION ENERGETIQUE DES LOGEMENTS PRIVES’. Available at: https://igedd.documentation.developpement-durable.gouv.fr/documents/Affaires-0009660/010867-01_rapport.pdf.

Jaffe, A.B., Newell, R.G. and Stavins, R.N. (1999) ‘Energy-Efficient Technologies and Climate Change Policies: Issues and Evidence’. Rochester, NY. Available at: https://doi.org/10.2139/ssrn.198829.

Jaffe, A.B., Newell, R.G. and Stavins, R.N. (2002) ‘Environmental Policy and Technological Change’, *Environmental and Resource Economics*, 22(1), pp. 41–70. Available at: https://doi.org/10.1023/A:1015519401088.

Jaffe, A.B. and Palmer, K. (1997) ‘Environmental Regulation and Innovation: A Panel Data Study’, *The Review of Economics and Statistics*, 79(4), pp. 610–619. Available at: https://doi.org/10.1162/003465397557196.

Jaffe, A.B. and Stavins, R.N. (1994) ‘Energy-Efficiency Investments and Public Policy’, *The Energy Journal*, 15(2), pp. 43–65. Available at: https://www.jstor.org/stable/41322875 (Accessed: 13 November 2023).

Jaffe, A.B. and Stavins, R.N. (1995) ‘Dynamic incentives of environmental regulations: The effects of alternative policy instruments on technology diffusion’, *Journal of Environmental Economics and Management* [Preprint]. Available at: https://doi.org/10.1006/jeem.1995.1060.

Johnstone, N., Haščič, I. and Kalamova, M. (2010) *Environmental Policy Design Characteristics and Technological Innovation: Evidence from Patent Data*. Paris: OCDE. Available at: https://doi.org/10.1787/5kmjstwtqwhd-en.

Kim, Y.J. and Brown, M. (2019) ‘Impact of domestic energy-efficiency policies on foreign innovation: The case of lighting technologies’, *Energy Policy*, 128, pp. 539–552. Available at: https://doi.org/10.1016/j.enpol.2019.01.032.

Nesta, L., Vona, F. and Nicolli, F. (2014) ‘Environmental policies, competition and innovation in renewable energy’, *Journal of Environmental Economics and Management*, 67(3), pp. 396–411. Available at: https://doi.org/10.1016/j.jeem.2014.01.001.

Newell, R.G. and Siikamäki, J. (2014) ‘Nudging Energy Efficiency Behavior: The Role of Information Labels’, *Journal of the Association of Environmental and Resource Economists*, 1(4), pp. 555–598. Available at: https://doi.org/10.1086/679281.

Noailly, J. (2012) ‘Improving the energy efficiency of buildings: The impact of environmental policy on technological innovation’, *Energy Economics* [Preprint]. Available at: https://doi.org/10.1016/j.eneco.2011.07.015.

Popp, D. (2002) ‘Induced innovation and energy prices’, *American Economic Review* [Preprint]. Available at: https://doi.org/10.1257/000282802760015658.

Popp, D. (2019) ‘Environmental policy and innovation: A decade of research’, *International Review of Environmental and Resource Economics* [Preprint]. Available at: https://doi.org/10.1561/101.00000111.

Stavins, R.G.N., Adam B. Jaffe, Robert N. (2002) ‘The Induced Innovation Hypothesis and Energy-Saving Technological Change’, in *Technological Change and the Environment*. Routledge.

Tassey, G. (1991) ‘The functions of technology infrastructure in a competitive economy’, *Research Policy*, 20(4), pp. 345–361. Available at: https://doi.org/10.1016/0048-7333(91)90094-7.

Ürge-Vorsatz, D. *et al.* (2016) ‘Measuring multiple impacts of low-carbon energy options in a green economy context’, *Applied Energy*, 179, pp. 1409–1426. Available at: https://doi.org/10.1016/j.apenergy.2016.07.027.