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Improving the Energy-Efficiency of Buildings: The Impact of Environmental Policy on Technological Innovation

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Summary

This paper investigates the impact of alternative environmental policy instruments on technological innovations aiming to improve energy-efficiency in buildings. The empirical analysis focuses on three main types of policy instruments, namely regulatory energy standards in buildings codes, energy taxes as captured by energy prices and specific governmental energy R&D expenditures. Technological innovation is measured using patent counts for specific technologies related to energy-efficiency in buildings (e.g. insulation, high-efficiency boilers, energy-saving lightings). The estimates for seven European countries over the 1989-2004 period imply that a strengthening of 10% of the minimum insulation standards for walls would increase the likelihood to file additional patents by about 3%. In contrast, energy prices have no significant effect on the likelihood to patent. Governmental energy R&D support has a small positive significant effect on patenting activities.

Keywords: Innovation, Technological Change, Patents, Energy-Efficiency, Buildings, Environmental Policy

JEL Classification: O31, O34, Q55

I am very grateful to Marcel Seip and Jos Winnink from the Netherlands Patent Office for outstanding research assistance in building the patent dataset and valuable expertise on patent related questions. I also thank Wolfgang Eichhammer from the Fraunhofer Institute Karlsruhe, for introducing me to the MURE database and for providing me complementary information on thermal building regulations in Europe. I also wish to thank Suzanne Joosen, Anton Schaap and Frank Zegers from Ecofys for providing the technical information on the relevant technologies. Finally, I thank Frans de Vries (University of Stirling), Arno van der Vlist (University of Groningen), Herman Vollebergh (Netherlands Environmental Assessment Agency), Paul Koutstaal, Rob Aalbers, Roger Smeets, Stefan Boeters, Bas Straathof, Bas ter Weel (CPB) for valuable comments. This study is part of the research project "Environmental Policy and Economics" initiated by the Dutch Ministry of Economic Affairs.

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The impact of environmental policy on technological innovation

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Abstract

This paper investigates the impact of alternative environmental policy instruments on technological innovations aiming to improve energy-efficiency in buildings. The empirical analysis focuses on three main types of policy instruments, namely regulatory energy standards in buildings codes, energy taxes as captured by energy prices and specific governmental energy R&D expenditures. Technological innovation is measured using patent counts for specific technologies related to energy-efficiency in buildings (e.g. insulation, high-efficiency boilers, energy-saving lightings). The estimates for seven European countries over the 1989-2004 period imply that a strengthening of 10% of the minimum insulation standards for walls would increase the likelihood to file additional patents by about 3%. In contrast, energy prices have no significant effect on the likelihood to patent. Governmental energy R&D support has a small positive significant effect on patenting activities.

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[*] Authors contact details: Joëlle Noailly, J.Noailly@cpb.nl, Tel: +3170 338 3498. Address: CPB Netherlands Bureau for Economic Policy Analysis, P.O. Box 80510, 2508 GM The Hague. I am very grateful to Marcel Seip and Jos Winnink from the Netherlands Patent Office for outstanding research assistance in building the patent dataset and valuable expertise on patent related questions. I also thank Wolfgang Eichhammer from the Fraunhofer Institute Karlsruhe, for introducing me to the MURE database and for providing me complementary information on thermal building regulations in Europe. I also wish to thank Suzanne Joosen, Anton Schaap and Frank Zegers from Ecofys for providing the technical information on the relevant technologies. Finally, I thank Frans de Vries (University of Stirling), Arno van der Vlist (University of Groningen), Herman Vollebergh (Netherlands Environmental Assessment Agency), Paul Koutstaal, Rob Aalbers, Roger Smeets, Stefan Boeters, Bas Straathof, Bas ter Weel (CPB) for valuable comments. This study is part of the research project ŚEnvironmental Policy and EconomicsŠ initiated by the Dutch Ministry of Economic Affairs.

1 Introduction

Buildings account for 40% of the world's total primary energy consumption and are responsible for 24% of world's CO_2 emissions (IEA, 2008).[1] According to a report from the Intergovernmental Panel on Climate Change (IPCC), CO_2 emissions from buildings have doubled from 4 gigatonnes (Gt) per year in 1971 to about 8 Gt per year in 2004 and are expected to reach up to 14 Gt per year in 2030 mainly as the result of increasing energy consumption from developing countries (Levine et al., 2007). By 2030, the share of buildings will reach one third of total world CO_2 emissions.

As a result, improving the energy efficiency of buildings is a growing priority on the policy agendas of many countries and of the international community. The International Energy Agency, the IPCC and the United Nations Environment Program have recently released recommendations to mitigate greenhouse gases emissions and reduce energy consumption of buildings (IEA, 2008; Levine et al., 2007; UNEP, 2007). Some of these recommendations include strengthening the regulatory energy standards for new buildings, controlling the quality and maintenance of existing buildings, encouraging energy-saving behaviour by home owners and stimulating the diffusion and innovation of energy-efficient technologies. Technological innovation, in particular, could play a large role in reducing further the energy consumption of buildings. The energy efficiency of insulation materials, heating systems, and other appliances has greatly improved over the past decades and recent developments in solar boilers, geothermal energy or lighting technologies have been also very promising (IEA, 2008).

The aim of the current paper is to analyse empirically the impact of alternative environmental policy instruments on technological innovations aiming to improve the energy efficiency of buildings. The analysis compares in particular the impact of three main types of instruments, namely regulatory energy standards set in buildings codes, energy taxes (captured by energy prices) and specific governmental energy R&D expenditures. Technological innovation is measured using patent counts data for eight technological fields specifically relevant for the energy efficiency of buildings, namely insulation, high-efficiency boilers, heat and cold distribution, ventilation technologies, solar boilers (and other renewables), energy-saving lightings, buildings materials and climate control technologies. Data on regulatory energy standards for new buildings, energy prices and public energy R&D expenditures are collected for several European countries over the last decades. The study first describes the trends in regulation and patenting activities over the last thirty years in the different countries. Then, the econometric analysis

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[1] Based on direct energy use, not including the production of inputs to construct buildings.

estimates the impact of the different policy instruments on technological innovation. The estimates for seven European countries over the 1989-2004 period imply that a strengthening of 10% of the minimum insulation standards for walls would increase the likelihood to file additional patents by about 3%. In contrast, energy prices have no significant effect on the likelihood to patent. Governmental energy R&D expenditures have a small positive significant effect on patenting activities: a 10% increase in specific R&D expenditures implies a 0.3% increase in the number of patents filed.

This paper is related to the small but growing empirical literature on the impact of environmental policy on technological innovation. An extensive review of the literature is given in Popp et al. (2009). A general result of this literature is that environmental policy has a positive impact on the direction and rate of technological innovation. The current study makes two new contributions to this literature. Firstly, the analysis brings insights on the impact of environmental policy on innovation for a technological field – energy efficiency in buildings – which, despite its importance for climate change issues, has received little attention in the literature. Several studies focus on SO_2 and NO_x abatement technologies (Popp, 2006; De Vries and Withagen, 2005). More recently, Johnstone et al. (forthcoming) also study the case of renewable energy technologies. Looking at different technological fields is important, since the incentives to invest in innovation are likely to differ across sectors. A well-known issue in the building sector is that incentives to invest in new technologies might be suboptimal due to principal-agent issues (Gillingham et al., 2009). When the home owner (agent) does not observe the level of energy efficiency of the building, the builder (principal) may not be able to recoup the costs of energy efficient investments and, therefore, will tend to underinvest in new equipment. Jaffe and Stavins (1995) is the only paper looking at energy efficiency in home construction, although their analysis focuses on the adoption of technologies and not – as the current paper does – on innovation. Jaffe and Stavins (1995) compare the effects of energy prices, adoption subsidies and building codes on the average energy efficiency level in home construction[2] in the United States between 1979 and 1988. Although they find that energy taxes (captured by relatively high energy prices over the period) have a positive impact on technology adoption, the effect is relatively small. In particular, adoption subsidies of the same magnitude as a tax would have a much greater impact. Finally, measuring the presence of a building code requirements by a dummy variable, Jaffe and Stavins (1995) find no effect of direct regulation by technology standards – arguing that the building codes were often set too low to be effective. Another paper related to the

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[2] They measure energy efficiency by the average R-level, indicating thermal resistance. The R-value is the reciprocal of the U-value used later in this study.

current study is Newell et al. (1999), although they focus more specifically on home appliances and define innovations in terms of introduction of new products. Newell et al. (1999) evaluate the impact of energy prices and regulatory standards on the introduction of new home appliances (e.g. air conditioners and gas water heaters) in the US between 1958 and 1993. They find that falling energy prices worked against the development of energy-efficient appliances. Energy efficiency in 1993 would have been 25 to 50% lower in air-conditioners and gas water heaters if energy prices had stayed at their 1973 levels. Also, regulatory standards worked largely through energy-inefficient appliances being dropped.

A second contribution of the present study is the empirical comparison of the effects of alternative policy instruments on technological innovations. Most of the previous studies have looked either at broad measures of environmental policy stringency (such as pollution abatement control expenditures in Jaffe and Palmer (1997)) or at a specific type of regulation (such as regulatory standards in Popp (2006) or international protocols in Dekker et al. (2009)). Empirical evidence on the effects of different policy instruments still remains scarce. An exception is Johnstone et al. (forthcoming) who, for the case of renewable energy, use data on six different policy types, namely R&D support, investment incentives, tax incentives, tariffs incentives (feed-in tariffs), voluntary programs, obligations and tradable certificates for a panel of 25 countries over the 1978-2003 period. Their dataset includes continuous variables for three types of policy measures, namely R&D support, feed-in tariffs and renewable energy certificates. For other policy types, they use dummy variables to capture the introduction of the measures. Their results show that quantity-based policy instruments (obligations, tradable quotas) are most effective in stimulating innovations that are closely competing with fossil fuels, such as wind energy. More targeted subsidies, such as feed-in tariffs, are most effective for innovations in more costly technologies such as solar energy.

The paper is organised as follows. Section 2 describes the data on policies measures aiming to improve energy efficiency in buildings in a set of European countries over the last decades. Section 3 describes the patent data and describes the major trends in innovation activities. Section 4 describes the econometric methodology and presents the results. Section 5 concludes.

2 Policy measures for improving energy efficiency in buildings

According to Eichhammer and Schlomann (1999), energy regulations for buildings in Europe present two main characteristics. First, the number of regulations tends to be very large in all countries. Eichhammer and Schlomann (1999) argue that this is due to the absence of a strong lobby in the building sector to campaign against (or in favour) of regulation as is the case in other sectors (such as the automobile industry). Second, energy regulations for buildings tend to be set at the national level rather than the international level, although recently European regulations are being harmonized (most countries implemented this harmonization after 2006). The building sector remains a national market to a large extent.

This section describes the data on environmental policy measures used in the empirical analysis. The study focuses on nine European countries, namely Austria, Belgium, Denmark, France, Finland, Germany, Ireland, the Netherlands and the United Kingdom. The MURE database[3] provides a qualitative overview of policy measures undertaken by these countries to promote energy conservation in the residential sector. In order to estimate the impacts of different policy instruments, such as regulatory standards, subsidies or taxes, the analysis would ideally require to be able to construct continuous measures over time, allowing to compare the stringency of each measure within and across countries. In practice, however, collecting a quantitative overview of policy measures across countries is a colossal task. In addition, comparisons across countries are tedious since policies tend to differ on many dimensions. For instance, a tax credit may differ on the tax rate, the technologies or types of firms eligible for the tax credits. Hence, this paper focuses on three main types of policy instruments for which it was possible to construct continuous variables for several countries over a long period of time, namely: regulatory energy standards enforced by building codes, energy taxes as captured by energy prices and specific R&D support for energy efficiency in the residential sector.

2.1 Building codes

In most European countries, energy requirements for new buildings are set in national building codes. A detailed comparison of the different building codes in Europe can be found in Eichhammer and Schlomann (1999) and Beerepoot (2002). There are generally two forms of regulatory standards: (1) thermal insulation standards that set requirements on the minimum level of insulation of different building components and (2) energy performance standards that set a maximum on the energy demand of a building as a whole (in this case energy-saving appliances can thus compensate for lower levels of insulation).

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[3] The MURE (Mesures d'Utilisation Rationnelle de l'Energie, www.mure2.com) database is a European project collecting information on measures for the rational use of energy and for renewables in Europe. The database is maintained by the Fraunhofer Institute in Karlsruhe.

Thermal insulation standards are based on an ‘unit-approach’ which divides the building shell into its individual components (e.g. walls, windows, roofs, floors) and states a maximum heat transmission value, the so-called ‘U-value’, for each of these components separately. The ‘U-value’ is the amount of heat that flows through a square meter of building component with a temperature difference of 1 degree Celsius (kWh/m2).[4]Accordingly, low U-values indicate more stringent standards. More recently, thermal regulations have evolved in many countries towards the use of energy performance standards for buildings, as recommended by the 2002 European Building Energy Performance Directive. Energy performance standards set a maximum on the energy demand for the whole building, and not for the individual parts. This is also coined as the ‘fully integrated approach’. In that case, energy savings obtained through the use of efficient appliances can compensate for high energy use in other parts of the building. Many different technologies, for instance solar boilers or energy-saving lightings, can contribute to lower the total energy use of a building and are thus accounted for in energy performance standards.[5].

Using data from the MURE database, I collected data on the stringency of the national building codes for nine European countries over the last 30 years. Table 1 gives the years of introduction and revision of the building codes in every country.

[Table 1 about here.]

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[4] U-values are also expressed in terms of kWh/m2 K, i.e. with a temperature difference of 1 degree Kelvin. Under standardized conditions, one degree Kelvin is equivalent to one degree Celsius.

[5] Besides the unit approach and the fully integrated approach, Beerepoot (2002) distinguishes two other intermediary approaches: the average U-values of the building, in which higher heat transmission through one component (for instance walls) can be compensated for by better values of other components (roofs, windows), or maximum values for heating demand of buildings, including heat increases due to solar heat recovery and internal heat sources in the house. In some countries, the different approaches co-exist next to each other.

In the dataset, seven countries (Germany, Denmark, Finland, Austria, Belgium, Ireland and UK) make use of the 'unit approach' setting U-values for individual building components.[6] For two additional countries, namely France and the Netherlands, data on U-values are not available or not comparable because building codes in these countries are based on energy performance standards.

For countries using the unit approach, I compare the stringency of the building codes using the U-values. Since countries in colder climate have by definition more stringent insulation standards, the U-values are corrected for climate factors using data on the number of heating degree days in each country.[7] I use separate data on the U-values for walls, roofs, floors and windows for new residential buildings. When the building codes set values for different construction parts (e.g. heavy massive walls, cavity walls), I follow the methodology used in IEA (2008) and compute the average values over the different types of building components. Finally, I also compute an overall U-value given by: $U_{overall} = U_{walls} + U_{roofs} + U_{ceilings} + 0.2 * U_{windows}$. Windows are calculated with 20% since the area of windows for small residential buildings normally will be less than 20% of the floor, ceilings and walls (see IEA (2008)). Figure 1 gives the evolution of the U-values for walls corrected for climate in the different countries. Denmark has had very stringent standards for wall insulations since the end of the 1970s. Standards in Germany were initially not too stringent but have been strengthened sharply over time. Finally, several countries such as Austria, Belgium or Ireland only introduced minimum U-values for walls in the mid-1990s.

[Figure 1 about here.]

As an alternative measure to U-values, I also use data on the energy demand of a model house under current regulation. A model house has the same geometry in all countries and is insulated to the current building regulations of each country. This indicator reflects thus only the level of regulatory energy

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[6] Denmark and Austria only use the unit approach. Other countries introduced energy performance standards around 2002 next to the unit approach.

[7] Heating degree days are a measure of how much (in degrees), and for how long (in days), the outside air temperature was below a certain level. They are commonly used in calculations relating to the energy consumption required to heat buildings. Data on heating degree days are extracted from Eurostat. To correct for climate factors, I multiply the U-values by the average number of heating degree days in each country over the period under study (Eichhammer and Schlomann, 1999). As an illustration, assume Denmark and Ireland have set U-values for walls at 0.2 and 0.25 kWh/m2, respectively and the average heating degrees day value in Denmark is 3500 compared with 2800 in Ireland. In this case, after correcting for climate factors (0.2*3500=0.25*2800=700), building codes in both countries have the same level of stringency.

standards in place.[8] The data are borrowed from Eichhammer and Schlomann (1999) who present computations using engineering models for the energy demand of a model house under current regulations at the end of the 1990s. Using extra information from the MURE database on the percentage of energy reduction introduced by the new standard compared to the previous stage, I extrapolate their calculations to a larger number of years. These data are only used in the remainder of the analysis as a robustness test. The main advantage of using the energy demand of a modelhouse is that it allows us to include France and the Netherlands in our empirical estimations. In addition, data on energy demand of a model house might be better able to capture regulations affecting other types of technologies than insulation alone. Figure 2 shows the evolution of thermal building regulations according to the energy demand of a model house. Lower values indicate more stringent energy regulations. According to this indicator, Denmark has again the most stringent regulations, even after correcting for climate factors. Over the last decade, the Netherlands have strengthened their regulations at several occasions and the level of Dutch standards is nowadays as stringent as the Danish standards.

[Figure 2 about here.]

2.2 Energy prices

Next to command-and-controls regulation in the form of building codes, innovating firms in the building sector may also respond to direct economic incentives in the form of energy prices. In the literature, this hypothesis is derived from the *demand-pull* theories of innovation. Higher energy prices make energy-efficient inventions more valuable, either because larger energy savings occur, or because the market for energy-efficient inventions will be larger. Impacts of energy prices can provide an approximation of the likely effects of energy taxes.

To correct for energy prices in the building sector, I construct a weighted average of energy prices based on the specific energy mix of each country in the residential sector. Figure 3 describes the various energy mixes in 9 European countries. The figure includes four main sources of energy used in buildings: electricity (including heat), natural gas, petroleum products and others (mainly formed by coal products and combustible renewable and wastes). Energy prices are extracted from the *Energy prices*

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[8] The values are expressed in heating use in kWh per year and cubic meter house volume (kWh/m^3) and are corrected for climate factors.

and taxes database from the IEA.[9] The prices correspond to real end-user prices for households including taxes and are expressed in US dollars per tons of oil equivalent (corrected for purchasing power parities). Prices are deflated by the consumer price index.

The price of energy is constructed as the weighted sum of fuel, electricity and gas prices:

$$\bar{p}_{it} = \sum_{s} w_{is} p_{ist} \tag{1}$$

where $\bar{p}_{it}$ is the fixed-weight price of energy in country i in year t, w_{is} is the share of energy used in the residential sector for country i for energy source s (natural gas, electricity and petroleum products) in a fixed year, and p_{ist} is the real price in US dollars (using 2007 prices and PPP, deflated by the consumer price index) per ton of oil equivalent by country, source and year. Linn (2008) suggests to fix the weights w_{is}, so they do not change over time. This is to address the possibility that energy prices may be endogenous. Energy prices may have an effect on technological change and thereby affect the substitution between energy sources over time. A rise in the price of oil might induce innovation in heating systems based on gas, rather than fuel oil, leading to a lower share of petroleum products in the energy mix of the residential sector and ultimately a lower demand and price for petroleum products. By fixing the weights [10], substitutions between energy sources over time – an effect of technological change – do not affect the price index.

Figure 4 plots the evolution of the fixed-weight price index (in logarithms) for the countries under study. Remarkably, real energy prices in the building sector have decreased in all countries, except Denmark. This is explained by the fact that Denmark has had a long tradition of energy taxes since the beginning of the 1980s. A revision of the Danish tax took place in 1998. From 2000 on, energy prices are increasing again in a few countries, in particular in the Netherlands, Germany and Austria. These countries introduced energy taxes in 1996, 1999 and 1996, respectively.

[Figure 3 about here.]

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[9] Since there are often a multitude of tariffs or contracts, the IEA uses the average unit value to construct a representative overall price of electricity and natural gas.

[10] In the remainder of the analysis, w_{is} is fixed as the 1991 share of each energy source in total energy used, which corresponds to the middle of our sample.

[Figure 4 about here.]

2.3 Governmental energy R&D expenditures

Finally, governmental R&D support is also commonly used to promote the development of new technologies for improving the energy efficiency of buildings, for instance in the form of demonstration projects. Data on public energy R&D budgets are collected annually by questionnaire by the IEA. Budgets are available for several types of R&D activities: energy efficiency, fossil fuels, renewable energy sources, nuclear fission, nuclear fusion, hydrogen and fuel cells and other power and storage technologies. I use specific data for the subsector of energy efficiency in the residential sector[11], which covers space heating and cooling, lighting control systems other than solar technology, new insulation and building materials, low energy housing design other than solar technologies, thermal performance of buildings, domestic appliances. Since these data do not include solar energy and other renewables, I also use specific expenditures on solar (solar heating and cooling, photovoltaics, solar thermal power) and geothermal energy. [12] These data will be used specifically to estimate the development of solar and renewable technologies in the empirical analysis.

3 Technological innovations related to improving energy efficiency in buildings

3.1 Patents data

Innovations related to improving energy efficiency in buildings are measured using patent data. Besides being readily available, patents present the advantage of being a good indicator of innovative activity and tend to be highly correlated with a large number of alternative measures of innovation (see Griliches, 1990; Comanor and Scherer, 1969; Acs and Audretsch, 1989; Hagedoorn and Cloodt, 2003). A good overview of patent-related issues and their pitfalls is given in OECD (2009).

Patents are granted by national offices in individual countries. Protection is then valid in the country granting the patent. If an inventor wants protection in other countries, he must file applications at the relevant national offices or by using the Patent Cooperation Treaty. These additional filing in different

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[11] IEA Classification I.1 Energy efficiency - residential sector.

[12] IEA Classification: III.1 Total solar energy. and III.5 Geothermal.

countries are called family patents. Next to patents filed at national offices, inventors can also file directly so-called European patents (EP) or international patents (WO) patents which give protection directly in a bundle of countries. An EP patent is granted by the European Patent Office and gives protection in those member states which have been designated by the applicant on the application. These EP and WO patents have become increasingly popular over time and are nowadays a standard. The difference between patents filed at national offices and patents filed as the EPO (European Patent Office) or the WIPO (World Intellectual Property Organization) often reflect the value of the innovation. Patents filed only in one country have a lower market value than patents filed in several countries or filed at the EPO or WIPO where the granting process might be more strict.

I collected patent applications from the nine European countries under study in the field of energy efficiency in buildings. Patents data were extracted from EPODOC, an internal database from the European Patent Office. The search was performed directly by patent experts from the Dutch Patent Office, who are familiar with working with patent statistics. Patents are sorted by 'applicant country', rather than 'inventor country' (OECD, 2009). This allows to include patent applications from foreign affiliates of national firms, as these might also be influenced by national environmental policy. Patents are sorted by year of application (oldest priority year) as this better corresponds to the date of inventive activity than granted year and by application country. The data include domestic applications, i.e. patents filed by national applicants at the national office, and European and international patents (EP and WO). In general, applicants file first a patent at the national office and subsequently at national offices in other countries (these subsequent filings are coined as 'family patents'). Here, only domestic applications, i.e. applications filed at the domestic patent office of the country considered, are considered. This means that family patents applications filed in foreign patent offices are not included. Similarly, only EP and WO patents which were not first filed as a national patent at the national office are kept in the dataset.

I identified the relevant patents related to energy efficiency in buildings through the following steps. In a first step, the relevant technologies and specific keywords associated to these technologies were inventorized by experts from Ecofys Netherlands, a consultancy company specialized in sustainable energy. In a second step, the relevant International Patent Classification classes were identified. A major difficulty with the building sector is that technologies related to energy efficiency encompass many different IPC classes. For instance, patents related to insulation can be found in the IPC section of Fixed Construction, Chemistry and Metallurgy, Mechanical Engineering, as well as Performing Operations/Shaping. The main difficulty is to avoid type 0 and type I errors as defined by Lanjouw and Mody (1996). This implies avoiding including patents which are not relevant for energy efficiency in buildings (for instance, when searching for energy-saving lightings technologies, lightings related to vehicles and aircrafts and not buildings had to be excluded), and avoiding excluding relevant patents. To minimize these errors, the search strategy combined IPC classes with specific keywords. Table 11 in the Appendix gives the example of the insulation query. This process was carried out directly by patent and technical experts from the Netherlands Patent Office, who carefully scrutinized the set of patents. Subsequently, patents were grouped within 8 different groups of technologies as given in Table 2. Patents related to heat pumps, heat and cold storage and cooling could not easily be disentangled from one another, so they are combined in a single group.

[Table 2 about here.]

3.2 Patents trends

Figure 5 plots the evolution the total number of patents in energy-efficient innovations for buildings over the 1978-2006 period in all nine countries. There is a clear increasing pattern in particular at the end of the 1970s and in the second half of the 1990s. After 2000, the number of patents decreases and tends to remain stable in recent years. Over the 1978-2006 period, Germany accounts for 63.7% of the patents, France for 18%, United Kingdom for 6.5%, Austria for 4.9% as shown in Table 3. In small countries such as Belgium, Denmark and the Netherlands, filing an EP or WO patent directly is preferred over a domestic application at the national office. In other countries, such as France or Germany, applicants tend to file the patent first at the national office. Table 4 gives the share of patents per technology group over the 1978-2006 period. Patents related to HE-boilers account for 22% of all patents. Patents in insulation and energy-demand reduction form the second largest group with about 18.2% of the patents. Lightings and Heat and Cold distribution technologies account for 17.8% and 16.4% of the patents, respectively.

[Figure 5 about here.]

[Table 3 about here.]

[Table 4 about here.]

Figure 6 plots the evolution of the number of patents in the different technological fields. Patents related to HE-boilers, insulation and heat and cold distribution exhibit the same patterns of slow rise over the 1980s, followed by a sharp increase in the mid-1990s and a decline after 2000. The number of patents in solar energy experiences first a sharp increase at the end of the 1970s followed by a steady decrease over the 1980s. Patenting in solar energy starts again at a slow pace over the 1990s and experiences a recent rise in the last years. The number of patents in lighting technologies reaches a peak after 2000, slightly later than other technologies.

[Figure 6 about here.]

Finally, Figure 7 plots the evolution of patents for a few selected countries together with the years of introduction or revision of the countries' building codes. The impact of the building code on the number of patents also depends upon the stringency of the new standards and on the level of enforcement (through monitoring and controls) of the codes. Inspection of the graphs suggests that the overall patenting efforts tend to increase already before some major revisions of the building codes are implemented. In Germany, the number of patents, first relatively stable over the 1980s, starts to increase from 1992 on before an important revision of the building code is introduced in 1995 (as shown also on Figure 1). In England, the number of patents increases regularly over time and also in the period before the new regulation is implemented. In Austria, national standards were introduced in 1995, but regional regulations started to be implemented before this date. Here again, firms seem to anticipate the introduction of the regulation. In France, where the enforcement of the building code has been lax, regulations seem to have no clear impact on the number of patents. A striking feature of the evolution of the number of patents in France is the decreasing trend over the 1980s. A similar declining trend is observed for the French public R&D budget in energy efficiency. A potential explanation is the choice of French energy policy in the 1980s to focus primarily on nuclear energy. According to Martin (1998), the preference for nuclear energy implied that fundings were shifted away from energy efficiency to nuclear energy. In addition, the overcapacity in electricity created by nuclear energy and the beliefs in public opinion that energy can be clean and abundant made it less urgent to invest in energy efficiency.

[Figure 7 about here.]

4 Empirical methodology and results

4.1 Empirical methodology and summary statistics

In this section, I estimate the effect of the stringency of thermal regulations on the number of patent applications related to energy-efficient innovations in buildings. Let y_{ijt} be the number of patents for country i in technology j at time t. Since the number of patents is a nonnegative integer, I use count data estimation techniques to model the conditional mean as a multiplicative function of explanatory factors:

$$E(y_{ijt}/x_{ijt}) = exp(\beta x_{ijt} + \alpha_i + \gamma_j) \tag{2}$$

where x_{ijt} is the vector of observable explanatory variables and α_i and γ_j are the country and technology specific effects reflecting any permanent differences in the number of patents across countries and technologies. The elements of the explanatory variables vector have the interpretation that a one-unit change in variable x will lead to a β x 100 percent change in the likelihood to observe additional patents. Even after correcting for observable characteristics, some countries or technological fields are likely to present higher innovation levels than others due to omitted specific country and technology effects. By correcting for country fixed effects, I also correct for specificities in the country building stock which might also be correlated with innovation. For instance, certain countries may have a tradition of buildings with large windows. This could in turn be related to the country's innovation efforts in glazing insulation. These omitted effects are likely to be correlated with included observable factors. Including fixed effects allows to account for (observed or unobserved) country and technology heterogeneity.

Hausman et al. (1984) suggest to use the conditional maximum likelihood to estimate β directly without estimating the country and technology effects. The Poisson likelihood is conditioned on the total number of patents over the period for each individual effect. This is analogous to scaling $exp(\alpha_i)$ and $exp(\gamma_j)$ on the ratio of means[13]. In the baseline specification, I use the conditional Poisson fixed effect estimator with robust standard errors. In the robustness analysis, I will also use different estimation models including negative binomial and tobit models.

As stated in Section 2, I estimate the effects of three different types of environmental policy measures, namely regulatory energy standards, energy prices (capturing energy prices) and governmental R&D expenditures on energy-efficiency in the residential sector. To ease the interpretation of the re-

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[13] See Wooldridge (2002), p. 674 for more details.

sults, these variables are expressed in logarithms. I expect to find that more stringent insulation standards (lower U-values) have a positive effect on the number of patents. Also, I expect to find a positive effect of energy prices and governmental energy R&D expenditures on the likelihood to patent. As additional controls, I include the size and growth rate of the building stock in every country in order to control for the evolution of market demand. The probability to patent is expected to be higher in markets with a large and increasing building stock. Data on the number of dwellings per country over the 1981-2004 period were obtained from the Human Settlements database from UNECE. In addition, the estimations also always include a full set of year dummies.

The main sample with data on the U-values for walls includes 856 observations (x_{ijt}) for seven countries (excluding France and the Netherlands) over the 1981-2004 period. Due to a large range of missing observations in the dwelling stock data over the 1980s for many countries, the preferred specification is estimated on the 1989-2004 sample. In the UNECE database, data on the number of dwellings are only available for Denmark and UK over the 1981-1989 period. In addition, there are many missing values for energy R&D expenditures (in particular there are no energy R&D data for Ireland), therefore some specifications exclude this variable. A second dataset with data on the energy demand of a model house for all nine countries is used in the robustness analysis. Table 5 provides key descriptive statistics for the main dataset.

[Table 5 about here.]

4.2 Baseline estimates

Table 6 presents the baseline estimates. Equation (2) is estimated by a conditional fixed effect Poisson model with robust standard errors clustered at the country level. The dependent variable is the number of patents for country i at year t in technological field j. Columns (1) and (2) in Table 6 give the estimates on the 1981-2004 sample. In column (1) estimates of the model with only the U-values for walls, fixed effects and year dummies as regressors are presented. In column (2) the estimates also include controls for energy prices, R&D expenditures and the size and growth rate of the building stock. Columns (3) and (4) present the estimates on the smaller sample of the 1989-2004 period for which a complete set of data for a larger range of countries is available. Column (4) presents the estimates on a larger sample of observations when the energy R&D variable is dropped. Since there might be a delay before R&D expenditures have an effect on the number of patents, columns (2) and (3) use a two-years lag for this variable.

In all specifications in Table 6, the level of U-values for walls has a significant negative effect on the likelihood to patent. Higher U-values tend to decrease the probability to file a patent, suggesting that more stringent standards (i.e. lower U-values) have a positive impact on innovation. A lowering of the U-values for walls by 10% increases on average the likelihood to patent by about 3% (up to 3.85% in column (4)). Revisions in building codes usually take the form of a lowering of the U-values for walls in steps of about 20 to 30%. In Germany, for instance, the minimum standard for wall insulation was strengthened in 2002 from a U-value of 0.35 to 0.25, i.e. a drop of 30%. According to the estimates in Table 6, such a strengthening would imply that the probability to patent increase on average by about 10%, which for a country like Germany with about 2000 patents per year over the 2000-2004 period represents about 200 more patents per year. For a country like the Netherlands with an annual average of 150 patents over 2000-2004, a similar strengthening of the U-values for walls would imply about 15 additional patents per year.

The energy price variable is consistently insignificant over all specifications. In column (2), the coefficient is negative and non-significant, while in columns (3)-(4), energy prices have the expected positive sign on the probability to patent, but here again the effect is not significant. This is surprising since other studies looking at the effects of energy prices on innovation generally find a positive effect (Popp, 2002; Jaffe and Stavins, 1995). Yet, as stated in the introduction, the building sector is characterized by the principal-agent or split-incentives market failure (Gillingham et al., 2009). This occurs because the builder (the agent) decides on the energy efficiency level of a building, while the consumer living in the building (the principal) is the one actually paying the energy bill. When the consumer has incomplete information about the energy efficiency of the building, the builder may not be able to recoup the costs of energy efficiency investments in the purchase price for the building. The builder will then underinvest in energy efficiency technologies relative to the social optimum. This could explain why firms in the building sector may perceive price incentives less directly than firms in other sectors. A second potential explanation for finding no significant effects of energy prices is that real energy prices were very low during the period under consideration. A close look at the evolution of energy prices in Figure 4 shows that real prices for energy in the residential sector have been decreasing in all countries – with the exception of Denmark – over the 1990s. Energy prices increase again slightly from 2000 on. Looking at the period in the early 1980s where prices in the United States were relatively high, Jaffe and

Stavins (1995) find that energy taxes would have noticeable impacts on the diffusion of technologies. Yet, they find that these effects would be much smaller than a subsidy of the same magnitude.

Finally, specific governmental R&D expenditures on energy-efficiency in the residential sector also have a significant positive effect on additional patents. When the government spends 10% more on specific energy R&D expenditures in year $t-2$, firms will apply for 0.3% more patents in year t. The effect is thus relatively small. At last, the growth rate of the building stock is always positive significant as expected. The size of the dwelling stock is mostly non-significant.

[Table 6 about here.]

4.3 Robustness checks

This section presents some additional results and robustness checks. Table 7 reports estimates for specifications using alternative measures of the energy standards. Columns (1) and (2) in Table 7 use one year and two years lead values of the U-values for walls, respectively. A lead of three years of more was never significant. When the U-values are expected to decrease by 10% in $t+2$, firms will apply for 2.3% more patents in year t, while a decrease of 10% of U-values in $t+1$ implies an increase of 5.5% patent applications in year t. This suggests that firms anticipate to a certain extent on the changes in regulatory standards. Column (3) reports estimates using the overall U-values, which is the average of walls, roofs, floors and windows U-values as stated in Section 2, while column (4) reports the estimates using the specific U-values for windows. In this case, the sample of observations is smaller since not all countries have introduced U-values for all separate building components. Regulations for other building components, such as windows, roofs and floors, do not always closely follow the insulation standards for walls. An example is Finland, which has strict standards on wall insulation, but much less stringent standards for windows. This explains why the estimates may differ across the various measures of the energy standards. According to column (3), a 10% increase in the overall U-values would increase the probability to patent by 7.8%.

As an additional robustness check, the estimations were also conducted by systematically dropping each country out of the sample. Columns (5) and (6) reports the results when we exclude Germany and Denmark. Germany is the largest patenting country in the sample and Denmark has the most stringent standards and the highest energy prices. The results remain quantitatively similar after excluding Germany as shown in column (5). The effects of the overall U-values are more important when we exclude Germany, suggesting that much of the effect is actually taking place in other countries than Germany. Excluding Denmark, the effect of the overall U-values on the probability to patent is slightly smaller as expected. More remarkably, energy prices have a negative significant effect when Denmark is excluded.Finally, some extra robustness tests are conducted by dropping systematically each technology group out of the sample. The results (not reported here) remain unaffected.[14]

[Table 7 about here.]

Finally, the estimates are repeated using an alternative measure for U-values. Table 8 shows the energy demand of a model house as an alternative measure of the stringency of the building codes. Column (1) uses the main dataset of the baseline estimation. A decrease of 10% in the energy demand of a model house as set in current regulations implies 7.13% additional patents. The coefficient is similar to the effect of overall U-values. Column (2) adds data for the Netherlands and France and column (3) includes only the Netherlands. Since in general France is an outlier due to the prominence of nuclear energy policy, I prefer to use specification (3) including only the Netherlands. Columns (4)-(5) report again the results when Germany and Denmark are excluded out of this sample.

[Table 8 about here.]

Table 9 reports estimates of specifications with alternative variables for energy R&D support and energy prices. Columns (1) and (2) use different lagged variables for the specific R&D expenditures. A lag of 1 year is not significant while a lag of 3 years is significantly positive, suggesting as expected that innovation responds gradually to an increase in public R&D expenditures. Finally, columns (3) and (4) includes alternative measures for the price of energy, namely the mean price of energy over the previous two years and the mean price over the coming three years. It could be that innovators respond only with a delay to the price of energy, or alternatively that they anticipate on future prices. In both cases, however, the coefficient of energy prices remains insignificant. At last, column (5) includes the price variation over time, since it could be that innovation investments are more influenced by the variation in

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[14] All coefficients have the same significance than in the baseline. The impact of building codes is slightly less (more) important when insulation (lighting) technologies are excluded, as expected. The coefficient on energy prices is higher (smaller) when insulation (lightings) technologies are excluded.

prices, than by the actual level of prices. Here again, however, the price coefficient is non-significant.

In addition, different specifications with alternative explanatory variables were estimated. I obtain results similar to the baseline estimates after (1) controlling for the total number of patents filed in all technology types, i.e. not only energy-efficiency in buildings to correct for the different propensity to patent across countries[15] (2) controlling for the number of heating degree days[16], (3) including a time trend in order to capture partly unobservable variation over time.[17]

[Table 9 about here.]

At last, Table 10 reports the estimates using different estimation models, namely a fixed-effect negative binomial[18], a pooled negative binomial and a pooled tobit. Again, the results are similar to the baseline estimates.

[Table 10 about here.]

5 Conclusions

This paper investigates the impact of alternative environmental policy instruments on technological innovations aiming to improve energy efficiency in buildings. The study brings new insights on how public policies can foster technological innovations in the building sector, a sector which despite its importance for climate change issues has received little attention in the literature. The empirical analysis focuses on three main types of policy instruments, namely regulatory energy standards in buildings codes, energy prices and specific governmental energy R&D expenditures. Technological innovation is measured using patent counts for eight specific technologies related to energy efficiency in buildings (insulation, high-efficiency boilers, heat-and-cold distribution, ventilation, solar boilers and other renewables, energy-saving lightings, building materials and climate controls).

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[15] In this case, the variable on the number of dwelling stocks was dropped since both variables were highly collinear.

[16] It could be that on average colder countries tend to innovate more in innovations related to improving energy efficiency in buildings than warmer countries. This coefficient, however, was never significant. This could be due to the fact that our sample focuses on Northern European countries, with relatively few variation in the number of heating degree days.

[17] Since the results are robust to including a deterministic time trend and since the time span of the data is not very long (12.5 years on average), time -series properties of the data are not likely to influence the results.

[18] The negative binomial model is generally more suited for overdispersed data. However, there is some discussion in the literature on whether the conditional fixed effects negative binomial is really a ‘true fixed effects’, see Allison and Waterman (2002).

The descriptive analysis of the data shows that the number of patents increases in particular at the end of the 1970s and in the second half of the 1990s. After 2000, the number of patents decreases and tends to remain stable. Patents related to HE-boilers, insulation and heat and cold distribution rise slowly over the 1980s and sharply in the mid-1990s and tend to decline after 2000. Patenting in solar energy experience a renewal in recent years after a steady decrease in the 1980s. Finally, the number of patents in lighting technologies reaches a peak after 2000, slightly later than other technologies. The estimates for seven European countries over the 1989-2004 period imply that a strengthening of 10% of the minimum insulation standards for walls would increase the likelihood to file additional patents by about 3%. In contrast, energy prices have no significant effect on the likelihood to patent. Governmental energy R&D support has a small positive significant effect on patenting activities. The results are robust to a large range of specifications. The fact that energy prices are never significant can be explained by the very low real energy prices over the period. Another potential explanation is the fact that economic incentives may have a lower effect in the building sector than in other manufacturing sectors, due to the presence of principal-agent type of issues. Overall, the results suggest thus that for the specific case of the building sector strengthening regulatory standards would have a greater impact on innovation than energy prices or R&D support.

Future work should take advantage of the disaggregated nature of patent data at the firm level and study how policies can influence firm behaviour. Beside differences across sectors, there might be differences across firms on how policies affect innovation. Further, beyond the types of policy measures, other attributes such as stability or flexibility or the measures might be particularly relevant (see Johnstone et al., 2009). In addition, more work is needed to measure how innovations and patents effectively contribute to reducing environmental impacts. Finally, the very interesting issue as to how various policy measures contribute to higher energy efficiency through the diffusion of technologies would also be interesting to consider.

Appendix

Tables

[Table 11 about here.]

[Table 12 about here.]

[Table 13 about here.]

[Table 14 about here.]

[Table 15 about here.]

[Table 16 about here.]

[Table 17 about here.]

[Table 18 about here.]

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Table 1: Years of introduction and revision of building codes

	Year of enforcement (or revision) of regulations
Austria	1995
Belgium	1992, 2006
Denmark	1977, 1982, 1995, 2005
Finland	1978, 1985, 2003
France	1974, 1982, 1989, 2001, 2006
Germany	1978, 1982, 1995, 2002
Ireland	1992, 1998, 2003
Netherlands	1992, 1996, 1998, 2000, 2006
UK	1976, 1985, 1991, 2002

Austria: national standards. Each region can in principle set more stringent standards than the national one.

Belgium: regulations for the Flanders region.

Table 2: Technology groups in energy-efficient innovations in buildings

Field of application	Specific technologies
Insulation and Energy demand reduction	Glazing, Window Frames, Insulation Materials, Floor and Roof Insulation, Insulation of pipes, Sun blinds, Warm Water Saving Devices
Heat Generation: HE-boilers	HE-boilers
Heat and Cold Distribution and CHP	Heat pumps, Heat and Cold Storage, Cooling, Heat Recovery, Heating Systems, Combined Heat and Power (CHP) or Cogeneration
Ventilation	Ventilation Technologies
Solar Energy and other RES	Thermal Solar Energy, Photovoltaic Energy (PV), Passive Solar Energy, Biomass, Geothermal Energy
Lighting	LEDs, Fluorescent Lamps, Daylight Systems, Timed Lighting
Building Materials	Phase Change Materials, Timber Frames
Climate Control Systems	Tuning Indoor Climate System, Room Thermostat with Timer, Home Automation

Table 3: Total number of patents (domestic and EP/WO applications), 1978-2006 per country

Country	Total number of patents	Share	Percentage of domestic applications
Austria	3298	4.9%	89%
Belgium	511	0.7%	55%
Germany	43206	63.7%	92%
Denmark	842	1.3%	55%
Finland	824	1.2%	81%
France	12047	17.8%	94%
United Kingdom	4413	6.5%	73%
Ireland	310	0.5%	72%
Netherlands	2378	3.5%	50%

Table 4: Total number of patents (domestic and EP/WO applications), 1978-2006 per technology group

Technology	Total number of patents	Share
Insulation	12353	18.2%
HE-boilers	14879	21.9%
Heat and Cold distribution	11142	16.4%
Ventilation	2613	3.9%
Solar energy and other RES	7492	11.0%
Lightings	12057	17.8%
Building materials	4332	6.4%
Climate control systems	2961	4.4%

Table 5: Descriptive Statistics

	Description	Unit	Mean	St Dev	Min	Max	Obs
$NPATENTS_t$	Number of patents		43.72	102.46	0	660	856
$UVALWALL_t^a$	U-values walls	kWh/m2	1.76	0.72	0.87	3.71	856
$UVALTOT_t^a$	U-values overall	kWh/m2	5.98	1.47	3.51	8.52	776
$UVALWIND_t^a$	U-values windows	kWh/m2	9.24	3.00	4.20	15.12	776
$MODELHOUSE_t$	Energy demand of a model house	kWh/m3	23.73	6.57	13.27	42.15	856
$PRICES^b$	Energy prices	USD/toe	7.91	2.61	4.46	14.68	856
$ENERGYRD_t^c$	Governmental energy R&D expenditures	millions USD	0.86	1.48	0	13.09	738
$\Delta DWSTOCK_t$	Growth rate building stock	%	1.06	1.03	− 6.61	3.74	856
$DWSTOCK_t$	Building stock (number of dwellings)	100,000s	126.35	134.10	10.56	391.41	856

The table gives the descriptive statistics for the 1981-2004 period, excluding France and the Netherlands.

[a] The U-values and the energy demand of a model house are corrected for climate factors (number of heating degree days). Not all countries have introduced U-values for windows over the 1981-2004 period, therefore the number of observations for $UVALWIND_t$ and $UVALTOT_t$ is smaller than for $UVALWALL_t$.

[b] Real energy prices are the weighted price index defined in equation 1 deflated by the consumer price index. The fixed weights in 1 are the 1997 share of each energy source in the residential sector. Energy prices are expressed in US dollars per ton of oil equivalent (USD/toe, 2007 prices) using PPP. Prices are thus expressed in terms of the heat content of the fuel rather than price per physical unit. The IEA converts energy prices in tons of oil equivalent using the country specific calorific value for light fuel oil. For all countries, a factor of 0.000086 is used to convert electricity from kWh to 10^7 kcal and a factor of 0.9 is used to convert natural gas from gross to net heat equivalents.

[c] Energy R&D expenditures are expressed in USD (2007 prices) using PPP and deflated by the consumer price index.

Table 6: Baseline estimates

	(1) 1981-2004	(2) 1981-2004	(3) 1989-2004	(4) 1989-2004
Log($UVALWALL_t$)	-0.319***	-0.366***	-0.311***	-0.385***
	(0.060)	(0.077)	(0.080)	(0.061)
Log($PRICES_t$)		– 0.182	0.054	0.102
		(0.388)	(0.548)	(0.334)
Log($ENERGYRD_{t-2}$)		0.033**	0.028***	
		(0.016)	(0.011)	
$\Delta DWSTOCK_t$		0.165***	0.292***	0.266***
		(0.018)	(0.075)	(0.067)
$DWSTOCK_t$		– 0.001	0.001	0.000
		(0.005)	(0.006)	(0.005)
Obs	1264	678	570	736
Number of groups	56	48	48	56
Log-likelihood	– 4348	– 2085	– 1797	– 2128

Robust standard errors clustered per country in brackets. ***/**/* indicates significance at the 1/5/10 % level, respectively.

The dependent variable is the number of patents in country i in technology group j in year t.

The estimations includes a full set of year dummies.

All regressions are estimated by a conditional Poisson fixed effect model.

Table 7: Robustness: Alternative measures of building energy standards

	(1)	(2)	(3)	(4)	(5) excl. DE	(6) excl. DK
Log($UVALWALL_{t+1}$)	– 0.552***					
	(0.086)					
Log($UVALWALL_{t+2}$)		– 0.231***				
		(0.083)				
Log($UVALWIND_t$)			– 0.519***			
			(0.091)			
Log($UVALTOT_t$)				– 0.780***	– 0.951***	– 0.654***
				(0.084)	(0.139)	(0.061)
Log($PRICES_t$)	0.067	0.125	– 0.074	0.016	0.758	– 0.545**
	(0.310)	(0.348)	(0.347)	(0.319)	(0.671)	(0.227)
$\Delta DWSTOCK_t$	0.188***	0.272***	0.229***	0.214***	0.252***	0.130
	(0.042)	(0.048)	(0.052)	(0.060)	(0.070)	(0.083)
$DWSTOCK_t$	– 0.003	0.004	0.000	– 0.003	0.017**	0.004**
	(0.004)	(0.004)	(0.004)	(0.004)	(0.008)	(0.002)
Obs	752	768	720	720	600	592
Number of groups	56	56	56	56	48	48
Log-likelihood	– 2128	– 2179	– 2075	– 2066	– 1266	– 1813

Robust standard errors clustered per country in brackets. ***/**/* indicates significance at the 1/5/10 % level, respectively.

The dependent variable is the number of patents in country i in technology group j in year t over the 1989-2004 period.

The estimations includes a full set of year dummies.

All regressions are estimated by a conditional Poisson fixed effect model.

Table 8: Robustness: Alternative specifications using the energy demand of a model house as a measure of the stringency of building codes

	(1)	(2)	(3)	(4)	(5)
		inc FR, NL	inc NL	inc NL	inc NL
				excl DE	excl DK
Log($MODELHOUSE_t$)	-0.713***	-0.584***	-0.539***	-0.505*	-0.511***
	(0.123)	(0.052)	(0.135)	(0.267)	(0.120)
Log($PRICES_t$)	0.030	– 0.169	0.288	0.598***	0.130
	(0.305)	j(0.411)	(0.252)	(0.207)	(0.374)
$\Delta DWSTOCK_t$	0.309***	0.156**	0.340***	0.219***	0.333***
	(0.082)	(0.074)	(0.070)	(0.067)	(0.104)
$DWSTOCK_t$	0.003	0.005	0.004	0.009	0.006***
	(0.004)	(0.003)	(0.002)	(0.009)	(0.002)
Obs	736	936	824	704	696
Number of groups	56	72	64	56	56
Log-likelihood	– 2134	– 2907	– 2431	– 1621	– 2181

Robust standard errors clustered per country in brackets. ***/**/* indicates significance at the 1/5/10 % level, respectively.

The dependent variable is the number of patents in country i in technology group j in year t over the 1989-2004 period.

The estimations includes a full set of year dummies.

All regressions are estimated by a conditional Poisson fixed effect model.

Table 9: Robustness: Alternative energy R&D and price variables

	(1)	(2)	(3)	(4)	(5)
Log($UVALWALL_t$)	-0.326***	-0.356***	-0.394***	-0.378***	-0.386***
	(0.081)	(0.085)	(0.068)	(0.051)	(0.062)
Log ($ENERGYRD_{t-1}$)	0.010				
	(0.008)				
Log ($ENERGYRD_{t-3}$)		0.018**			
		(0.008)			
Log($PRICES_t$)	0.166	0.164			
	(0.436)	(0.480)			
Log(av PRICE last 2 years)			– 0.004		
			(0.004)		
Log(av PRICE coming 3 years)				0.203	
				(0.399)	
ΔLog($PRICES_t$)					0.115
					(0.301)
$\Delta DWSTOCK_t$	0.276***	0.276***	0.228***	0.274***	0.257***
	(0.052)	(0.089)	(0.060)	(0.068)	(0.037)
$DWSTOCK_t$	0.003	– 0.000	– 0.000	– 0.001	– 0.000
	(0.005)	(0.006)	(0.004)	(0.005)	(0.002)
Obs	587	569	744	728	736
Number of groups	48	48	56	56	56
Log-likelihood	– 1822	– 1754	– 2147	– 2111	– 2128

Robust standard errors clustered per country in brackets. ***/**/* indicates significance at the 1/5/10 % level, respectively.

The dependent variable is the number of patents in country i in technology group j in year t over the 1989-2004 period.

The estimations includes a full set of year dummies.

All regressions are estimated by a conditional Poisson fixed effect model.

Table 10: Robustness: alternative estimation models

	Neg Bin FE (1)	Neg Bin FE (2)	Neg Bin Pooled (3)	Neg Bin Pooled (4)	Tobit Pooled (5)	Tobit Pooled (6)
Log($UVALWALL_t$)	-0.209***	-0.171**	-0.491***	-0.402***	-0.530***	-0.393***
	(0.065)	(0.079)	(0.102)	(0.105)	(0.132)	(0.151)
Log($PRICES_t$)	0.151	– 0.077	0.176	0.054	0.263	0.140
	(0.215)	(0.304)	(0.198)	(0.306)	(0.255)	(0.339)
Log($ENERGYRD_{t-2}$)		0.040**		0.035**		0.026
		(0.018)		(0.017)		(0.026)
$\Delta DWSTOCK_t$	0.256***	0.299***	0.201***	0.224***	0.122*	0.197**
	(0.054)	(0.074)	(0.056)	(0.080)	(0.068)	(0.091)
$DWSTOCK_t$	0.004***	0.004***	– 0.006	– 0.005	– 0.006	– 0.002
	(0.001)	(0.001)	(0.004)	(0.004)	(0.004)	(0.004)
Observations	736	570	736	578	664	556
Log likelihood	– 1819	– 1496	– 2023	– 1685	– 495	– 382

In columns (1)-(4), the dependent variable is the count number of patents. In column (5)-(6), the dependent variable is the log of the number of patents. In columns (7)-(8), observations for which the number of patents is zero are excluded (9% of the sample).

All specifications include a full set of year dummies.

Columns (3)-(6) include countries and technologies interactions.

Standard errors in brackets. Robust standard errors are computed in columns (2)-(8).

Table 11: Queries for energy-efficient innovations in buildings, Insulation and energy demand reduction

Insulation and energy demand reduction			General IPC	Sub-classes	Keywords
Heat saving	Glass				
		double-glazing	E06B	3/24, 3/64 3/66, 3/67	
		high performance glazing	E06B	3	high perform+ OR insulat+ OR low energy
		low-e coating	C03C	17/00, 17/36	low e
		vacuum glazing	E06B	3/67F	vacuum
		translucent insulation (aerogel)	E06B		aerogel
	Window frames				
		vinyl window frames	E06B	3/20	
		window frames with thermal break	E06B	1/32, 3/26	thermal break
	Insulation material	general	E04B	1/74,1/76	
		foams	E04B		polyurethane OR PUR OR polystyrene OR EPS OR XPS OR heavy gas+ OR pentane OR insulat+
		cavity wall insulation materials	E04B		flax OR straw OR (sheep+ AND wool)
	Floor insulation	foil with air cushions	E04F	15/18	
		shells	E04F		sea shell
	Roof insulation	general	E04D	11	insulat+
		green roof	E04D	11	green roof
		thatched roof	E04D	11, 9	thatch+
	Insulation of pipes		F16L	59/14	
Water saving	Water-saving devices		F24H		water AND (sav+ OR recover+)
			F16K	1	water AND (sav+ OR recover+)
			E03C	1	water AND (sav+ OR recover+)
Cooling reduction	Sunblinds	sunblinds	E04F	10	
		reflecting, sunproof or heat resistant glass	C03		glass AND (reflect+ OR sunproof OR heat resist+)
			E06B	3	glass AND (reflect+ OR sunproof OR heat resist+)
			B32B	17	glass AND (reflect+ OR sunproof OR heat resist+)

Table 12: Queries for energy-efficient innovations in buildings, High-Efficiency Boilers

High-Efficiency Boilers	General IPC	Sub-classes	Keywords
HE-boilers	F23D	14	
	F24D	1	low
	F24D	3, 17	
	F24H, excluding F24H7		

Table 13: Queries for energy-efficient innovations in buildings, Heat and Cold Distribution and CHP

Heat and Cold Distribution and CHP	General IPC	Sub-classes	Keywords
Heating Systems	F24D	5, 7, 9, 10, 11, 13, 15, 19	
Storage heaters	F24H	7	
Heat exchange	F28F	21	
Cooling	F25B	1, 3, 5, 6, 7, 9, 11, 13, 15, 17	
CHP (Cogeneration)	X11-C04 R24H240/04 (ICO code)		

CHP/Cogeneration codes are taken from the Thomson patent database - the World Patent Index (WPI). In case of CHP the classification in the WPI is better than the IPC. The extra ICO code makes sure additional applications in cogeneration from the EPODOC are addedd to the list.

Table 14: Queries for energy-efficient innovations in buildings, Ventilation

Ventilation	General IPC	Sub-classes	Keywords
Ventilation	F24F	7+	

Table 15: Queries for energy-efficient innovations in buildings, Solar Energy and other Renewables (RES)

Solar Energy and other RES	General IPC	Sub-classes	Keywords
Solar Energy	F24J	2	
	H01L	31/042, 31/058	
	H02N	6	
Biomass	F24B		wood+
Geothermal	F24J	3	

Table 16: Queries for energy-efficient innovations in buildings, Lighting

Lighting	General IPC	Sub-classes	Keywords
Lighting	F21S		not vehicle, not aircraft
	F21K	2	not vehicle, not aircraft
	H01J	61	not vehicle, not aircraft
	F21V	7	house or home or building
LED	H01L	33	light and LED
	H05B	33	light and LED

Table 17: Queries for energy-efficient innovations in buildings, Building Materials

Building Materials	General IPC	Sub-classes	Keywords
Construction structures	E04B	1	building+ or house+
Materials	C09K	5	building+ or house+

Table 18: Queries for energy-efficient innovations in buildings, Climate Control Systems

Climate Control Systems	General IPC	Sub-classes	Keywords
Control of temperature	G05D	23/02	
Electric heating devices	H05B	1	

Figure 1: Thermal insulation standards, U-values walls, corrected for climate

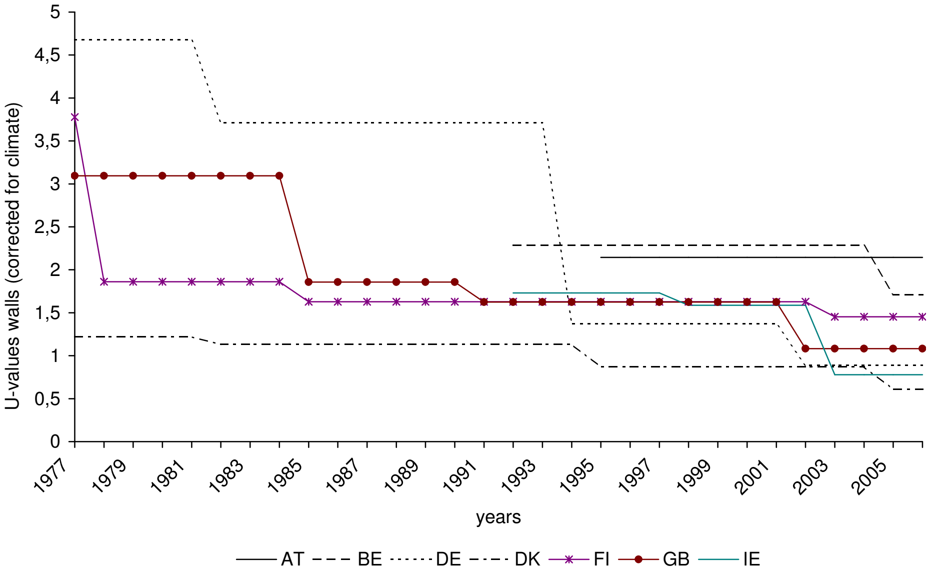


Figure 2: Evolution of the energy demand of a model house due to thermal building regulations

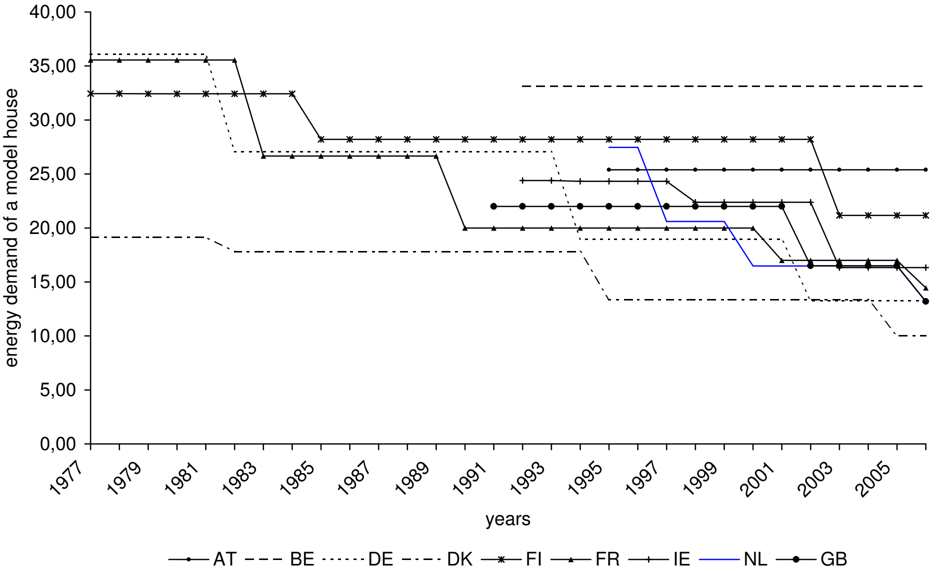


Figure 3: Energy mix in the residential sector

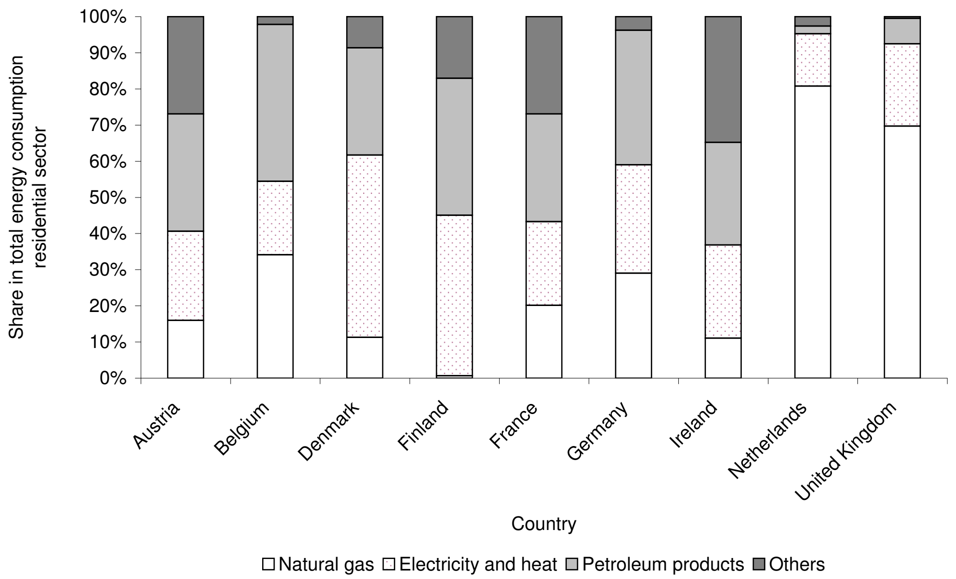


Figure 4: Evolution of the fixed-weights energy price index (using logarithms)

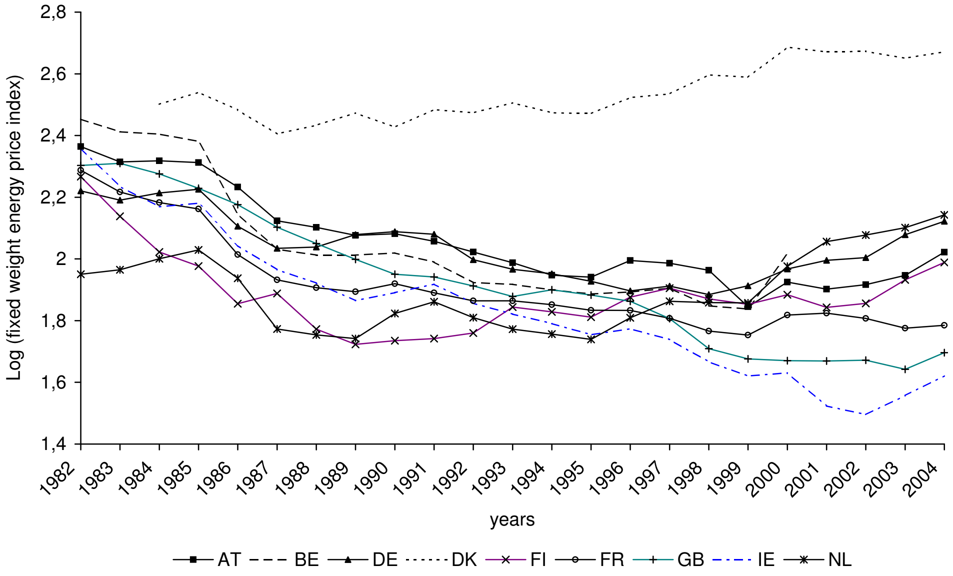


Figure 5: Evolution of the total number of patents on energy-efficient innovations in buildings, 1978-2006

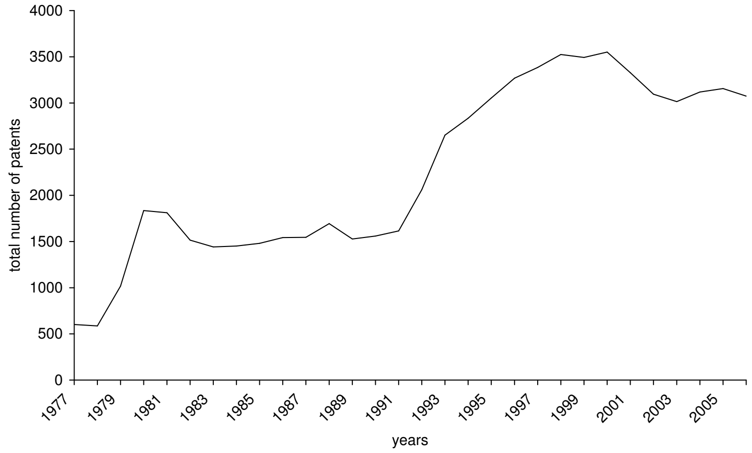


Figure 6: Evolution of the total number of patents on energy-efficient innovations in buildings per technology field, 1978-2006

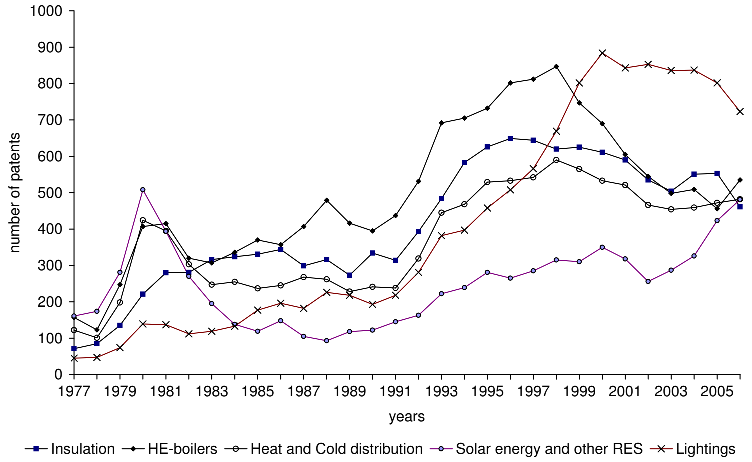
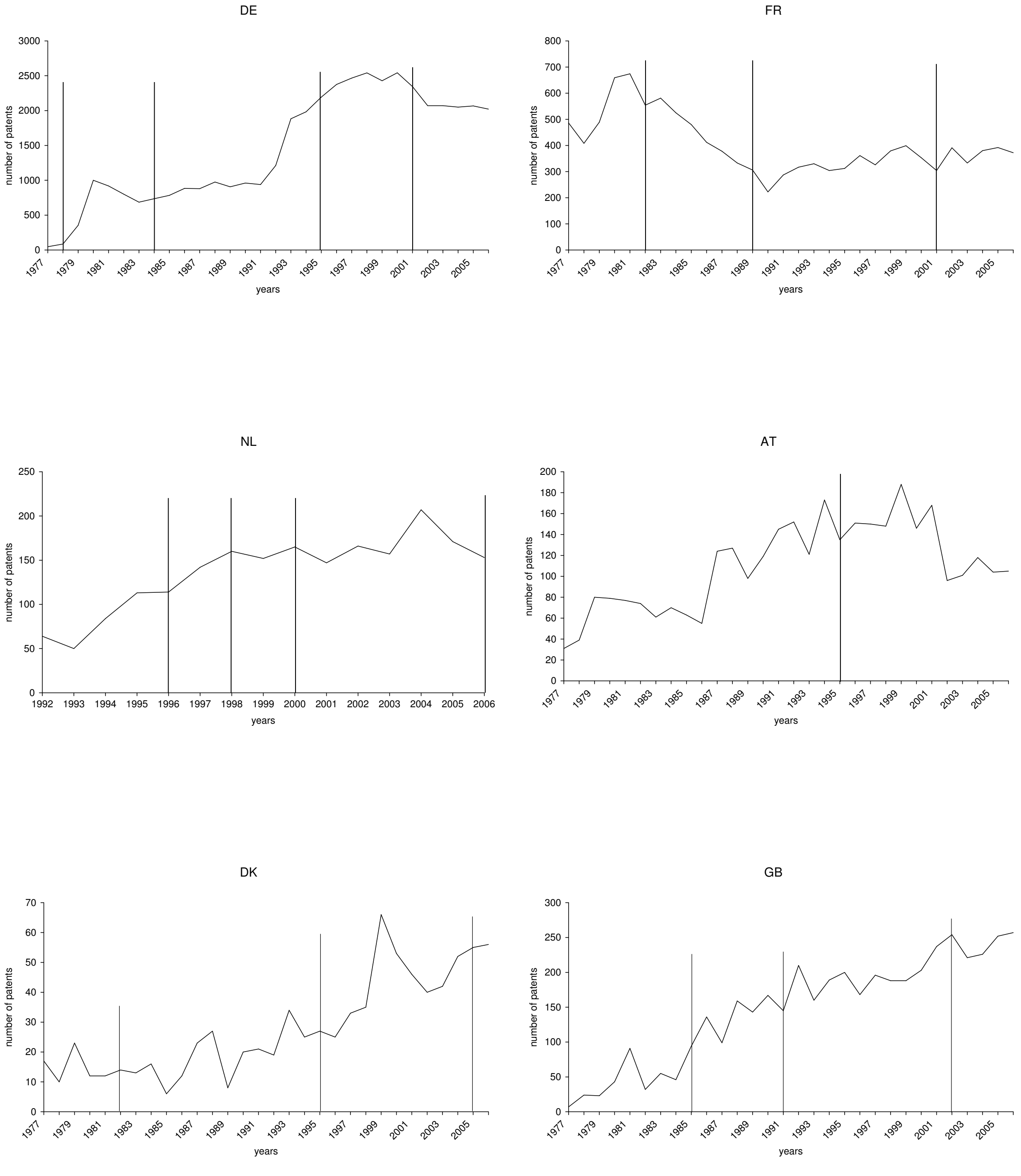


Figure 7: Patent trends in selected European countries



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