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Policy Inducement Effects in Energy Efficiency Technologies. An Empirical Analysis on the Residential Sector*

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Abstract

The study provides a wide-ranging empirical analysis of the drivers of innovation, with a particular focus on the policy side, in residential energy efficiency technologies. The panel analysis of 23 OECD countries over the period 1990-2010, confirms the importance of adopting a systemic perspective when eco-innovation is under scrutiny. In particular, the innovation systems, both national and sectoral, together with the energy systems, spurred the propensity to innovate and significantly shaped the rate and direction of technical change in the residential sector. A general policy inducement effect is found to be relevant, but the size of its contribution for new EE technologies changes if disaggregated policy instruments are investigated. The role of policy mix as well as of policy coordination and coherence also positively affect the innovative activity in EE residential technologies.

Keywords: energy efficiency, policy mix, residential sector, innovation, patents.

J.E.L. O31, O38, Q48, Q55, Q58

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1. Introduction

Energy efficiency (EE) represents one of the most effective mean for achieving several goals, as increasing energy security, fostering international cost competitiveness, and reducing polluting emissions. In particular, achieving a more secure, sustainable and affordable energy system is a key challenge for the future world development (EC, 2011; IEA, 2010, 2012a). In this context, the availability and adoption of new energy-efficient technologies represents a key driver for reducing the overall energy demand as it influences the levels of EE (EE). This aspect appears to be particularly relevant in the residential sector, where the demand for energy to power residential appliances and equipment does not show a slowing trend with, on the contrary, a continuous growth over the last 20 years in electricity demand.

The understanding of the determinants of the pace of inventive activities in this sector therefore appears to be an important step for the design of appropriate policies to foster the generation and diffusion of environmental technologies aiming at increasing EE. However, the residential sector is a complex system in which several energy services are used such as space heating, cooling systems, water heating systems, lighting and several electrical appliances. This implies that relevant research efforts are needed to properly map the evolution of technologies in this sector and to systematically collect information of specific policy strategy.

Given the limited number of studies that analysed the drivers of innovation in this field, we propose a comprehensive analysis of the factors affecting the dynamics of EE technologies in the residential sector, with a specific attention to the role played by public policies. In so doing, we contribute the current literature: i) by including in the analysis the domain of electrical appliances which – although rather unexplored – constitute an important share of residential energy consumption for their large potential due to the multiplicative effect of each single appliance; ii) by extending the country coverage of the empirical analysis to a comprehensive number of high-income OECD countries; iii) by analysing the impact of the full array of policy instruments that are supposed to influence innovation activities.

The rest of the work is organised as follows. Section 2 shows the consumption patterns as well as the innovation dynamics in EE in the residential sector for better understanding the energy-growth decoupling process occurred in most of OECD countries. In Section 3, we describe the data used for the econometric analysis, with a particular focus on the policy framework, while Section 4 lays out the empirical strategy and presents the model results. Finally, Section 5 concludes with some policy implications and further research lines.

2. Consumption patterns and innovation dynamics in EE for the residential sector

2.1 Energy consumption trends and energy-growth decoupling

During the past decades energy consumption trends have changed substantially after the first oil shock, due to several modifications occurred in energy policy as well as in consumption behaviours, especially in the developed world. Decreasing dynamics in energy and carbon intensity may be detected in almost all economic sectors, with a stronger effect in the manufacturing industries. By looking at the last two decades (1990-2010), it is worth noting that there are some divergences especially when the residential sector is under scrutiny. By comparing index numbers taking 1990 as base year, built on the ratio between total energy consumption and Gross Domestic Product (GDP) for selected OECD countries (Figure 1), the average trend for OECD countries as well as the path for three major energy consumers (namely Germany, Japan and the US), is continuously decreasing over time, with the exception of Japan up to 2004. The residential sector shows, on average, a similar dynamics for OECD economies, with increasing values for Japan and a less evident negative trend for Germany (Figure 2). Index numbers built on the ratio between energy consumption in the residential sector and household final consumption expenditures provides interesting differences with the previous overall trend, where the divergence between Japan and the rest of OECD countries appears much higher.

This evidence provides a first broad picture of cross-country specific features, signalling that some countries have reduced efforts to improve EE in the residential sector with respect to others, while other countries obtained EE gains especially in this sector. Reasons behind these divergences may be detected in several directions.

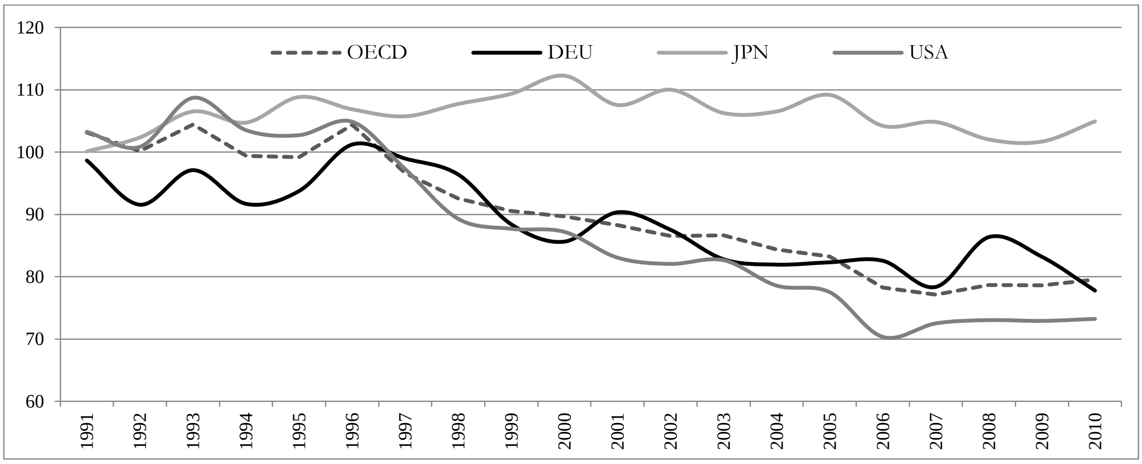
A first explanation can be found by the different policy stringency adopted in OECD countries during these two decades for EE in the residential sector. Indeed, the number of policies has increased substantially after year 2000 (see Section 3), with countries as Japan, the United Kingdom and the US adopting more stringent and pervasive policies only recently, while other countries as Denmark, Finland and Germany introduced a relatively smaller number of policies, but they have been adopted them since the early 1990s. It is also worth noting that the effectiveness of environmental policies is closely related to the adopted instruments. Several differences arise when comparing for instance command and control with market-based instruments (Baumol and Oates, 1988), where the latter are considered as cost effective as well as more suitable for pushing technological change (Porter and van der Linde, 1995).

As a matter of fact, this field of analysis requires a complex framework, where several driving factors may help explaining divergent performance trends, as institutional and technological capabilities, as well as the more general innovation system at country level. It is also true that gains in resource efficiency are forced to be strictly related to technological innovation, giving impulse to a large number of scientific contributions trying to disentangle this issue.

2.2 Eco-innovation and energy efficiency

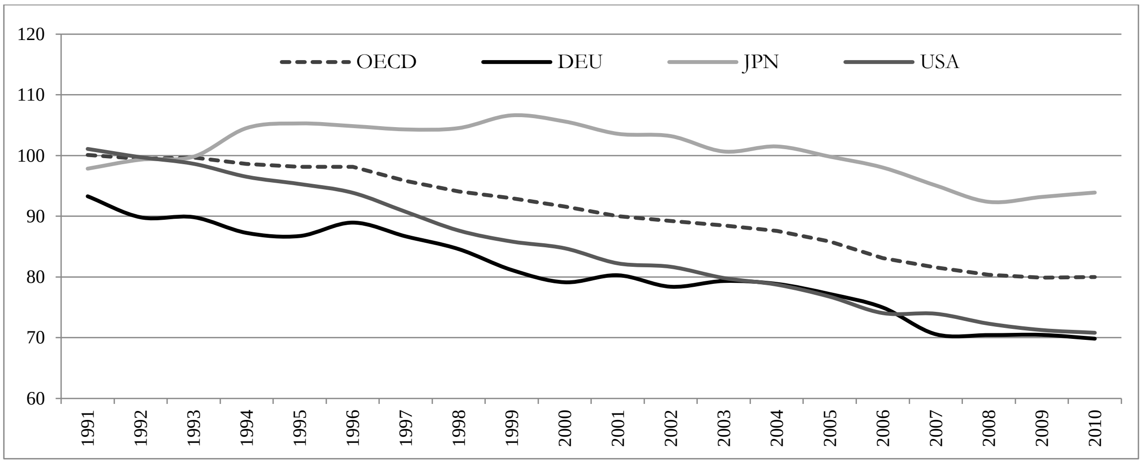
Broadly speaking, the reduction of the overall residential energy demand can be thought as a function of the level of EE, which in turns depends on the availability and adoption of new EE technologies, such as intelligent building design and high-performance buildings including highly efficient heating, ventilation and water heating systems. With respect to this, the dynamics of employed technologies in the residential sector is a key issue.

Figure 1 – Energy intensity trends in total economy, 1990-2010 (1990=100)



Source: own elaborations on IEA (2012b), World Bank (WDI, 2013)

Figure 2 – Energy intensity trends in the residential sector 1990-2010 (1990=100)



Source: own elaborations on IEA (2012b), World Bank (WDI, 2013)

Considering the strong linkage between the energy system, the environment and innovation processes, EE can be well included EE into the broader eco-innovation framework (Kemp and Pearson, 2008; OECD, 2010). In this work, we are particularly interested in understanding how public policies may induce innovation efforts at the country level. By relying on the growing literature analysing different technological environmental domains (Arundel and Kemp, 2011; Berkhout, 2011; Borghesi *et al*., 2013; Haščič *et al*, 2009; Horbach *et al*., 2012; Johnstone *et al*., 2010; Kemp and Oltra, 2011; Lanjouw and Mody, 1996; Markard *et al*., 2012; Nameroff *et al*., 2009; OECD, 2011; Popp, 2002), a patent-based analysis seems to be the most appropriate way to study innovation dynamics in this field due to lack of specific data on efforts in research and development (R&D), especially in the private sector.

Despite some relevant limitations, the use of patent data is widespread in the economics of innovation literature (see Archibugi and Pianta, 1996; Arundel and Kabla, 1998; Cohen *et al*., 2000; Griliches, 1990; Hall *et al*., 2005; Jaffe and Trajtemberg, 2004; Malerba and Orsenigo, 1996; Oltra *et al*., 2010; Pavitt, 1984; Lanjouw *et al*., 1998; Lanjouw and Schankerman 2004; van Pottelsberghe *et al*., 2001; van Zeebroeck *et al*., 2006). Indeed, patents provide a public wealth of information on the nature of the invention and the applicant for rather long time series, indicating not only the countries where inventions are made, but also where such new technologies are used and derive from. Patent data frequently represent the direct result of R&D processes, a further step toward the final output of innovation that is useful knowledge through which firms are able to generate new profit sources. Moreover, patent applications are usually filed early (Griliches, 1990), hence they can be interpreted not only as a measure of innovative output, but also as a proxy of innovative activity (Popp, 2005). Besides this, it is worth noting that patent data are subject to an extensive updating process of their informative content, continuously enriched by national and international patent offices. In addition, EE technologies are only partially and roughly represented in the set of international patent classifications.

A first contribution in filling this gap is provided by Noailly and Batrakova (2010), analysing the building sector for a limited number of countries. They used patent applications per year in selected areas of environmental technologies in buildings, classified by applicant country and priority date. In order to identify the relevant patents, they referred to technical experts, providing IPC classes related to specific technologies together with a list of keywords for describing the state-of-the-art of EE technologies in the building sector. Although this work provides an important contribution in mapping EE technologies, it does not consider the important domain of domestic electrical appliances, which represent an important share in final energy consumption having at the same time a high potential impact in terms of EE gains thanks to the multiplicative effect for their widespread diffusion (IEA, 2009). This gap has been partially filled by the recent Cooperative Patent Classification (CPC), a joint collaboration between the European Patent Office (EPO) and the United States Patent and Trademark Office (USPTO), which integrates now some patent classes specific for EE, also including four domestic electrical appliances. In particular, for those patents related to building, we adopted the methodology based on keywords developed by Noailly and Batrakova (2010), extending the search to 23 OECD countries and 21 years. In this work, we also take into account EE patents in domestic electrical appliances, following the work already done in Essay 1, which provides a comprehensive and up-to-date contribution in mapping such a technological domain (including also the new EE classes based on the CPC-Y02 classification) while maintaining the same methodology of patent searching as for the previous sectors. As a result, we obtained a set of 55,261 patent applications related to EE technologies in different residential sectors and following a homogeneous extraction methodology. Once extracted patent data using the Thomson Reuters Core Patents search engine, the patent count has been calculated and sorted by application date, having dropped duplicates to avoid possible double counting of patents. Finally, the whole technological domain has been divided into three sub-domains: building, lighting and large residential appliances (see Section 3). A complete list of keywords is provided in Table A1a,b of the Appendix, while for a comprehensive description of patents extraction methodology, see Noailly and Batrakova (2010) and Costantini *et al*., (2014).

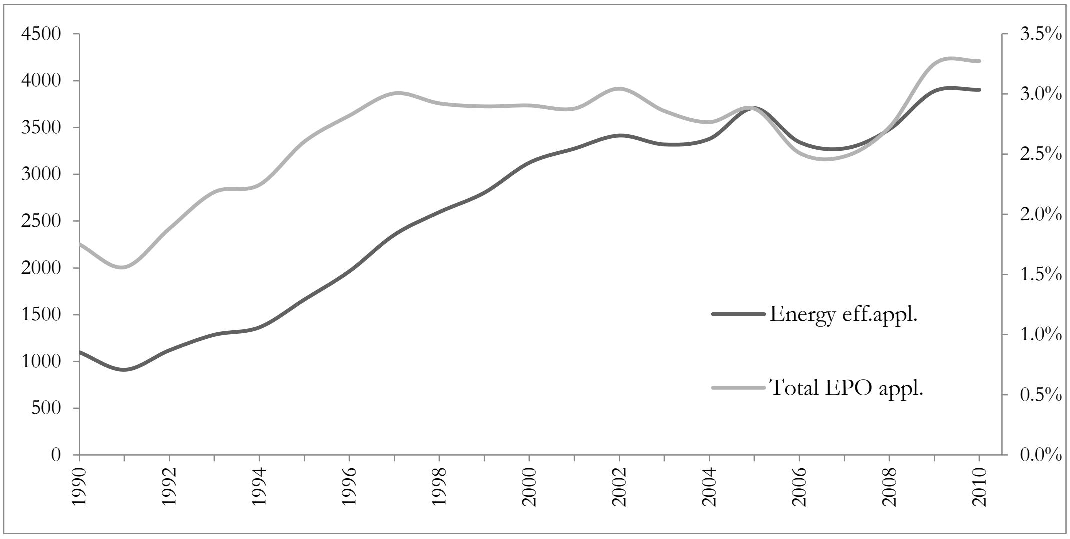
2.3 Energy efficiency patents trend

Patenting activity on EE residential technologies grew dramatically in the period 1990-2010. Figure 3 depicts the trends of EE patents in the residential sector and the share of these latter on total patents registered at EPO in the same period. Although a slight decrease between the 2005 and 2007, which mirrors a general less intensive patenting activity, EE patents show a constant growth. After the year 2007, EE patenting activity was subject to a new positive impulse, stronger with respect to the past, most likely due to the growth in EE regulations in each country (as for instance, the implementation of EE Action Plans, EEAPs, in the European Union). The growing trend is also confirmed by the sectoral analysis as showed in Figure 4, for the three considered sub-sectors of EE residential technologies, namely buildings, lighting and large electrical appliances. In the case of building, the increase in patenting activity was even stronger, especially in the period 2006-2010. It is worth noting that patents on highly efficient appliances are not affected by the general patenting activity downturn occurred in 2005, maintaining a constant growth over the entire analysed period. In terms of sectoral contribution, patents in buildings represent the largest share of EE technologies, followed by lighting and electrical appliances which both moderately contribute to the total number of EE patents set. Specifically, summing the total patents in the entire period, the share of buildings contribution is 73% corresponding to 33,973 applications, those of lighting and electrical appliances are 21% and 17%, corresponding to 11,669 and 9,619 patent applications, respectively.

3. Innovations drivers in residential EE technologies: the empirical framework

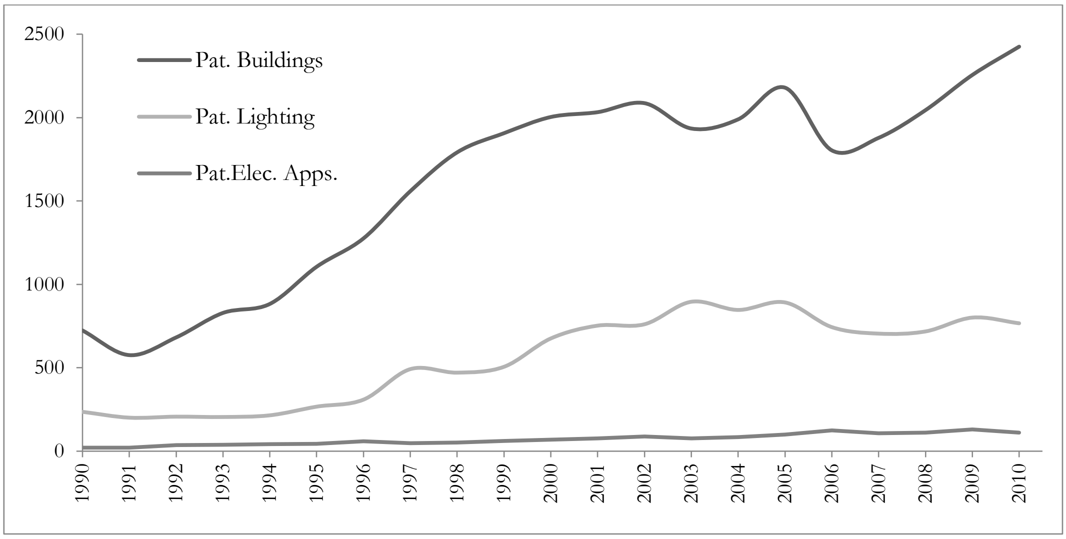
A large body of literature has contributed to find out which are the main forces pushing and supporting eco-innovation, both by means of theoretical and empirical models. Such analyses suggest that a systemic approach to study the determinants of introduction and the patterns of diffusion of eco-innovation appears to be appropriate (Del Rio, 2009; Horbach, 2008; van der Bergh *et al*., 2007) as it allows to shed light on the relevance of both demand-pull and supply-push forces and on the primary role played by public policies in this context (Horbach *et al*., 2012; Nemet, 2009; Popp, 2010). From a general point of view, Coenen and Díaz López (2010) clearly emphasize that a systemic approach is necessary in eco-innovation studies whatever theoretical framework is adopted. Whether technological innovation systems, or socio-technical systems, or sectoral systems of innovation is the analytical setting where the analysis is included, in any case private innovative efforts, technological and institutional capabilities, different public support policies should be accounted for in an integrated manner.

Figure 3 – Trends of EE patents as abs. count values and as share of total patents at EPO (1990-2010)



Source: own elaborations on EPO (2013)

Figure 4 – Trends of EE patents at EPO in the three sub-domains (1990-2010)



Source: own elaborations on EPO (2013)

Building on this comprehensive approach, the proposed empirical analysis takes into account the different forces able to shape the rate and direction of eco-innovation in the considered sector. In particular, our dependent variable, represented by the count of patent applications filed at EPO by 23 countries over the period 1990-2010, is regressed against a set of explanatory variables, referring to the innovation, the market, the institutional and the energy system. The groups of explanatory variables are described as follows.

The Innovation System. There is a large strand of literature discussing the role of national as well as sectoral innovation systems (OECD, 1997). More recently, the innovation process as a whole is interpreted as the result of complex relationships among different actors, including not only market players, but also private and public institutions, government interventions as well as intangible elements such as spillover effects and tacit knowledge flows. In this study, we particularly stressed the role of public policies for inducing innovation in EE but, besides this, other general aspects of the innovation system are taken into account. First, we measure the effort and capability to innovate at country level – considering as a proxy of knowledge stock the national gross expenditure in R&D (GERD) which includes expenditures by business enterprises, higher education institutions, as well as government and private non-profit organisations (data taken from OECD Main Science and Technology Indicators, 2013). Besides this, sectoral features of the energy-technology system have also to be considered. Indeed, the energy sector is characterised by some specific aspects affecting the performance of technological improvements as the slow response to the stimuli to innovate due to the high capital intensity, longevity of capital stock, time needed for learning and experimentation, as well as clustering and spillover effects (Smekens *et al*., 2003; Worrell *et al*., 2005). In light of this, we tested also the energy sectoral knowledge stock proxied by specific expenditures in R&D for EE, provided by IEA (2013a).

The technological knowledge is supposed to operate cumulatively, thus it can be summed over time. On the other hand, knowledge is subject to deterioration as it becomes obsolete (Evenson, 2002) and it should be discounted to take this effect into account. The literature suggests a range of yearly knowledge depreciation rate between 10 and 40 per cent (see Benkard, 2000; Gallagher *et al*., 2012; Hall, 2007, 2007; Nemet, 2009). We apply a moderate decay rate of 15 per cent considering the high level of "inertia" characterising the energy-technology system. In order to build the national and sectoral knowledge stocks, we followed the Perpetual Inventory Method suggested in OECD (2009) as follows:

$$\text{Stock}_{\text{R\&D}} = \sum_{s=0}^{t} \left\{ \text{RD}_{i,s} \cdot e^{[-\gamma(t-s)]} \right\} \tag{1}$$

where γindicates the discount rate, i indexes countries and t, s index time. All values, both for GERD and R&D in EE, have been changed in constant US dollars at year 2010.

The Market System. The market effects in spurring innovation have been extensively analysed in economics, dating back to the seminal work by Hicks (1932) which attributed to prices the role of driving force for more efficient input substitution in which part of this process relies on the innovation. Here we take into account an extensive interpretation of the price-induced effect, extending the framework to the government intervention as an attempt to control market prices. Indeed, it is worth noting that, despite the final substitution stimulus is related to the price, this latter can be divided in two components referring to different innovation drivers. Indeed, the final price influencing the substitution effect often includes government market instruments such as taxes or incentives. Taken out this public component, the residual part of price represents the pure market component, which is supposed not to be affected by public interventions.

Many contributions tested the effectiveness of the price-inducement effect (see Binswanger 1974; Popp, 2002; Verdolini and Galeotti, 2011, among the others), finding significant and positive role of prices for inducing input substitution through innovation, particularly over the long run. In the specific sector of EE, only few studies tried to analyse the relationships between prices and EE innovation. Jaffe and Stavins (1995) focused the empirical analysis on the adoption of technologies, comparing the effects of energy prices, building codes and adoption subsidies on the average EE level in home construction in the US over the period 1979-1988. They found that energy taxes had a positive but relative small impact on technology diffusion with respect to subsidies, whose positive effect was stronger than taxes. On the other hand, building code requirements (a form of direct regulation by technology standards, measured by using dummy variables) did not have effect. The paper by Newell *et al.* (1999) is the only contribution focusing specifically on home appliances. By evaluating the impact of energy prices and regulatory standards on the introduction of new home appliances (e.g. gas water heaters and air conditioners) in the US between 1958 and 1993, it confirms the price-inducement hypothesis finding out that falling energy prices worked against the development of energy-efficient appliances. Noailly (2012) is the most recent study and the only one related to the EE innovation measured by patent data. This investigates the impact of alternative environmental policy instruments (regulatory energy standards in building codes, energy prices and specific governmental energy R&D expenditures) on energy-efficient technological innovations in the building sector. The study has been conducted on seven European countries over the period 1989-2004 and finds that, for the specific case of the building sector, regulatory standards generated a greater impact on innovation than energy prices and R&D support.

In this analysis, the price effect is considered as a price-tax bundle, calculated as the ratio between the overall cost of energy taxation on the total cost of energy consumption as follows:

$$Price\_tax\_bundle_{it} = \frac{\sum_{n=1}^{3}\left(tax_{n,it} \cdot ener\_cons_{n,it}\right)}{\sum_{n=1}^{3}\left(price_{n,it} \cdot ener\_cons_{n,it}\right)} \tag{2}$$

where n indexes diesel, electricity and gas, while i and t, countries and time, respectively. Price and tax rates are taken by IEA Energy Prices and Taxes Statistics (IEA, 2012c), while data on energy consumption are taken by IEA Energy Balance Statistics (IEA, 2012b). All data refer strictly to the residential sector.

The institutional system. In our framework the institutional environment is taken into account by using the different public policies implemented at the country level for this specific domain (Table 1).

Using policy data, we investigate the hypothesis that, although many of the policy interventions were not initially implemented with the purpose of stimulating new EE technologies, all these measures were able to spur the complex process of innovation, in particular at the invention stage, through an inducement mechanism that we call policy-induced effect. Policy data have been extracted by the IEA's "EE Policy Database" (IEA, 2013b), that provides comprehensive, up-to-date information on EE policies in seven demand sectors (buildings, commercial/industrial equipment, energy utilities, industry, lighting, residential appliances and transport) and on policy measures across these sectors in 23 OECD countries. Public regulations can be considered on the basis of various criteria (e.g. type of measure, target audience, effective enforcement year, jurisdiction, policy status). National and supranational policies - still in force or ended during the 1990-2010 period - are included in the analysis. In order to exclusively capture residential-related EE policies, public regulations are selected according to the main residential target audiences, namely "buildings", "lighting" and "appliances" (see Table 1).

Table 1 – EE residential main target and specific sub-domains

Main Policy Target	Specific policy sub-domains
Buildings	Building Code, Building Type (only Residential), Energy class Existing buildings, New buildings
Lighting	Residential
Residential Appliances	Computer, Cooking & Laundry, Home entertainment, Other, Refrigeration, Space cooling, Space heating, Standby, Ventilation, Water heating

Source: IEA (2013b)

At a first look, EE policies trend behaved as the patents set (Figure 5). Indeed, OECD policies adopted to improve EE in residential buildings, lighting and electrical appliances dramatically multiplied during the last decade, showing an increasing heterogeneity among implemented instruments. This constitutes a stylised fact that deserves further investigation. According to IEA (2012a), new policies have been put in place to strengthen building codes for new buildings in Canada, Korea, Luxembourg, Netherlands and the United Kingdom during 2011; building certification has been implemented in EU member states as well. Information on EE in existing buildings are systematically collected and reported in Canada, Germany, Japan, Korea and New Zealand. Minimum Energy Performance requirements (MEPs) have been strengthened and extended to cover new appliances in many OECD countries. New MEPs and labelling for televisions, set-top boxes and digital television adaptors have been introduced in

Australia, Canada and Japan, as well as numerous standby power requirements, planned in 2009, have been completely implemented. Moreover, most of the OECD countries keep on phasing out inefficient incandescent lamps. Furthermore, Canada, Japan, the Netherlands, the United Kingdom and the US have supported international efforts to stimulate adoption of higher-efficiency alternatives to fuel-based lighting in off-grids communities in developing countries.

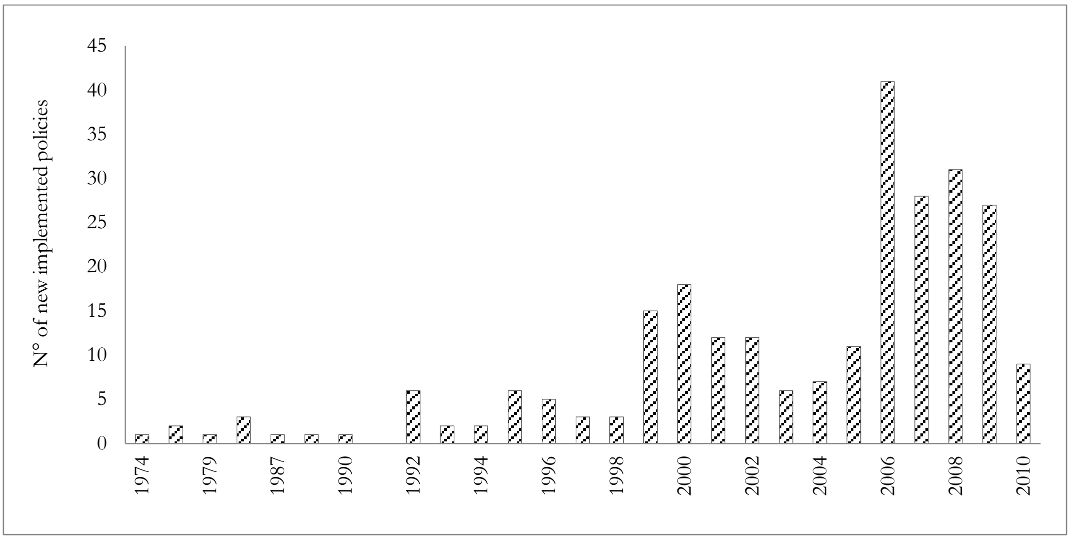
Table 2 – Policy types and instruments

Policy Type	Instrument
Economic Instruments	Direct investment Fiscal/Financial incentives Market-based instruments
Information and Education	Advice/Aid in implementation Information provision Performance label Professional training and qualification
Policy Support	Institutional creation Strategic planning
Regulatory Instruments	Auditing Codes and standards Monitoring Obligation schemes Other mandatory requirements
Research, Development and Deployment (RD&D)	Demonstration project Research programme
Voluntary Approaches	Negotiated agreement (public-private sector) Public voluntary schemes Unilateral commitments (private sector)

Source: IEA (2013b)

Although OECD countries have a strong tradition for promoting EE (dating back to the two oil crises of the 1970s), residential-related EE regulations have been constantly promoted merely since the beginning of the 1990s. Considering the 23 analysed OECD countries as a whole, 253 different policies were identified over the 1974-2010 period; 245 of them have taken place since the decade of the 1990s.

Figure 5 – Overall residential-related EE policies in rich OECD countries (1974-2010)



Source: own elaboration on IEA (2013b)

The first relevant peak of residential-related policy implementation occurred at the turn of the millennium (15 new regulations in 1999 and 18 new regulations in 2000), even though the year 2006, with 41 new implemented policies, was the most intense. After 2006, governments' law-making in residential-related EE field has continued to be significant until 2009, counting, on average, more than 25 new regulations per year. Notwithstanding, in 2010 there has been a slowdown, with only 9 new implemented regulations.

Public regulations in OECD countries have experienced an interesting evolution in their policy framework during the last two decades. It is worth noting that policy packages have become more heterogeneous, showing an increasing level of diversity in terms of both implemented instruments and reference targets.

Figure 6 provides a historical representation of the introduction of alternative policy types in the OECD analysed countries. Each point in the scatter plot represents the year in which a specific policy type was first introduced in that country. As expected, policy types present different timing in their first implementation. Analysed countries have early preferred implementing regulatory instruments (e.g. codes and standards, obligation schemes). Besides these, economic instruments (e.g. direct investment, fiscal/financial incentives) and information and education instruments (e.g. performance labelling) have been further implemented during the 1990s. This does not hold for policy support tools, research, development and deployment (RD&D) instruments and voluntary approaches that – with the exception of the US (which implemented each of the considered instruments during the 1970s) and Denmark (which implemented policy support instruments during the 1980s) – have known their first implementation only during the 2000s. Since the mid-2000s, the entire package of residential-related EE policy types has been in force in the majority of the analysed countries. As a consequence, the level of policy heterogeneity has significantly increased.

Figure 7 plots the level of each of the six policy types implemented over the period from 1990 to 2010. Respectively, regulatory instruments, information and education, and economic instruments have been the most widely employed policy types. Even so, policy support tools, RD&D instruments and voluntary approaches have shown relevant increases in their implementation since the mid-2000s. As mentioned above, persistently since the mid-2000 all of the six policy types have significantly increased and have been simultaneously implemented in almost all analysed countries. Indeed, the number of multi-instrument policies has recently shown an important proliferation in the OECD area, enhancing the level of variety. The same consideration is also evident with respect to residential-related EE targets, that have shown a continuous growth and an increasing co-occurrence during the last years (see Figure 8).

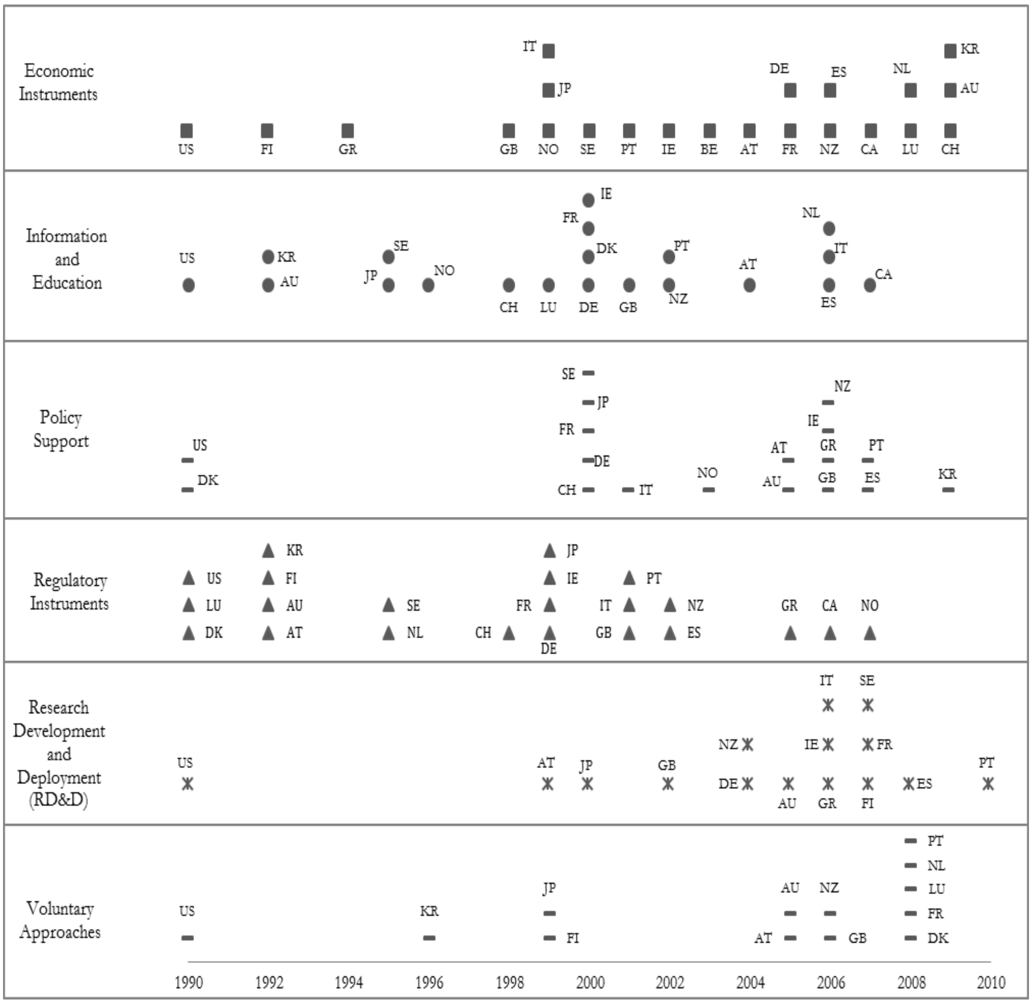
Building-related regulations, the most widely diffused residential-related policy interventions over the analysed period, are characterized by a massive introduction of economic, regulatory and information and education instruments. Notwithstanding, both lighting and appliances-related regulations have more than doubled since 2006. Respectively, lighting-related policies seem to prefer the implementation of regulatory instruments, while information and education tools, such as residential performance labelling, have been the most widely implemented policy instruments in appliances-related regulations. Nevertheless, as underlined above, each of the six policy types have dramatically increased in all the analysed policy targets since the mid-2000s, more and more in co-occurrence with other instruments.

Country-level analysis shows that EU-15 has implemented the largest number of residential-related EE public regulations. This is particularly evident since the mid-2000s, with 81 new policies. The crucial years were 2006, 2007 and 2008 with, respectively, 27, 19 and 19 new policy interventions. The US have maintained a constant considerable level of regulation activity from the 1970s to the mid-2000s, showing a high increase in 2008 and 2009. On the contrary, Japan faced a significant regulation peak over the period 1995-2000 and, after the slowdown of the early 2000s, a new relevant intervention activity in 2006 (Figure 9).

As stressed above, these trends have been also characterized by a significant change in the specific policy instruments mix. All the analysed countries moved over time to higher level of policy variety, increasing the framework complexity as more and more multi-target and multi-instruments policies have been implemented. This is particularly evident for the European Union and the United States that have employed the highest number of policy instruments in each policy target considered in the analysis (see figure 10).

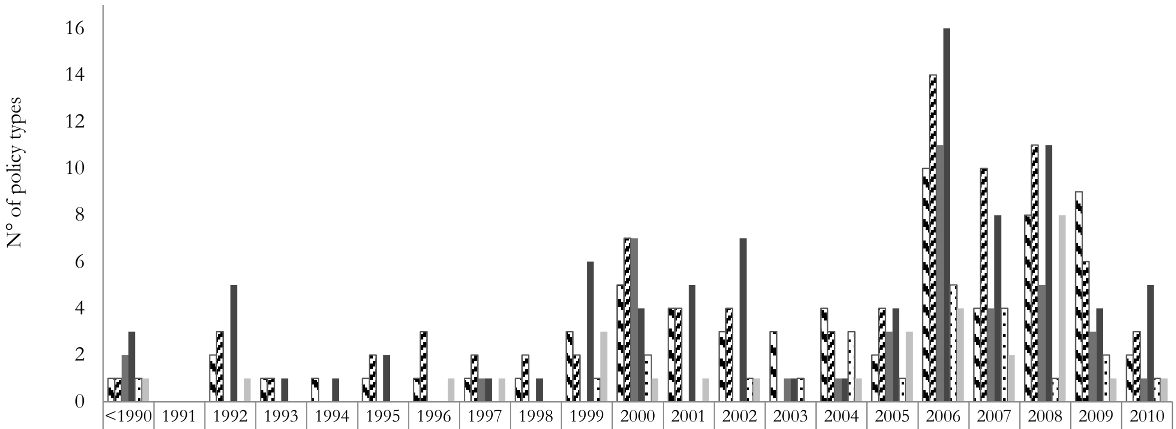
The issue of policy instrument variety for stimulating innovation processes deserves particular attention for its growing interest showed by the scientific literature and international institutions. In particular, the literature is recently focusing on the role of policy mix and the consequences of policy interactions and interdependencies between different policy instruments (Flanagan *et al*., 2011). A major contribution in this field can be attributed to scholars and practitioners in fields particularly relevant to eco-innovation (Kemp, 2011, Rennings, 2000) who emphasized the importance of analysing the properties and the effect of policies (Nill and Kemp, 2009; Smith *et al*., 2010; van den Bergh *et al*., 2007; Moreau; 2004) and policy mix combining several policy instruments, including climate policy (IEA, 2011b, Matthes, 2010), environmental policy (OECD, 2007, Ring and Schröter-Schlaack, 2011) and innovation policy (Flanagan *et al*., 2011, Nauwelaers and Wintjes, 2008). However, policy mix studies tend to be limited for examining the effects of policy mix design and instrument interactions (del Río and Hernández, 2007; IEA, 2011a, b) and further empirical analysis is required in order to assess the contribution of policy instruments interaction in a systemic view (Coenen and DíazLópez, 2010).

Figure 6 – First implementation of residential-related EE policies in 23 OECD countries by type



Source: own elaboration on IEA (2013b)

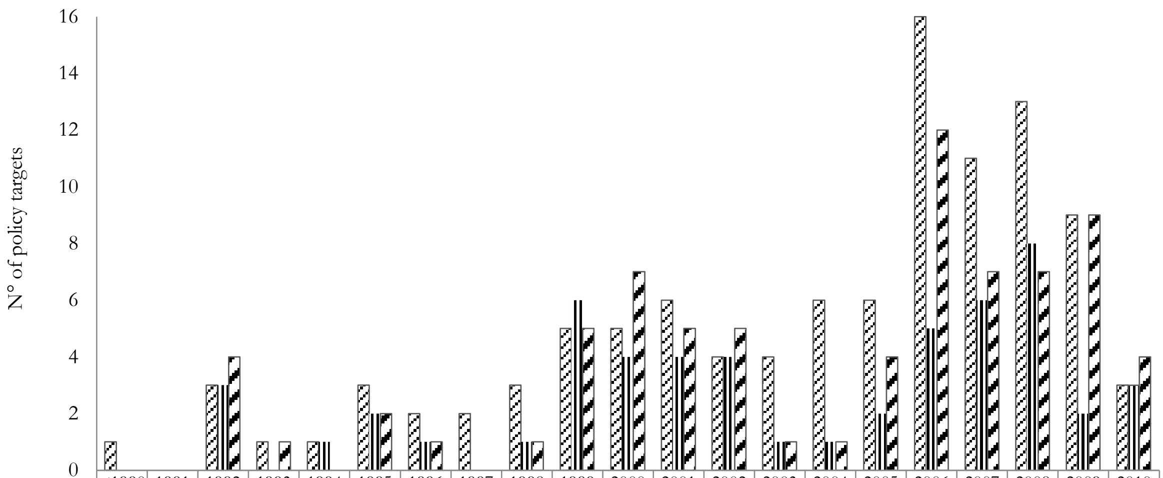
Figure 7 – General policy composition by instrument type (1990-2010)



	<1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Ec Instr	1	0	2	1	1	1	1	1	1	3	5	4	3	3	4	2	10	4	8	9	2
Info&Edu	1	0	3	1	0	2	3	2	2	2	7	4	4	0	3	4	14	10	11	6	3
Pol Supp	2	0	0	0	0	0	0	1	0	0	7	0	0	1	1	3	11	4	5	3	1
Reg Instr	3	0	5	1	1	2	0	1	1	6	4	5	7	1	1	4	16	8	11	4	5
RD&D	1	0	0	0	0	0	0	0	0	1	2	0	1	1	3	1	5	4	1	2	1
Vol App	1	0	1	0	0	0	1	1	0	3	1	1	1	0	1	3	4	2	8	1	1

Source: own elaboration on IEA (2013b)

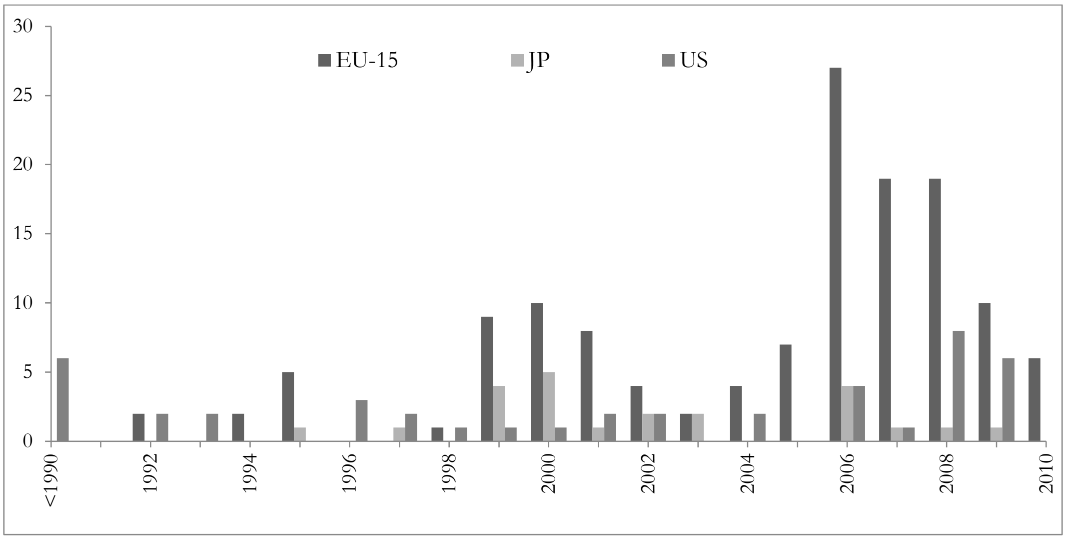
Figure 8 – General policy composition by target sub-domains (1990-2010)



	<1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Buildings	1	0	3	1	1	3	2	2	3	5	5	6	4	4	6	6	16	11	13	9	3
Lighting	0	0	3	0	1	2	1	0	1	6	4	4	4	1	1	2	5	6	8	2	3
Appliances	0	0	4	1	0	2	1	0	1	5	7	5	5	1	1	4	12	7	7	9	4

Source: own elaboration on IEA (2013b)

Figure 9 – General EE general policy activity, per country, 1990-2010



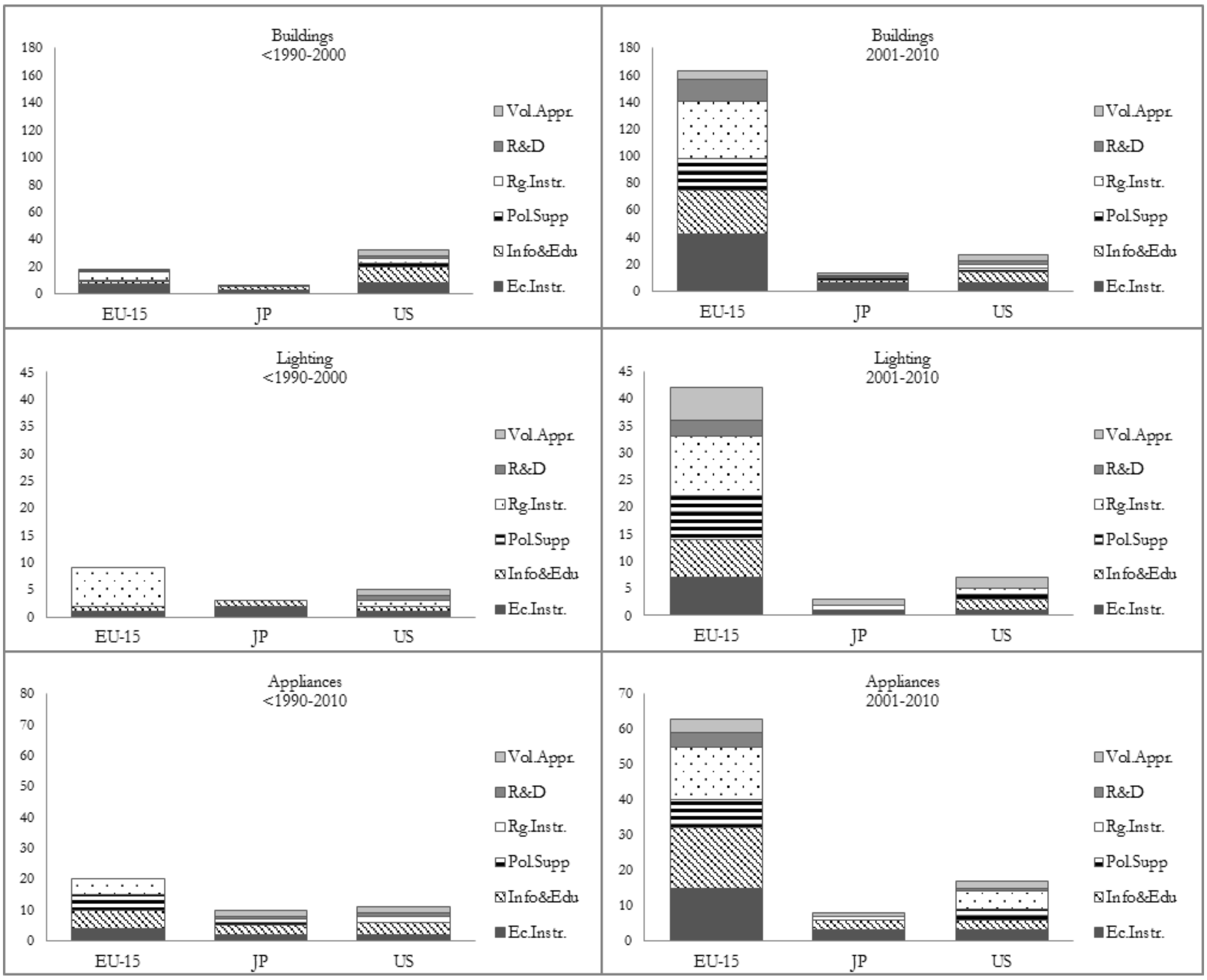
Source: Own elaboration on IEA (2013b)

A relevant impulse toward the conceptualisation of evolutionary approach of policy making is given by the paper by Rammel *et al*., (2003), who highlighted the limits and drawbacks of the neoclassical approach. Traditional policy instruments based on the optimal equilibrium price for internalising externalities such as command-and-control and market-based measures - as opposed as more flexible ones "moral suasion-oriented" instruments - have been retained by the economists as the most effective in the framework of static equilibrium efficiency (see, for instance, Baumol and Oates, 1988).

Notwithstanding, such an approach did not take into account bounded rationality and evolution phenomena and it was not exempt from many critiques (Cumberland, 1994 and van den Bergh *et al*, 2000, among all). On the other hand, the evolutionary approach seems to allow for integrating phenomena such as non-optimised change, uncertainty and long term sustainable development (see also Lundvall, 1992; Foxon, 2003). In particular, evolutionary policymaking would be able to well undertake the adaptive flexibility, which characterises the economic behaviour: that is the capacity to "maintain [...] variability and a large amount of pre-adaptive traits" (Rammel *et al*., 2003, p. 127). Although the paper by Rammel *et al*. dates back more than one decade ago, the authors anticipate the current debate on the optimal policy mix and draw the conclusion that a coherent and complete set of policy instruments would be highly desirable for the transition toward a sustainable path led by innovation processes.

A further call for integrated policy making comes from the paper by Foxon *et al*. (2004), which provides a wide-range analysis and comprehensive agenda for a sustainable transition toward innovation policies. The authors stressed the growing interrelatedness between social and long-term environmental problems leading to higher level of uncertainty and complexity in reforming and designing new effective innovation policies. In light of this, a system of innovation policy process is proposed, based on five key features, and namely: long-term sustainability goals; innovation and policy-making as systemic processes; new procedural and institutional basis for delivery of sustainable innovation policies incorporating monitoring, impact review and learning practises. The authors pointed out a lack of coherence and coordination in the current policy design, invoking a strong need for policies harmonisation by proposing an integrated and flexible policy instruments mix, coupled with a regulatory backstopping mechanism, indicated as strongly functional to this aim.

Figure 10 – Country-specific policy activity, per type and target, 1990-2010.



Source: Own elaboration on IEA (2013b)

Kemp (2011), provides an important contribution in analysing the weaknesses of the current eco-innovation policies and for a wider policy-making approach. Different rationales for policy makers aimed at spurring eco-innovation are presented, pointing out that this latter represents a special case of innovation affecting different issues involved: environment, natural resources depletion, market and trade patterns as well as institutions at national and international level

(Kemp and Pearson, 2008). Departing by the distinction between two different failures requiring the policy intervention, the market failures rationale (public good nature of innovation, uncertainty about the costs and benefits of innovation, monopolistic power and market barriers) and system failures rationale (knowledge barriers, institutional barriers, competition with old products and, in general, lack of interaction effects), a set of themes for eco-innovation policies is proposed together to a call for a specific and context-based policy agenda. Some important themes include the balance of policy measures and timing, targeted spending in areas where innovation is needed, policy learning and policy coordination as well as public-private interactions.

Further critiques to the standard neoclassical approach to policy-making are drawn also in the paper by Dodgson *et al.* (2011), in which a stylised scheme of different approaches to innovation-policies is defined. They analyse limits and possible trajectories of national innovation systems under the three different approaches, and namely:

- i) the free-market approach (Baumol, 2002; Baumol *et al*., 2007), identified by the Entrepreneurial Capitalism, in which the role of governments is limited to ensure free market structures and reduce market failures;
- ii) the coordinated approach (Johnson, 1982; Wade, 2004), interpreted by Dodgson *et al*. by following the Friedrich's List and Freeman (1992). The list includes a set of elements to be developed in the long-term view such as intellectual capital, interactions between tangible and intangible, imported foreign technology, investment and skilled migrants, skills and manufacturing sectors;
- iii) the complex-evolutionary approach (originally conceptualised by Schumpeter and further developed by Metcalfe (1994; 1995; 2007) and Nill and Kemp (2009) in the context of environmental sustainability. In such a framework, the concepts of uncertainty, adaptability as well as experimentation are crucial and the process of policy making follows a systemic perspective able to address firms along the complex and unpredictable nature of innovation processes. This implies an evolving and various nature of policy concept, which rejects the "one-size-fits-all" approach and has to address a wide range of factors (not only market failures) contributing to the success of innovation practises as social, political and legal institutions.

In recent times, the role of policy instruments for fostering innovation practices, has been subject to extensive investigation mostly following the evolutionary approach. This latter would be able to capture by various sides the complex process of innovation viewed as systemic process among different actors (individuals, governments, national as well as international private and public institutions) and at different levels (firms, sectoral innovation systems, national innovation systems).

Wieczorek and Hekkert. (2011), extending the analysis of Smits and Kuhlmann (2004), provide a definition of systemic instruments[1] and derive a series of their characteristics, which

[1] Systemic instruments are defined as "*tools that focus on the level of the innovation system instead of focusing on specific parts of innovation systems and support processes*

can be defined as systemic on the basis of the capability to: i) stimulate and allow participation of various actors, including users; ii) prevent lock-in and stimulate creative destruction; iii) prevent too weak and too stringent institutions; iv) stimulate physical and knowledge infrastructures. In the particular field of eco-innovation, the authors also pinpointed the unstructured character of sustainability, which differs from other scientific issues, as it involves complex, global and long-term impacts being often the result of a multitude of different factors contributing with different intensities. Such a heterogeneity of the system often goes with lack of specific data, increasing the level of uncertainty in the model design and analysis outcomes (see also Unruh, 2000 and Ritchey, 2007).

The notion of policy mix has been also recently investigated by Flanagan *et al*., 2011, developing a comprehensive and standard concept, fixing its limits and deriving some intrinsic characteristics. In particular, they mention the consistency (a policy mix showing absence of contradictions and synergies among the different policy elements), the coherence (no contradiction or overly among the different in-force policy mix), the credibility (how much a policy is believable and reliable), the stability (the level of policy certainty in the long term) and the comprehensiveness (the extensiveness and exhaustiveness of its elements).

Besides this, Borras and Edquist (2013) extensively reviewed and further categorised the set of policy instruments so far employed at global level and critically analysed their nature and scope. In doing so, they underlined the important nexus cause-and-effect, the uniqueness of each instrument (customization) as well as the coherency of the entire set of implemented instruments. The persistent growth of the so-called "soft instruments"- voluntary and non-coercive measures - is viewed as functional to the transition toward the concept of "policy governance" (pp. 1516). The authors also suggest the application of a well-combined set of different instruments as a crucial part of the innovation policies picking the systemic nature of innovation, together to an active process of re-designing and adaptation according to possible changed of contexts over time.

Further advices are also provided in Reichardt and Rogge (2013), who derive some important policy implications by developing a more comprehensive concept of policy mix and focusing also on the concept of coherence and consistency. According to the authors, the current literature only roughly analysed the policy instruments interactions and such few works are affected by a heterogeneous, and sometimes ambiguous, terminology. Differing from the instrument mix, the term policy mix should indicate not only a mere combination of policy instruments, but also "the processes by which such instruments emerge and interact" (page 3).

Departing by different definitions summarised in Table 3, they extrapolated three key elements which should be part of a proper policy mix:

- the ultimate *objective* (e.g. innovation);
- the *interaction* of different instruments;

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that play a crucial role in the management of innovation processes." Wieczorec and Hekkert. (2011), page 74.

- a *dynamic nature* and the *complex nature* of the policy mix, able to adapt to different changing context, which often refers to long-run strategies.

Table 3 – Different policy mix definitions

Source	Definition
Guy *et al.*, 2009 (p.1)	"An R&D and Innovation Policy Mix can be defined as that set of government policies which, by design or for- tune, has direct or indirect impacts on the development of an R&D and innovation system."
Kern and Howlett, 2009 (p.395)	"Policy mixes are complex arrangements of multiple goals and means which, in many cases, have developed incrementally over many years."
Nauwelaers and Wintjes, 2008 (p.3)	"A policy mix is defined as: The combination of policy instruments, which interact to influence the quantity and quality of R&D investments in public and private sec- tors."
Boekholt, 2010 (p.353)	"A policy mix can be defined as the combination of policy instruments, which interact to influence the quantity and quality of R&D investments in public and private sectors."
De Heide, 2011 (p.2)	"A policy mix is the combined set of interacting policy instruments of a country addressing R&D and innovation."
Ring and Schröter-Schlaack, 2011 (p.15)	"A policy mix is a combination of policy instruments which has evolved to influence the quantity and quality of biodiversity conservation and ecosystem service provision in public and private sectors."

(*Source: Rogge and Reichardt, 2013*)

Among the several characteristics, the coherency (or consistency[2]) appears to be particularly important to be enhanced by policy makers and analysed by empirical analysis, as called also by Ashoff (2005), OECD (1996), OECD (2003) and many other authors. Besides this, as Flanagan *et al.* (2011), also Rogge and Reichardt mention the policy credibility and stability as desirable features of a well-designed policy mix and systemic capabilities of policies to support coherent policy processes and feedback learning mechanisms. Again, Christopoulos *et al*. (2012) emphasised the current fragmentation of governance at global level and propose an approach having the potential to address economies toward a sustainable path. They strongly call for a

[2] Rogge and Reichardt (2013) distinguish between the two terms suggesting that consistency relates to policy mix elements and coherence to the policy processes, In other studies (see Hydén, 1999) and Picciotto *et al.*, 2004), under different definitions, the terms are equivalent.

"new, balanced, and context-sensitive policy mix" (page 305), supervised by a metagovernance[3] process able to influence and secure government practises as well as to improve bottom-up processes such as shared decision making and democratic participation at different scale and contexts (see also Meuleman, 2008).

Lastly, Crespi and Quatraro (2013) provide arguments on the importance of policy instruments for promoting new technologies generation and stress the role of these latter for addressing a sustainable growth path.

Building on this debate, the present study provides a first attempt to empirically evaluate the role played by policy mix in shaping energy efficiency technological innovation. This sector appears to be an appropriate technological domain since the role of policies both in the generation and diffusion of innovations is particularly relevant from both demand and supply sides. To this aim, we developed a set of policy measures and indexes in order to disentangle the contribution of different policy instruments as well as the characteristics of the policy mix as highlighted by the numerous theoretical contributions.

In the econometric model, the institutional framework is initially shaped by building a discrete variable as the stock of EE policies calculated as the cumulative number of policy instruments in force at time t in country i, as follows:

$$KPOL_{it} = \sum_{s=1}^{t} (POL_{is}) \qquad (3)$$

dividing by six policy instrument types and three policy sub-domains as specified in Table 1 and Table 2. This modelling choice allows to consider for each year the whole range of policies still into force at time t in country i, revealing not only a simple impulse given by the existence or not of EE policies, but also a sort of qualification of the strength and complexity of the overall institutional system. Besides this and departing from the (3), the following indexes and measures are built:

- *Policy variety*, calculated as the variety of policy instruments stock (represented by the six different policy instruments, namely Economic Instruments, Information and Education, Policy Support, Regulatory Instruments, RD&D support, Voluntary Approaches) in force at time t in a given country i, as follows:

$$POL\_Variety_{it} = \text{std}(KPOL_{m,it}) \cdot \sum_{m=1}^{6} (KPOL_{m,it}) \qquad \forall m[1,6] \qquad (4)$$

  with variation range $[0, +\infty]$. Policy instruments count has been taken from OECD-IEA Energy Policy database (available online). The expected effect here is uncertain. According to Porter hypothesis (Porter, 1991; Porter and van der Linde,

[3] Christopoulos et al. (2012) defines the metagovernance as "the governance of governance", which in the context of sustainable development "concern the reflexive coordination and organisation of the framework conditions under which governance take place". (page 306).

1995) and interpreting the policy variety as increased flexibility in achieving the policy goals, higher levels of flexibility should provide stronger impulse for firm's innovative activity. On the other hand, when the level of variety is particularly high, innovating firms also face a high level of uncertainty and the risk of policy coordination failure may occur. In order to test such a hypothesis, a quadratic term of the policy variety variable has been also calculated.

- *Ratio between RD in EE and in Total Energy*, calculated as the ratio between public expenditures on RD in energy efficiency (million USD at 2010 prices) and public expenditures on R&D in total energy (million USD at 2010 prices) as follows:

$$RD_{EE}Ratio_{it} = \frac{RD_{EE,it}}{RD_{TOTEN,it}} \tag{5}$$

Public R&D flows in EE and in total energy are taken by IEA Technology Statistics (IEA online database). we expect a positive correlation between this ratio and the level of innovative activity in EE technologies.

- *Policy Similarity*, calculated as the coherence of policy instruments total stock in force at time t for country i with respect to policy instruments stock adopted by all other countries (r) applying a similarity formula as follows:

$$POL\_Sim_{it} = \sum_{r=1}^{N} \left(\frac{|KPOL_{it} - KPOL_{rt}|}{\sqrt{KPOL_{it} + KPOL_{rt}}} \right)^{-1} \qquad \forall r \neq i;\ N = 22;\ \forall KPOL_{it} \neq 0 \tag{6}$$

The variation range is $[0, +\infty]$. This index measures the similarity between the policy stock of a given country with respect to the policy stock of the other countries, or in other terms, the level of global coordination among similar country's policies, considering that higher level of similarity can be also interpreted as a measure of potential market exploitation driven by policies able to affect the demand of new energy efficient technologies, thus further inducing the Porter hypothesis mechanism. The expected sign is thus positive.

- *Policy spillovers*, calculated as the influence played by the policy instruments stock for each specific technology sub-domain (here classified as w = Building, Lighting, Electrical Appliances) in force at time t for all countries but i weighted by bilateral export flows in energy consuming manufacturing sectors X_{irt} from country i to country r as follows:

$$POL\_Spill_{it,2}^{w} = \sum_{r=1}^{N} X_{irt} \cdot KPOL_{rt}^{w} \qquad \forall r \neq i \;\; N = 22 \tag{8}$$

We also calculated the policy-spillover index weighted by the inverse of geographical distance D_{ir}^{-1} from country i to country r as follows:

$$POL\_Spill_{it,2}^{w} = \sum_{r=1}^{N} X_{irt} \cdot D_{ir}^{-1} \cdot KPOL_{rt}^{w} \qquad \forall r \neq i \;\; N = 22 \tag{9}$$

Export flows have been taken by UN-COMTRADE database (Table A3), while bilateral distances derive from the CEPII database.

The hypothesis that policy-leading countries spill over other countries part of their stringency for adopting EE technologies by technology-follower countries is here investigated. We linked such a leadership to the export capacity of energy intensive manufacturing goods of a given country. Policy spillovers are few investigated in the literature. Gray and Shadbegian (2007) and Costantini *et al*. (2013) provide some contributions in this respect, finding significant and positive relationships between extra-regional regulation and regional innovation performances.

The energy system. EE performances are able to affect all the components of the energy system, allowing this latter to be more efficient (Florax *et al.*, 2011, among others). Indeed, EE technologies can be found in the entire set of energy technologies, both on the side of energy production and consumption. On the other hand, EE performances can be affected by the characteristics of the energy system itself. For instance, the lack of energy generation in a given country might induce higher level of generation and adoption of EE technologies able to counterbalance the suboptimal supply of energy. In light of this, the evaluation of the energy system as a whole appears crucial, especially in a panel setting.

A recent study develops the concept of energy-technology innovation system (ETIS), defined as "the application of a systemic perspective on innovation to energy technologies comprising all aspects of energy systems (supply and demand); all stages of the technology development cycle; and all innovation processes, feedbacks, actors, institutions, and networks" (Gallagher *et al*., 2012, pp. 139). Such a system relies on the role of innovation for improving the overall EE but it is strictly related to specific contexts and incentive structures, thus implying to take into account the processes and mechanisms at work within the system, including the roles of actors, networks, and institutions.

In light of this, we identified a set of specific variables to capture intrinsic characteristics of the energy system, and precisely:

- the level of energy independence. The mechanism at work here is based on the hypothesis that if a country is a net-energy exporter, this implies richness in energy supply and most likely less stringency to innovate in EE technologies. In other terms, the more the energy abundance, the less is the stimulus to make the national energy system more efficient through the generation of EE technologies;

- the effect of important extra non-coal energy sources as the presence of nuclear power plants. In many countries nuclear energy represents a relevant share of energy production and this extra source of energy might contribute to mitigate the effort in EE gains. Moreover, the presence of nuclear power plants mirrors long-run national energy strategies, since their construction implies long time for reaching the investment returns. We expect a positive impact of this variable for those countries having a low nuclear energy power production.
- the level of energy intensity, to test the overall efficiency of a system, which also is an indicator for evaluating different national energy strategies. According to Patterson (1996), there are different indicators to assess the aggregated level of efficiency in the energy system. We used the ratio of energy consumption divided by the level of population, being well aware that, although largely widespread, such an indicator is not exempt from any bias.

In the empirical model, we combined the effects of the presence of nuclear power generation with the level of energy intensity by interacting these two variables.

4. Econometric strategy and empirical results

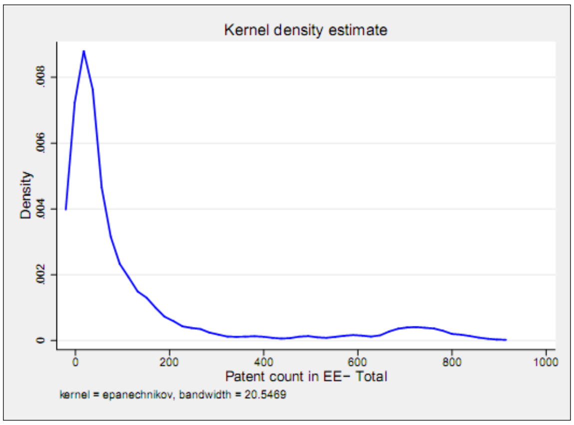
The use of patent data as a proxy of the innovative activity implies that we have to deal with count variables, that is, variables with non-negative integer values. In our analysis, the variable under scrutiny is represented by the patent count. As confirmed by Hausman *et al*. (1984) and Baltagi (1994), patent data usually show a high degree of skewness with upper tails, over dispersion (relatively low medians and high means) and a large share of zeros, as confirmed by Kernel density estimates of the patent applications distribution (Table 4 and Figure 10).

Table 4 - Summary statistics of dependent variable

Patent applications in residential EE technologies (dependent variable)				
	Total	Buildings	Lighting	Electrical appliances
Mean	114.4	70.33	21.15	19.91
Variance	38512.79	13609.71	2294.89	2641.15

Source: own elaboration on EPO.

Figure 11 - Kernel density of the patents distribution



Source: own elaboration on EPO.

Such features can mirror observed factors, as the firms size (larger firms usually patent more than smaller ones) and unobserved heterogeneity (a firm can patent less than one other but producing breakthrough technologies). The empirical literature has suggested specific modelling strategies to deal with patents, which can be mainly reduced to two options: the Poisson Regression Model (PRM) and the Negative Binomial Regression Model (NBRM). When the dependent variable is affected by the presence of many zero, the Zero-Inflated Negative Binomial Model (ZINB) may also represents a viable modelling strategy (for a comprehensive explanation, see Cameron and Trivedi, 1998; Winkelmann, 2008).

In our dataset, the presence of zeros in the dependent variable is negligible and the Vuong's test[4] do not justify the use of the ZINB. In light of this, we decided to use the NBRM, in which the variance is modelled as a quadratic term (NB-2). Equation (4) represents the general expression of the linear estimated model, in which the five groups of variables referring to the specific drivers of innovation previously described are considered, together to a set of controls:

$$Y_{i,t} = \alpha_i + \beta_o + \beta_1(Inn\_Sys_{i,t-1}) + \beta_2(Market\_Sys_{i,t-1}) + \beta_3(EE\_Policy_{i,t-1}) + \beta_4(Energy\_Sys_{i,t-1}) + \beta_5(Controls_{i,t}) + \varepsilon_{i,t} \quad (4)$$

We used a log-log fixed effects specification to take into account country-specific unobservable heterogeneity; the Hausman's test confirmed the choice of fixed effects (Table 7).

The maximum likelihood method is used to estimate the model parameters. All variables referring to the investigated systems are modelled with one year lag in order to reduce potential endogeneity bias while preserving the standard inducement effect framework. To this sense, by accounting for the resilience of the innovation process, it is a common knowledge to expect that the policy or market inducement effects present a temporal gap from the time in which the phenomenon occurs and the reaction in innovative terms by firms. As a standard method of

[4] Test results is available upon request.

addressing such an issue, one year lag reduces endogeneity, allows for accounting resilience but a minimum number of observations is lost.

Different model specifications have been estimated for testing the contributions of the different systems affecting the dynamics of invention of EE technologies. The policy variables have been maintained in all the specifications, while different variables for measuring the contribution of other innovation drivers have been tested. Moreover, further estimations show the impacts of each policy type by disaggregating the policy dataset according to Table 2, as well as the policy indicators explained in Section 3.

Table 4 - General policy inducement effect on specific technological domains.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Total EE Patents	Patent count in EE-Building	Patent count in EE-Lighting	Patent count in EE-Elec. Appl.	**Total EE Patents**	Patent count in EE-Building	Patent count in EE-Lighting	Patent count in EE-Elec. Appl.
Stock of GERD	**0.51***** **(8.87)**	0.52*** (8.74)	0.58*** (6.41)	0.66*** (5.84)				
Stock of R&D in EE					**0.20***** **(4.65)**	0.20*** (4.03)	0.37*** (4.81)	0.32*** (4.89)
Price-tax bundle	**0.17**** **(2.19)**	0.13 (1.49)	0.45*** (4.44)	0.70*** (4.90)	**0.13** **(1.33)**	0.04 (0.36)	0.50*** (4.20)	0.47*** (3.38)
Stock of EE policy - Total	**0.22***** **(8.58)**				**0.28***** **(9.66)**			
Stock of EE policy - Building		0.19*** (5.59)				0.26*** (6.44)		
Stock of EE policy - Lighting			0.47*** (6.04)				0.44*** (5.00)	
Stock of EE policy – Elec. App.				0.71*** (10.41)				0.74*** (9.62)
Constant	**-5.64***** **(-6.47)**	-5.94*** (-6.67)	-7.00*** (-4.84)	-7.94*** (-5.18)	**1.10***** **(4.20)**	0.82*** (2.96)	0.81* (1.81)	0.11 (0.26)
N	317.00	317.00	317.00	303.00	298.00	298.00	298.00	284.00
chi2	306.39	184.38	132.86	216.83	198.66	101.10	111.11	170.35

t statistics in parentheses; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

The general policy inducement effect, together with the contribution of two different proxies of the innovation system, has been initially tested (Table 4). More specifically, estimations (1)-(4) include the stock of GERD, while in estimations (5)-(8) the innovation capacity is measured by the specific stock of R&D in EE. Broadly speaking, the contribution for invention of the national innovation system is positive and significant both when we test the effect on the total number of patents as well as when patents are divided into the three sub-domains. Unfortunately, my dataset suffers from a high number of missing data for specific R&D in EE, which translates in several missing observations. Therefore, in the next estimations, we prefer to keep only the GERD variable for measuring the contribution of national innovation system.

The price-inducement effect, represented by the price-tax bundle, also positively and significantly affects our dependent variable, although the statistical robustness is lower than R&D. Since we measured prices at end-use level, it can be inferred that producers pay rather attention to price changes, probably for demand-driven effects in which consumers are highly sensitive to energy consumption and preferably choose high-efficiency goods to counterbalance increases in energy prices.

In the case of electrical appliances and lighting, two sectors characterised by intensive energy use but prompt responsiveness for energy saving, such an effect is particularly strong. There are at least two motivations for that. First, the lifecycle of lamps and appliances is faster than buildings; hence, the reactivity of consumer's choices in adopting more efficient goods also reflects this quicker pace. Moreover, in the building sector who actually benefits from EE performances and pays the energy bill (the owner) is different from who builds the building (the contractor). Such an effect is known as the principal-agent problem, which generally describes a situation in which the "agent" (the builder, in this case) can operate not always in favour of the "the principal" (the building's owner or user). In this context, the builder might sub-invest in building dwellings provided with suboptimal EE performances, dumping the higher costs of energy bills on the future users (see also Jaffe *et al.*, 2004).

With respect to the policy effect, in the general model specification we note a modest but positive impact of EE policies for generating new patents, confirming the important role of public regulation in stimulating new economy-useful technologies (Johnstone *et al*., 2012; Popp, 2010). Moreover, the contribution of EE policies seems to follow the same trend of the innovation system, being the impact of policies amplified in those sectors highly dependent on R&D. For instance, the elasticity related to public regulation in the sector of electrical appliances is almost three times as that in buildings. The same trend can be found using specific EE-R&D expenditures in the place of GERD.

In the set of estimations showed in Table 5, a robustness check is provided, by enlarging the framework of analysis for capturing also the effect of the energy (estimations 1-4) system as further innovation drivers. Although the main results remain rather unchanged, when we test the energy system, here represented by an interaction term between the level of energy intensity and a dummy variable signalling the presence of nuclear power production, a significant and negative impact on new patents only on sectors using mostly electrical power (lighting and appliances) can be noted. This means that those countries making intensive energy use are also less innovative on the side of EE, confirming the hypothesis that the energy abundance relaxes the stimulus to innovate in EE technologies. The same pattern, although lower, can be found when the environmental stringency, in terms of CO_2 residential emissions, is tested.

Table 5 - The role of the energy and environmental systems.

	(1) **Total EE Patents**	(2) Patent count in EE-Building	(3) Patent count in EE-Lighting	(4) Patent count in EE-Elec. Appl.	(5) **Total EE Patents**	(6) Patent count in EE-Building	(7) Patent count in EE-Lighting	(8) Patent count in EE-Elec. Appl.
Stock of GERD	**0.50*** (7.67)**	0.49*** (7.20)	0.73*** (6.14)	0.81*** (6.77)	**0.53*** (7.39)**	0.52*** (6.81)	0.84*** (6.32)	0.87*** (6.96)
Price-tax bundle	**0.17** (2.06)**	0.11 (1.28)	0.60*** (4.60)	0.81*** (5.12)	**0.15* (1.73)**	0.09 (1.01)	0.54*** (3.97)	0.74*** (4.54)
Energy intensity interacted with nuclear production	**0.02 (0.21)**	0.06 (0.77)	-0.32* (-1.83)	-0.66*** (-2.81)	**0.05 (0.53)**	0.09 (1.01)	-0.23 (-1.29)	-0.58** (-2.50)
CO2 emissions in residential sector					**-0.05 (-0.86)**	-0.05 (-0.82)	-0.20* (-1.72)	-0.12 (-1.24)
Stock of EE policy - Total	**0.22*** (8.39)**				**0.21*** (7.44)**			
Stock of EE policy - Building		0.20*** (5.62)				0.19*** (4.85)		
Stock of EE policy - Lighting			0.39*** (4.40)				0.33*** (3.51)	
Stock of EE policy – Elec. App.				0.59*** (7.64)				0.56*** (6.82)
Constant	**-5.55*** (-5.76)**	-5.59*** (-5.58)	-8.79*** (-5.14)	-9.86*** (-6.24)	**-5.86*** (-5.75)**	-5.93*** (-5.51)	-9.86*** (-5.40)	-10.53*** (-6.37)
N	317.00	317.00	317.00	303.00	317.00	317.00	317.00	303.00
chi2	306.52	185.50	134.95	222.17	302.52	182.12	134.31	219.20

t statistics in parentheses; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table 6 - Inducement effect of alternative policy instruments on total patents.

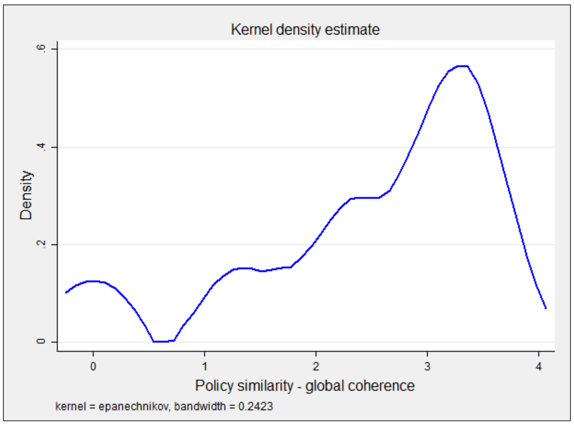
	Total Patents in EE					
Stock of GERD	0.56*** (8.79)	0.54*** (8.05)	0.59*** (9.27)	0.52*** (8.07)	0.63*** (9.97)	0.66*** (9.84)
Price-tax bundle	0.20** (2.43)	0.18** (2.02)	0.18** (2.12)	0.17** (2.05)	0.15* (1.69)	0.12 (1.29)
Energy intensity interacted with nuclear production	-0.02 (-0.20)	-0.02 (-0.23)	-0.07 (-1.01)	-0.04 (-0.51)	-0.09 (-1.19)	-0.12 (-1.62)
Stock of EE policy - Economic Instruments	0.26*** (6.93)					
Stock of EE policy - Information and Education		0.25*** (6.15)				
Stock of EE policy - Policy Support			0.21*** (4.59)			
Stock of EE policy - Regulatory Instruments				0.25*** (7.12)		
Stock of EE policy - RD&D					0.20*** (3.73)	
Stock of EE policy - Voluntary Approaches						0.15 (1.50)
Constant	-6.39*** (-6.76)	-6.13*** (-6.18)	-6.90*** (-7.30)	-5.89*** (-6.14)	-7.57*** (-8.10)	-8.07*** (-8.09)
N	317.00	317.00	317.00	317.00	317.00	317.00
chi2	261.32	237.14	220.22	268.11	196.40	161.15

t statistics in parentheses; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table 6 shows the impact of the policy mix, by testing the contribution of each policy instrument over the total stock of EE patent applications. This set of estimations provides some interesting insights for analysing the role of different policy types and shed first light on the role of policy mix further investigated afterwards. A first important remark regards the size effect of different policy types, which was found rather similar among them. This result appears particularly important, since the economic theory has mainly relied on standard economic instruments (as direct investments, taxes or subsidies) (Baumol and Oates, 1988), rather than on the so-called "moral suasion-oriented" or soft instruments, aimed to improve the level of consumer's information and awareness. Indeed, although the effect of economic instruments are positive and significant in affecting the inventive activity, what emerges as a novelty from our analysis is that also other instruments contributed, to the same extent, to the growth of EE patenting activity. Precisely, the impact of each policy instrument measured as elasticity is - on average - 0.23%, with the exception of voluntary approach instruments which are found to be not significant. It is also worth noting the contribution of information and education policies, which include the energy labelling and performance codes for the three considered sectors. Besides this, not only regulatory instruments as codes, performance standards and other mandatory requirements, but also monitoring activities, public research programs as well as demonstration projects represented good stimuli to the growth of EE technologies.

This bearing in mind, in the next set of estimations (Table 7-9), we further enrich the empirical framework by testing the set of indexes and measures described in Section 3. As showed in Table 7, the joint impact of different policy instruments, measured by the level of the policy mix variety, enhanced the level of policy-inducement effect, although the premium for the augmented policy variety is modest. As showed in Figure 12, the effect of policy variety seems to follow a non-linear relationship. In particular, a U-shape curve characterises the distribution of the policy variety variable. The squared of the policy variety variable (Table 7) is found to be slightly negatively correlated to the level of EE innovative activity and strongly significant, confirming the hypothesis of the existence of a optimal level of variety, beyond which its positive effects begin to decrease. The ratio between R&D in EE and in total energy sector also positively impacts on the dependent variable, and such an effect is further confirmed by the interaction of the two variables. Moreover, other modest but positive and strongly significant contributions to the innovative activity, are provided by other interactions, between R&D in EE and the stock of policy instruments and between the stock of policy and the policy variety, respectively.

Figure 12 - Kernel density of the policy variety variable.



Source: own elaboration on IEA (2013b).

Table 7 – Policy inducement effect. The role of policy mix and variety

	Total Patents in EE						
Total stock of GERD	0.73*** (12.52)	0.53*** (9.11)	0.53*** (8.18)	0.54*** (9.39)	0.54*** (9.31)	0.54*** (8.44)	0.62*** (10.12)
Price-tax bundle	0.15* (1.73)	0.20** (2.47)	0.19** (2.36)	0.19** (2.34)	0.26*** (3.04)	0.19** (2.24)	0.04 (0.41)
Ratio between RD in EE and in Total Energy	0.14*** (3.42)						
Stock of Total EE policy		0.21*** (8.44)					
Interaction between RD in EE and the stock of policy instruments			0.07*** (7.35)				
Policy variety				0.13*** (7.37)			0.29*** (7.56)
Interaction between stock of policy and policy variety					0.03*** (5.36)		
Interaction between RD in EE and policy variety						0.04*** (6.43)	
Policy variety sq							-0.04*** (-4.88)
Constant	-9.76*** (-10.91)	-6.01*** (-6.69)	-6.07*** (-6.18)	-6.30*** (-7.04)	-6.26*** (-6.79)	-6.37*** (-6.49)	-7.81*** (-8.00)
N	299.00	317.00	299.00	317.00	317.00	299.00	317.00
chi2	167.50	314.88	249.80	276.97	236.95	224.63	295.41
Hausman test for FE vs. RE	χ^2 = 27.88***						

t statistics in parentheses*;* * *p* <0.1, ** *p* <0.05, *** *p* <0.01

Table 8 presents the effects of policy coherence. Higher level of policy stock coherence, tested on both the global stock of policy instruments as well as at single instrument level, shows a positive and significant impact on the number of residential EE patents. When the total stock of instruments is considered, the impact is rather large, around 0.30%. At instrument level, with the exception of voluntary instruments, the contribution of the policy coherence for spurring new energy efficiency technologies is, on average, one third (0.10%) with little variation among the instruments.

Lastly, Table 9 provides estimation results when policy spillover effects are considered. As expected, a positive contribution in each of the policy sectors can be noted, with a particular intensity in the case of electrical appliances (0.33% and 0.17%, respectively in the case of trade weighted and trade-distance weighted). The higher impact in electrical appliances can be justified by the fact that domestic appliances represent the lion's share in the trade sectors taken into account. It is worth noting that trade-distance weights produce lower impacts of policy spillovers.

Table 8 – Policy inducement effect. The role of international coherence.

	Total Patents in EE						
Total stock of GERD	0.61*** (10.41)	0.57*** (10.32)	0.56*** (10.06)	0.59*** (10.71)	0.53*** (9.27)	0.61*** (11.13)	0.63*** (11.18)
Price-Tax bundle	0.16** (2.13)	0.18** (2.17)	0.17** (2.08)	0.21** (2.49)	0.16** (1.99)	0.20** (2.30)	0.17* (1.69)
Policy similarity (global coherence)	0.29*** (12.58)						
Stock of EE policy - Economic Instruments - weighted by country coherence		0.11*** (7.61)					
Stock of EE policy - Information and Education - weighted by country coherence			0.11*** (7.26)				
Stock of EE policy - Policy Support – weighted by country coherence				0.09*** (5.44)			
Stock of EE policy - Regulatory Instruments - weighted by country coherence					0.11*** (8.15)		
Stock of EE policy - RD&D – weighted by country coherence						0.09*** (4.14)	
Stock of EE policy - Voluntary Approaches - weighted by country coherence							0.05 (1.54)
Constant	-7.46*** (-8.49)	-6.67*** (-7.71)	-6.71*** (-7.73)	-7.00*** (-8.16)	-6.25*** (-7.02)	-7.44*** (-8.71)	-7.98*** (-8.79)
N	317.00	317.00	317.00	317.00	317.00	317.00	317.00
chi2	452.00	284.72	267.89	241.04	297.91	211.05	168.71

t statistics in parentheses; * p <0.1, ** p <0.05, *** p <0.01

Table 9 - Policy inducement effect. The role of international policy spillover.

	Patent count							
	Total	Building	Lighting	Elec. Appl.	**Total**	Building	Lighting	Elec. Appl.
Total stock of GERD	**0.28*** (4.03)**	0.26*** (3.51)	0.34** (2.54)	0.32** (2.23)	**0.30*** (4.51)**	0.30*** (4.23)	0.39*** (3.03)	0.43*** (3.12)
Price-tax bundle	**0.06 (0.76)**	0.01 (0.17)	0.40*** (3.23)	0.46*** (2.98)	**0.16** (2.22)**	0.08 (0.95)	0.49*** (4.40)	0.61*** (4.02)
Total policy spillovers in EE- trade weight	**0.23*** (10.09)**							
Building policy spillovers in EE-trade weight		0.22*** (9.38)						
Lighting policy spillovers in EE-trade weight			0.17*** (3.81)					
Elec. App. policy spillovers in EE-trade weight				0.33*** (5.66)				
Total policy spillovers in EE-trade-distance weight					**0.15*** (9.01)**			
Building policy spillovers in EE- trade-distance weight						0.15*** (8.56)		
Lighting policy spillovers in EE-trade-distance weight							0.10*** (3.41)	
Elec. App. policy spillovers in EE- trade-distance weight								0.17*** (4.08)
Constant	**-5.82*** (-6.37)**	-5.51*** (-5.61)	-6.39*** (-3.29)	-8.95*** (-5.16)	**-3.60*** (-3.79)**	-3.69*** (-3.64)	-5.08*** (-2.64)	-6.46*** (-3.67)
N	317.00	317.00	289.00	276.00	317.00	317.00	289.00	276.00
chi2	466.13	301.25	130.65	216.20	414.78	276.86	125.56	189.98

t statistics in parentheses; * p <0.1, ** p <0.05, *** p <0.01

5. Conclusions

The present study provides a broad analysis of the drivers of innovation in EE by looking at the residential sector in 23 OECD countries and a rather long time series. As evidenced by the descriptive analyses on the evolution of EE patterns and public policy interventions, cross-country specific features emerge, which appear to be related to different policy stringency adopted in the OECD countries during the last two decades in this field. The econometric analysis, based on an original dataset comprising sectoral patent data and information on specific policy instruments, confirmed the importance of public policies as drivers of innovation activities in this poorly explored sector.

More specifically, this study highlights that national and sectoral innovation systems explain a large portion of country's propensity to innovate in EE technologies adopted within the residential sector. In parallel, environmental and energy systems are shown to shape the rate and direction of technical change in this sector, with energy availability playing an important role, as large abundance of cheap energy sources (as nuclear power) tends to reduce the propensity to innovate.

Regarding the specific role of general and sectoral public policies, economic instruments as energy taxation seem to play an inducement effect on the likelihood to innovate in energy saving devices. Moreover, public policies specifically designed to induce efficiency in energy consumption emerge as crucial for giving impulse to innovations in technologies necessary to reach higher resource efficiency standards. In this respect, the analysis of the impact of different policies provides interesting and novel insights. In particular, the econometric results point out that the policy inducement effect on innovation is relevant not only when standard instruments such as direct investments, taxes or subsidies are adopted, but its importance extends to "soft policies" aimed at improving the level of consumer's information and awareness. Among these, information and education policies, which include the energy labelling and performance codes for the considered sectors, emerge as strongly capable of affecting innovation dynamics in residential EE technologies. Moreover, the closer the relationship between agents paying energy bills and agents adopting efficient technologies, the higher the impulse to innovate in related technological domains as clearly emerges from the analysis of lighting and electrical appliances cases.

These results appear to have relevant policy implications and to suggest the way to further develop research in this field. First, the joint relevant influences of the innovation and the energy systems on invention activities in the sector under scrutiny, confirms the importance of adopting a systemic perspective to the analysis of eco-innovation. Second, this implies that different policy dimensions both working on the multiple elements influencing innovation dynamics and at the system level should be combined in a properly designed policy mix. Third, an appropriate policy mix should contain not only traditional market-based instrument as standard environmental economics theory claimed in the past, but should include information/education based instruments or policy instruments designed as voluntary approaches. Moreover, policy instruments should be planned in order to be as much as possible related to the market of final use of technologies, giving the correct signals to those agents investing in energy saving technologies. Finally, the emerging complexity of policy mix in this field calls for specific attention to coordination problems to enhance the coherence and persistence of the whole policy strategy, including possible situations governed by policy-leading countries able to spill over policy induced-effects for giving further impulse for new patenting activity.

Although the present work takes into account in a single empirical framework all of these elements deriving from a growing set of theoretical contributions and shows how such elements play a role in spurring the complex process of innovative activity in the field of residential EE, further efforts both from the scientific and policy communities are needed in order to increase our understanding of policy interactions and consequently enhance the effectiveness of the adopted policy framework.

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Appendix

Table A1a – Patent classes by technological domains and keywords

Source: adapted from Noailly and Batrakova (2010)

Main domain	Sub-domain	CPC Class	Sub-classes	Keywords
Insulation	Heat Saving	E06B	3/24, 3/64, 3/66, 3/67	
		E06B	3	high perform+ OR insulat+ OR low energy
		C03C	17/00, 17/36	low e
		E06B	3/67F	vacuum
		E06B		aerogel
		E06B	3/20	
		E06B	1/32, 3/26	thermal break
		E04B	1/74, 1/76	
		E04B		Polyurethane OR PUR OR polystyrene OR EPS OR XPS OR heavy gas+ OR pentane OR insulat+
		E04B		Flax OR straw OR (sheep+ AND wool)
		E04F	15/18	
		E04F		Sea shell
		E04D	11	Insulat+
		E04D	11	Green roof
		E04D	11, 9	tatch+
		F16L	59/14	
	Water saving	F24H		Water AND (sav+ OR recover+)
		F16K	1	Water AND (sav+ OR recover+)
		E03C	1	Water AND (sav+ OR recover+)
	Cooling reduction	E04F	10	
		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+)
High-efficiency boilers	HE-boilers	F23D	14	Low
		F24D	1	
		F24D	3, 17	
		F24H, excluding F24H7		
Heat and cold distribution and CHP	Heating system	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	
	Combined heating and refrigeration systems	F25B29		
	Heat pumps	F25B30		
	CHP	X11-C04		
		R24H240/04 (ICO		
Ventilation	Ventilation	F24F	7+	
Solar energy and other RES	Solar energy	F24J	2	
		H01L	31/042, 31/058	
		H02N	6	
	Biomass	F24B		Wood+
	Geothermal	F24J	3	
Building materials	Construction structures	E04B	1	Building+ or house+
	Materials	C09K	5	Building+ or house+
Climate control systems	Control of temperature	G05D	23/02	
	Electric heating devices	H05B	1	
Lighting	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 A1b – Patent classes by technological domains and keywords

CPC general Class related to each appliance		Technologies aiming at improving the efficiency of home appliances	Description
Refrigerators and freezers	F25D See http://www.cooperativepatentclassification.org/cpc/scheme/F/scheme-F25D.pdf	Y02B 40/32	Motor speed control of compressors or fans
		Y02B 40/32	Thermal insulation
Dish-washers	A47L 15/00 See http://www.cooperativepatentclassification.org/cpc/scheme/A/scheme-A47L.pdf	Y02B 40/42	Motor speed control of pumps
		Y02B 40/44	Heat recovery e.g. of washing water
Washing machines	D06F (excluding D06F31/00, D06F43/00, D06F47/00, D06F58/12, D06F67/04, D06F71/00, D06F89/00, D06F93/00, D06F95/00 as well as their subgroups). See http://www.cooperativepatentclassification.org/cpc/definition/D/definition-D06F.pdf	Y02B 40/52	Motor speed control of drum or pumps
		Y02B 40/54	Heat recovery, e.g. of washing water
		Y02B 40/56	Optimisation of water quantity
		Y02B 40/58	Solar heating

Source: own elaboration based on EPO-PATSTAT

Table A2 – Countries

Country	Code	Country	Code
Austria	AT	Ireland	IE
Australia	AU	Italy	IT
Belgium	BE	Japan	JP
Canada	CA	Korea	KR
Switzerland	CH	Luxembourg	LU
Germany	DE	Netherland	NL
Denmark	DK	Norway	NO
Spain	ES	New Zealand	NZ
Finland	FI	Portugal	PT
France	FR	Sweden	SE
United Kingdom	GB	United States	US
Greece	GR		

Table A3 – SITC Rev 3 CODE in COMTRADE taken for the aggregate "energy consuming manufacturing sectors plus building sector"

Code	Description	Code	Description
201	Milling, planning and impregnation	287	Other fabricated metal products
202	Panels and boards of wood	291	Machinery for production, use of metal products
203	Builders' carpentry and joinery	292	Other general purpose machinery
204	Wooden containers	295	Other special purpose machinery
205	Other products of wood; articles of	297	Domestic appliances n. e. c.
243	Paints, coatings, printing ink	300	Office machinery and computers
251	Rubber products	311	Electric motors, generators and transport
252	Plastic products	312	Electricity distribution and control
261	Glass and glass products	313	Isolated wire and cable
262	Ceramic goods	314	Accumulators, primary cells
263	Ceramic tiles and flags	315	Lighting equipment
264	Bricks, tiles and construction prod	316	Electrical equipment n. e. c.
265	Cement, lime and plaster	321	Electronic valves and tubes, other
266	Articles of concret, plaster and cement	322	TV, and radio transmitters, apparatus
267	Cutting, shaping, finishing of stone	323	TV, radio and recording apparatus
268	Other non metallic mineral products	401	Production and distribution of electricity
282	Tanks, reservoirs, central heating	742	Architectural and engineering activity
283	Steam generators		