Mapping policy mix and innovation performance in energy efficiency for the residential sector: clusters and trajectories over the last twenty years in EU countries

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Abstract

This paper aims to measure some significant characteristics of the energy efficiency system and map European countries in terms of four dimensions, energy system, innovation dynamics, policy design and export competitiveness, over the past twenty years. The empirical analysis we propose, based on a large sample of EU countries, focuses on the case of technologies designed to improve energy efficiency in the residential sector. By applying a cluster analysis, we map country groups according to several characteristics in order to investigate the co-evolution of technological trajectories and structural change in this specific domain. Results suggest the distinction of EU countries into four groups. By investigating the four clusters individually, we shed light on how the four dimensions here considered dynamically interact. Empirical findings reveal that the design of the domestic policy mix plays a key role in shaping a technological trajectory that in turns allows an increase in external competitiveness performance. At the same time, such positive impact is substantially influenced by international relationships with main economic partners. Our results show that if the domestic policy mix is coherent with that of destination markets, and if such destination markets correspond to those countries at the top of technological ladder and highly regulated, the overall export performance of the scrutinized country improves considerably, gaining comparative advantages in all target markets.

Keywords: eco-innovation; policy mix; international competitiveness; structural change; energy efficiency; residential sector

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

1. Introduction

Energy efficiency (hereafter EE) is one of the core pillar of the EU 2030 Climate and Energy Strategy. In particular, EE has been identified as a preferential means to improve the performance of the national energy system as it could help fostering a sustainable energy transition. The overall performance of the energy system from one side depends on the structural characteristics of countries. At the same time, at the EU level, an increasing effort to spur EE is also pursued through the implementation of national and sector-specific policies to foster eco-innovation. This, in turn, can generate positive effects not only in terms of environmental benefits, but also in terms of economic competitiveness. From the one side gains in EE might affect the techno-economic structure by providing the economic system new and more resource-efficient production technologies that would allow the system to profit from cost savings. From the other side, the exploration of new technological trajectories might help gaining privileged positions in international markets thanks to first movers' advantages. In this regard, there is growing interest in understanding the role played by different policy instruments in stimulating and directing technical change in eco-innovation domains and more specifically in the EE branch.

Given the central role of EE in the European long term strategy, here we propose a descriptive analysis based on a large sample of EU countries that aims to measure some significant characteristics of the EE system and map EU countries' behaviour over the past twenty years. The empirical analysis we propose focuses on the case of EE technologies in the residential sector, which appears to be appropriate for three main reasons. First, since a large number of different policies in several countries aims to enhance EE, especially by fostering the generation and diffusion of new technologies (IEA, 2015; Sovacool, 2009), this is a technological domain that is experiencing an increasing number of different instruments for public policy support with a large heterogeneity at the country level. Second, the innovative efforts invested in creating new technologies can be directly traduced in efficiency impacts from the consumption side, thus giving the opportunity to measure how innovation influences market mechanisms. Third, the high market integration at the EU level thanks to a well-established free trade system allows including in the analysis the role played by trading partners in eventually shaping different patterns of structural change occurring in highly integrated but still substantially different economic systems as the EU countries.

The analysis is organized in two steps. The first step consists in applying a descriptive statistical tool as the cluster analysis, in order to map country groups according to several characteristics related to EE dynamics. This clustering procedure is implemented considering four dimensions that well describe the evolution of the EE tecno-economic structure at the country level over time: i) the energy system at the country level; ii) the innovation pattern; iii) the policy mix design; iv) the competitiveness performances on the international markets.

In the second step the analysis moves from the characterization of each single cluster to the more complex investigation of potential co-evolutionary patterns of different countries and/or clusters. Given the growing interest in literature on the potential influence of foreign (innovation and environmental) policies on domestic policy design, and consequently on eco-innovation trajectories (Costantini et al., 2017; Dechezleprêtre and Glachant, 2014; Peters et al., 2012), we investigate if clusters and countries have been influenced by foreign decisions and if they have undertaken a convergence path within each cluster and between clusters. By exploring such convergence patterns under the lens of the aforementioned four dimensions it is also possible to visualize which countries faced structural changes in terms of industrial specialization and comparative advantages in those sectors strictly related to the EE technological domain. This last part of the analysis allows discovering in detail the mechanisms behind the virtuous cycle hypothesized by Porter and Van Der Linde (1995) where the (environmental) regulatory framework induces positive effects on innovation dynamics and consequently on the whole economic competitiveness performance of the scrutinized sector, by also including the role played by bilateral and multilateral relationships. Such complexity in the analytical framework guarantees that several aspects related to structural change can be jointly considered if the definition by

Malerba and Cantner (2006, p. 1) is adopted: "the main analytical concern is that over time industries evolve and change their structure, and that in this dynamic process knowledge and technologies, the capabilities and incentives of actors, new products and processes (as well as variants of existing ones) and institutions affect and constraint change, sometimes more smoothly and sometimes in a rather radical way. Thus, what is meant here with the term [...] structural change is [...] all those elements and relations among actors, knowledge and technologies which drive innovative activities and greatly affect economic performance in an industry."

The remainder of the paper is organized as follows. Section 2 provides a description of the background framework. Section 3 defines the dataset and the methodology. Section 4 presents the results and, finally, Section 5 summarizes the main insights emerging from this analysis.

2. Background

Although global final energy consumption more than doubled between 1971 and 2014 (from 4,244 Mtoe to 9,426 Mtoe, respectively), especially because of non-OECD countries, which account for a continuously growing share of world energy use, OECD countries have been assisting to a general decoupling of economic growth from final energy consumption since the first big oil crisis (1973) (IEA, 2016b). This was mainly because developed nations have become significantly more energy efficient after the shock thanks to the introduction of many different regulatory instruments and the invention and adoption of new technologies (Geller et al., 2006).

In this regard, EE constitutes one of the most cost-effective strategies for reducing energy consumption and it allowed OECD countries to decrease their energy intensity over time, even though changes in final energy intensities are different across countries, depending on their economic structures and sectors where EE efforts mostly occurred (IEA, 2016b). In line with the OECD trend, the EU has registered a substantial decrease in energy intensity over the same period. Both primary and final energy consumption decreased over time, and in the past two decades this phenomenon was particularly evident for Eastern EU countries. The New Member States have faced a radical change in their economic structures in general, and more specifically they were forced to adapt their policy and legal framework to the that of the EU, including the energy policy (Saheb and Ossenbrink, 2015). Accordingly, in 2015 the EU final energy consumption was equal to 1,083 Mtoe, returning to 1990 levels (Eurostat, 2017b) but with a substantial difference in the energy mix composition and in the relative contribution of different sectors to national energy consumption.[1]

Despite these huge changes in the whole energy system, the EU economy still suffers from a high dependency rate in energy imports. In 2015 the EU average dependency rate on energy imports was equal to 54%, which means that more than half of the EU's energy needs were met by

[1] See Table A1 in Appendix A

net imports, mainly from Middle East, Norway and Russia.[2] In addition, there is still a large heterogeneity in energy system at the country level, with strong divergences both in dependency rates and in energy mix composition (Eurostat, 2017b). As an example, there are countries where petroleum products account for a significant share of total energy available (e.g., Cyprus with 93%, Malta with 85%, and Luxembourg with 63%), while other countries mainly use natural gas (e.g., Italy, the Netherlands, and the UK) or nuclear power (as in the case of France and Sweden, with 45% and 32% respectively). Finally, Eastern countries, especially Estonia and Poland, still rely on solid fuels (mainly coal, 62% and 51% respectively). Similar heterogeneity can be found in energy intensity, where the least intensive economies in the EU in 2015 were Ireland, Denmark, Luxembourg, Malta and the UK, while the most energy-intensive EU Member States were Bulgaria and Estonia.[3] Indeed, although energy intensity decreases all over the EU, deep differences still occur among countries, depending on their economic structures and energy systems.

In this specific regard, while in the past three decades huge investments in EE have characterized most of the EU countries in manufacturing sectors (mainly energy-intensive industries), energy consumption in the residential sector is still far from being on a robustly declining path. On the contrary, despite the strong emphasis put by the EU legislation on achieving EE targets in all sectors, only few countries have implemented effective regulatory mechanisms for improving EE in the residential sector.

In 2015 the residential sector represented 25% of EU final energy consumption, absorbing alone about 29% of total electricity consumption (Eurostat, 2017b). Quite intriguingly, the introduction of modern technologies in daily life as devices, systems and equipment fuelled by electricity has more than compensated the reduction in energy consumption due to more efficient technologies. Accordingly, the residential sector deserves particular attention by policy makers in order to implement effective regulatory mechanisms that will allow cutting energy consumption in the next decades in order to reach the challenging target of an increase in energy efficiency by 2030 of around 27% with respect to a business as usual scenario as expected by the EU2030 Strategy (EC, 2014).

Together with a deep knowledge of the energy system, it is necessary to understand those mechanisms that could shape the technological trajectory in EE. Innovation and diffusion of more energy-efficient technologies is a key factor to achieve the EU2030 targets and increase the energy performance of national system In this regard, technological advancements in EE might be included in the wider category of eco-innovation. Indeed, eco-innovation is considered a key factor for delivering the EU2030 Strategy's objectives, as highlighted with the adoption of the Eco-innovation Action Plan (EcoAP) that aims to accelerate market uptake of eco-innovation by

[2] The dependency rate describes the extent to which an economy relies upon imports to meet its energy needs. It is measured by the share of net imports (imports minus exports) in gross inland energy consumption (i.e., the sum of energy produced and net imports).
[3] See Figure A1 in Appendix A

addressing its barriers and drivers.[4]

International debate has provided several definitions of eco-innovation (Carrillo-Hermosilla et al., 2010). Among them, the most complete one is provided by Kemp and Pearson (2007, p. 7), according to which eco-innovation is "the production, assimilation or exploitation of a product, production process, service or management or business method that is novel to the organization (developing or adopting it) and which results, throughout its life cycle, in a reduction of environmental risk, pollution and other negative impacts of resources use (including energy use) compared to relevant alternatives". From this definition, it is evident that a deep knowledge of all mechanisms behind the introduction, diffusion and adoption of eco-innovative actions deserves a complex framework of analysis. Several studies have investigated determinants and characteristics of eco-innovation (Arundel and Kemp, 2009; Beise and Rennings, 2005; Cainelli and Mazzanti, 2013; OECD, 2011; Wagner, 2007).

A variety of factors drive eco-innovation, such as environmental regulations (Hojnik and Ruzzier, 2016; Veugelers, 2012), investments for the improvement of technological capabilities (Horbach, 2008), as well as knowledge diffusion, good institutions and cooperation (Ghisetti et al., 2015). Accordingly, it is not surprising that deep differences exist among countries, in terms of both eco-innovation performances and drivers. This is also true for the EU, despite the increasing financial and institutional efforts in this field (Borghesi et al., 2013). In this respect, Horbach (2016) finds that, on average, the Eastern EU countries are less eco-innovative compared to the other EU countries, both on the demand and supply side. Given the low environmental awareness of population and the high dependency on subsidies of the industrial system, the role of the public support to foster eco-innovation seems to be much more important for these countries lagging behind.

More generally, Hojnik and Ruzzier (2016) find that among the several potential determinants, regulation is the most relevant in fostering eco-innovation and constitutes the most commonly and frequently reported driver. Certainly, the role of regulation is strictly related to the nature of eco-innovation. In fact, among its characteristics, one peculiarity of eco-innovation is the so-called double-externality problem, namely the fact that it produces positive spillovers in both the innovation and diffusion phases (Rennings, 2000). This reduces incentives for firms to invest in eco-innovations due to free-riding risks, generating as a market failure a lack of investments that could be solved only by the adoption of public policy measures (Beise and Rennings, 2005).

Indeed, eco-innovation achievements are strictly connected to the instruments identified to implement domestic public policies in order to foster the introduction and diffusion of new environmental technologies (del Río, 2009; Horbach et al., 2012; Johnstone et al., 2010; Mowery et al., 2010; Newell, 2010).

A first distinction among the role of environmental regulatory instruments in fostering

[4] European Commission, COM(2011) 899 final: Communication from the Commission "Innovation for a sustainable Future - The Eco-innovation Action Plan (Eco-AP)"

environmental innovation is between demand-pull and technology-push policies. The former instruments aim at expanding the markets and increasing the profitability of innovation, by means of changes in market size and demand, e.g. changes in the prices of fossil energy sources, subsidies for consumer purchases, tax credits, direct government procurement or technological standards. On the other hand, technology-push instruments are characterized by the idea that innovation is driven by invention, new discoveries and advances in scientific knowledge, thus policies such as public research and development (R&D), government funding for private R&D and adoption incentives are designed to support and promote the development and deployment of new technologies. As a general result for eco-innovation domains, while demand-pull policy seems more appropriate for supporting mature technologies, technology-push instruments are needed for stimulating early-stages innovation (Costantini et al., 2015; Hoppmann et al., 2013; Horbach et al., 2012; Nemet, 2009; Peters et al., 2012).

Beside the conventional classification between these two policy types, further measures that have been introduced are voluntary instruments, as information-based instruments, rating and labelling programme or voluntarily negotiated agreements between governments and industrial sectors. As a general remark, eco-innovation is positively affected by the adoption of environmental management schemes and other voluntary managerial activities designed to improve environmental performances (Rennings et al., 2006; Wagner, 2008).

More recently, the role of policy has been analysed in a more complex setting, jointly considering all the instruments in place and their combination in terms of policy mix (Flanagan et al., 2011). In this case, besides the specific instrument used for environmental and innovation purposes, the overall impact is the result of the interactions and interdependencies between different policy instruments, as several studies investigating the effect of policy mix on innovation and eco-innovation show (Guerzoni and Raiteri, 2015; Uyarra et al.,2016). With respect to the instruments combinations, two relevant aspects of the policy mix have been identified: consistency, which refers to the positive effects emerging from instruments interaction, and comprehensiveness, if all the policy purposes have been covered (Rogge and Reichardt, 2016). Coherently, Costantini et al. (2017a) suggest that a balanced policy mix between demand-pull and technology-push instruments has a positive effect on eco-innovation, whether favouring demand-pull policy could result in the risk of lock-in in inferior technologies, while an unbalanced mix towards technology-push could induce a reduction in private investment for new technologies.

Apart from the specific effect on innovation dynamics, more generally it is also worth mentioning that the design of the policy mix might contribute to changing the structure of the socio-economic system (Antonelli, 1998). In this regard, a sustainable innovation policy implies changes in the techno-economic dynamics also in terms of production and consumption structure and, inevitably, in market dynamics, institutions and social norms (Costantini and Crespi, 2013; Nill and Kemp, 2009; Smink et al., 2015). This viewpoint has its roots in the seminal contribution by Porter and Van der Linde (1995) also known as the Porter Hypothesis (PH), according to which there are potential complementarities and private beneficial effects of a properly designed environmental regulation framework. In its strong version, the PH assumes a dynamic evolutionary setting claiming that environmental regulation would enhance economic performance for compliant firms, the sector to which they belong and, eventually, those sectors interlinked with the regulated one. Indeed, agents could consider new market opportunities and innovation offsets – both through process efficiency and product value enhancement – that may derive from the policy driven early adoption of both technological and organizational innovation (Jaffe and Palmer, 1997).

To this purpose, the technological innovation system (TIS) approach that focuses the analysis on the interactions occurring in a network of institutions and agents that affect the generation, diffusion and utilisation of specific technologies (Negro and Hekkert, 2008) constitutes a proper analytical framework. The dynamics of a TIS and its success can be analysed through the lens of the multiple activities and relationships among all agents defined by Hekkert et al. (2007) as entrepreneurial activities, knowledge development, knowledge diffusion through networks, guidance of the search (to positively influence the visibility of the technology), market formation, resources mobilization (finance and human), creation of legitimacy (to limit resistance to change).

In addition, according to Alkemade et al. (2011), while innovation policy tends to stimulate innovative efforts of industries and firms to enhance competitiveness and international performances of a TIS, transition policy is meant to increase the sustainability of the overall socio-economic system, creating a market for more sustainable goods and services. In this context, a systemic approach to policy design covering innovation, environmental, energy and economic goals seems particularly appropriate to analyse the sustainable transition of a TIS. At the same time, the complexity of such a policy framework strongly require attention to coordination and effectiveness issues related to the multiple instruments and targets involved.

The aspect related to the impact of policy design on economic competitiveness at the international level deserves a specific consideration. According to the early version of the PH, a first approach is to analyse if and to what extent domestic environmental regulation might positively influence international competitiveness, as in the case of environmental goods exported by the EU explored by Costantini and Mazzanti (2012). Nonetheless, more recently literature has contributed in shading light on the role played by decisions and policy strategies adopted by other countries, which have been recognized as key driving factors of domestic eco-innovation performances through international knowledge and policy spillovers (Dechezleprêtre and Glachant, 2014; Dekker et al., 2012; Peters et al., 2012; Popp et al., 2011). This mechanism seems to be reinforced by trade relationships that contribute shaping the domestic innovation system and performances.

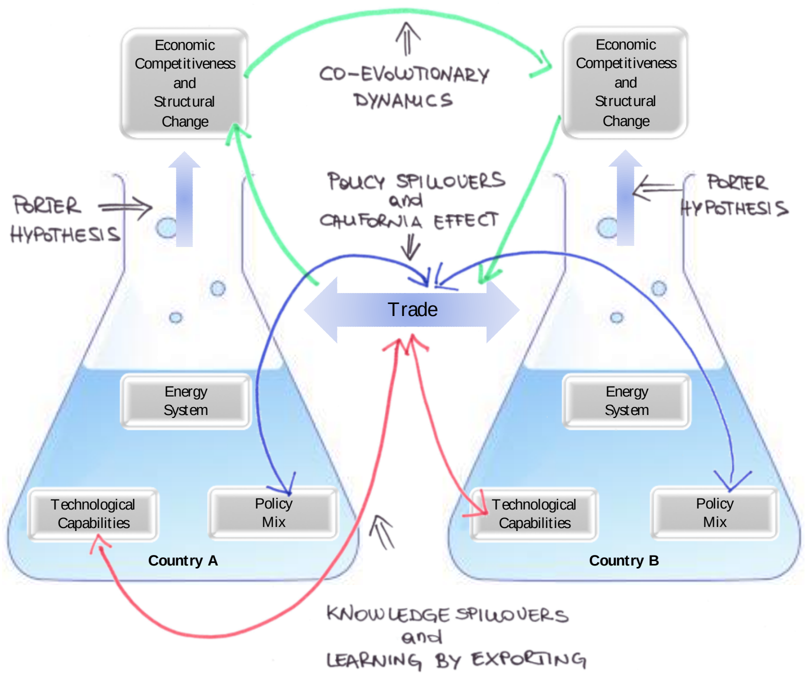
The development and deployment of eco-innovative technologies and behaviours are from the one side influenced by foreign activities, but they can also generate positive effects on the relative performance of the national system on the international market (Ambec and Lanoie, 2008;

Costantini and Crespi, 2008, 2013; Markard and Wirth, 2008).

Furthermore, especially in highly globalized economies, foreign TISs are increasingly affecting the domestic innovation performances, becoming more internationalised and not confined to national boundaries. Even though national policy is still a crucial driver of domestic innovation activities, internationalisation of science and technology is also affecting the dynamics of TISs (Carlsson, 2006). An example is the success of Chinese photovoltaic industry from learning and technology acquisition through global value chains and vertical integration strategies (Zhang and Gallagher, 2016).

From a conceptual viewpoint, the overall effect determined by the interaction with foreign markets might be synthesised in three different (but interconnected) channels (Figure 1).

Figure 1 – Conceptual analytical framework



The first one is a *learning by exporting* effect, since international trade benefits the trading parties both in static terms through comparative advantage, and in dynamic terms through exposing countries to the knowledge stocks of their trading partners (Grossman and Helpman, 1991; Love and Ganotakis, 2013). More specifically, the learning effect depends on the direct benefit from foreign knowledge spillovers in technologically advanced markets, and on an indirect effect since the increase of demand induced by the access to foreign markets increases also the profitability of introducing innovations (Fassio, 2017).

The second one is a *gains from trade* effect mainly regarding environmental regulatory standard convergence as well expressed by Vogel (1995) in the so-called *California effect* that describes the tendency of environmental product standards to ratchet upwards towards levels found in high-regulating countries that are export destination markets. This evidence has been found mainly for product standards because while process standards set domestic producers at a competitive disadvantage, product standards can constitute non-tariff barriers to trade because they also apply to foreign producers (Kono 2006; Perkins and Neumayer, 2012).

The third one relies on the role played by market integration and sustainable (global) value chains. As an example, the environmental performance of downstream industries can improve due to the innovation adopted by suppliers, or more generally invention and diffusion activities promoted by foreign actors can compensate for the lower innovative efforts of domestic firms (Costantini et al., 2017b).

All these channels through which economic systems are mutually influenced contribute to strengthen the relationship between the development and change of domestic economic structures bringing to what we can define a co-evolutionary dynamics. Obviously, this is a simplified view of the real world where several additional factors influence the evolution of an economic system, but it is useful to transform such a complex network of linkages into measurable dimensions. While we acknowledge how limiting is the choice of confining bilateral relationships into trade flows, we consider this analytical framework as adaptable to other relationships, as for instance foreign direct investments, or human capital mobility, or direct cooperative behaviours in knowledge creation.

3. Methodology

3.1. The operationalization of multiple and interlinked drivers for clustering countries

The descriptive statistical analysis is based on a sample of 19 EU countries,[5] where two driving criteria are used for the selection: (i) the EU membership and (ii) the availability of information covering the widest range of the selected structural features for the years 1990–2012.[6] As for a computational caveat, the three-year moving average value of variables has been considered to avoid the biasing effect of fluctuations and conjunctural events.

On the basis of the aforementioned analytical framework, we have selected 19 variables that can describe the four dimensions of the energy system, the technological innovation system of EE, the policy mix, and the competitiveness performance on international markets.[7]

The first dimension provides a description of the country energy profile, focusing on the performances of the residential sector. At the country level, we consider: the national energy efficiency index, as the ratio between GDP and total energy consumption, and its change over time (with respect to t-5); energy imports as percentage of energy use and the mean annual temperature. Data for GDP, energy imports and temperature are taken from World Bank database while the final energy

[5] The 19 European countries included in the analysis are: Austria, Belgium, Czech Republic, Germany, Denmark, Estonia, Greece, Spain, Finland, France, Hungary, Ireland, Italy, Netherlands, Poland, Portugal, Slovakia, Sweden, United Kingdom.

[6] Given the amount of missing data in 1990, for the descriptive analysis we take as our base year the period 1995-1997.

[7] The complete list of variables used in the analysis and data sources are provided in Table B1, Appendix B.

consumption data (expressed in thousand tonnes of oil equivalent) are from the EUROSTAT database.[8] In order to describe the performance of the residential sector in terms of EE, we also include four additional variables. Data from EUROSTAT and World Bank database are used to construct two indicators: the share of residential energy consumption with respect to the total energy consumption and the residential energy consumption per capita. Finally, and coherently with national EE indicators, we include the household energy efficiency index, as the ratio between the household consumption expenditures and residential energy consumption, and a variable representing the change in household energy efficiency (with respect to t-5).

The second dimension included in the analysis provides information related to EE technologies of the EU countries considered in terms of innovation performance. Following the contribution by Costantini et al. (2014), innovation in the EE domain is measured by the count of patent applications filed at the EPO by EU countries over the period 1990-2012 from OECD PATSTATS. Accordingly, the patents included combine the technologies in the class Y02 of the Cooperative Patent Classification (CPC) with those relative to the residential EE appliances, thus including the following main technological domains: Insulation, High-efficiency boilers, Heat and cold distribution and CHP, Ventilation, Solar energy and other RES, Building materials, Climate control systems and Lighting. The selected EPO patents are classified by application date and assigned to the applicant's country. When multiple assignee countries are present for a single patent, we have assigned a proportion of the considered patent to each country on the basis of the number of assignees for each country.

We build the patent stock indicator applying a decay rate (μ) of 15 per cent, where i indexes countries, and s represents an index of years up to and including year t. Accordingly:

$$KPAT\_EE_{i,t} = \sum_{s=0}^{t} \left\{ Pat\_EE_{i,s} \cdot e^{[-\mu(t-s)]} \right\} \tag{1}$$

The patents stock is then used to build alternative measures of technological performance, in terms of comparative advantages (Archibugi and Pianta, 1996) and specialization (van Zeebroeck et al., 2006) in order to map EU technological trajectories and performances over time. First, we build an EE patent Balassa index as it follows:

$$EE\_Pat\_Balassa_{i,t} = \frac{KPAT\_EE_{\,i,t} / KPAT\_Tot_{\,i,t}}{KPAT\_EE_{EU,t} / KPAT\_Tot_{\,EU,t}} \tag{2}$$

which is given by the ratio between the share of EE patent with respect to the overall patenting activity for country i at time t and the corresponding ratio at the EU level.

Furthermore, in order to provide a more detailed description of the state of the national innovation system, we also include two additional indicators: the EE patent stock per capita and the EE patent specialisation, calculated as the ratio between the patent stock in EE and the total patent stock at the country level ($KPAT\_EE_{\,i,t} / KPAT\_Tot_{\,i,t}$).

[8] Data originally expressed as constant 2010 USD have been converted in constant 2010 Euro using OECD deflator and exchange rate indicators.

The third dimension refers to policy mix design and includes information divided in three pillars. The first is the *Demand-pull* policy indicator, a price-based instrument that represents the impact of energy taxation on the market price for energy demand in the residential sector. In so doing, we follow previous contributions that generally found that prices played a significant and positive role in fostering innovation dynamics in more efficient energy technologies (Jaffe and Stavins, 1995; Newell *et al.*, 1999; Noailly, 2012; Popp, 2002; Verdolini and Galeotti, 2011). What we are interested in, it is capturing the role of this policy in affecting residential energy consumption and consequently favouring EE innovation via a price mechanism. Accordingly, we calculate the average tax rate applied to energy consumption in the residential sector for each country and year as an ad valorem equivalent on energy market price (here expressed as Euro at constant 2010 prices per tonnes of oil equivalent (toe) of energy consumed). In order to account for different mixes of energy commodities used in the residential sector at the country level, we weight energy tax rates by consumptions related to each specific source as follows:

$$Demand\_Pull_{i,t} = Energy\_Tax_{i,t} = \frac{\sum_{n=1}^{2}\left(Energy\_Tax_{i,t}^{n} \cdot Ener\_Cons_{i,t}^{n}\right)}{\sum_{n=1}^{2}\left(Ener\_Cons_{i,t}^{n}\right)} \quad (3)$$

where n indexes the energy commodity (electricity and natural gas), whereas i and t refer to countries and time, respectively. Tax rates are taken from the Electricity and natural gas prices and taxes database (EUROSTAT), whereas data on energy consumption are taken from Electricity and natural gas Consumption database for the residential sector (EUROSTAT). In this way, the stringency level of the policy adopted and its relative impact on the specific residential energy input mix used in each country can be considered simultaneously, thus controlling also for the peculiarity of the residential sector within the country-specific national energy system.

The second is the *Technology-push* policy indicator. This policy instrument is quantified by taking the stock of public R&D efforts in EE. Accordingly, R&D expenditure flows taken from IEA Technology Statistics (IEA, online database) have been used in a Perpetual Inventory Method (PIM) formulation to compute stock values as follows:[9]

$$Technology\_Push_{i,t} = KRD\_EE_{i,t} = \sum_{s=0}^{t}\left\{RD\_EE_{i,s} \cdot e^{[-\partial(t-s)]}\right\} \quad (4)$$

where $\forall s = 0 \Rightarrow RD_{EE_{i,s}} = RD_{EE_{i,s}}/g$ with g representing the average annual growth rate of R&D expenditures at constant prices throughout the whole period. In so doing, we are supposing that technological knowledge has a cumulative character and, hence, can be summed over time, but that knowledge capital is also subject to an obsolescence rate (Evenson, 2002).

We have applied an average discount rate of 15 per cent as suggested by OECD (2009), so that

[9] Data originally expressed as constant 2015 USD have been converted in constant 2010 Euro using OECD deflator.

similarly to eq. (1) ∂ indicates the discount rate, i indexes countries and t and s indicate time.

Afterward, we build a quantitative measure of the *Policy mix balance* between demand-pull and technology-push instruments in the domestic policy mix, computed as the difference between these two policy domains. Considering that these are expressed in different units, Euro per toe for energy tax and millions Euro for R&D in EE, we have scaled this second indicator by total residential energy consumption, thus obtaining two homogenous measures expressed in Euro per toe. The empirical formulation of this measure is built as follows:

$$Pol\_Balance_{i,t} = Energy\_Tax_{i,t} - \frac{KRD\_EE_{i,t}}{\sum_{n=1}^{2}\left(Ener\_Cons_{i,t}^{n}\right)} \tag{5}$$

Given the structure of this indicator, values close to 0 indicate a close similarity in the intensity of the two policy instruments, while negative values indicate a preference towards technology-push with respect to demand-pull and vice versa.

A further characteristic of the policy mix under scrutiny refers to its *Comprehensiveness* and thus includes all types of instruments, where different instruments are homogeneously mapped and quantified in a binary (0-1) system. Here, we collect information from the IEA database on Energy Efficiency Policy Online Database (IEA, 2016) in three sectors (buildings, lighting, residential appliances) for EU countries in the 1990-2012 period, classified in six types: Economic instruments; Information and education; Policy Support; Regulatory instruments; Research, development and deployment; Voluntary approaches (Table 1).

Table 1 – Policy types and instruments

Type #	Policy Type	Instrument
1	*Economic Instruments*	Direct investment
		Fiscal/financial incentives
		Market-based instruments
2	*Information and Education*	Advice/aid in implementation
		Information provision
		Performance label
		Professional training and qualification
3	*Policy Support*	Institutional creation
		Strategic planning
4	*Regulatory Instruments*	Auditing
		Codes and standards
		Monitoring schemes
		Obligation schemes
		Other mandatory requirements
5	*Research, Development and Deployment (RD&D)*	Demonstration projects
		Research programmes
6	*Voluntary Approaches*	Negotiated agreements
		Public voluntary schemes
		Unilateral commitments

Source: IEA (2016a)

Considering the qualitative information of the IEA database, we have assigned value 1 if there is a policy for each country and year. The final measure is given by the sum of counts as the cumulative number of policy instruments in force at time t in country i. According to Johnstone et al. (2010), this modelling choice allows the whole range of policies still in force at time t in country i to be considered for each year and changes occurring to policies over time can also be accounted for.

Accordingly, we calculate a proxy for policy mix *comprehensiveness* as an aggregate stock of total policies for EE given by the sum of the stocks of policies belonging to the whole range of policy types described in Table 1:

$$Comprehensiveness_{i,t} = \sum_{q=1}^{6}\left(\sum_{s=0}^{t}(POL_{i,s}^{q})\right) \tag{6}$$

where $q \in [1,2, \dots ,6]$ represents all the six policy types.[10] With respect to this variable, we also consider the non-linear effects. According to Johnstone *et al*. (2010), this modelling choice allows the whole range of policies still in force at time t in country i to be considered for each year and changes occurring to policies over time can also be accounted for. In addition, we can test the existence of a threshold level beyond which the number of policy instruments contemporaneously implemented becomes excessive, with an increasing risk of conflicting interactions leading to negative effects in terms of innovation performance.

The fourth indicator includes information on EE policy *soft and systemic instruments*. For the construction of this indicator, we only consider policies collected by the IEA database (Table 1) and classified in types 2, 3, 6, namely Information and Education, Policy Support and Voluntary Approaches. With regard to the first type, it includes all forms of support to the cognitive-informational context as guidelines and recommendations to improve the adoption of energy saving behaviours at the household level or to diffuse the notion of EE at different education degrees in order to prepare executives to be ready to adopt an energy-efficient managerial culture. The second type includes systemic instruments that aim to reinforce the support provided by the institutional context in achieving EE targets such as, for instance, through the creation of ad hoc government agencies (e.g., the creation of the National Agency for Energy Efficiency in Italy in 2008).[11] The third type refers to all voluntary approaches that may help the introduction and adoption of energy-efficient behaviours, as described by Kemp (1997), consisting in agreements between private agents and governments to assist consumers and building industries in achieving better energy performances (e.g., the Voluntary Agreement on the Phase Out of Incandescent Light Bulbs adopted in UK in 2007 and, similarly, the Incandescent Lamp Phase-out implemented in France in 2008). Considering the qualitative information of the IEA database, the final measure of soft and systemic instruments is given by the sum

[10] If multiple instruments are included in the same policy, when summed up in the comprehensiveness measure, each policy is univocally classified in order to avoid double counting bias.

[11] We acknowledge that policy instruments with systemic purposes can be in principle found in other policy types. However, in the absence of an *ad hoc* classification by IEA in this sense, in order to avoid arbitrary choices in the construction of the indicator, we focus on the policy types for which the systemic nature of instruments is prevalent.

of counts as the cumulative number of these policy instruments in force at time t in country i with respect to comprehensiveness:

$$Soft\_Systemic_{i,t} = \frac{\sum_{q=2,3,6}\left(\sum_{s=0}^{t}(POL_{i,s}^{q})\right)}{Comprehensiveness_{i,t}} \quad (7)$$

where $q \in [2,3,6]$ represents the three policy types selected as specified in Table 1.

The fourth dimension included in the analytical framework provides a representation of the competitiveness performances of EU countries related to the trade dynamics in EE technological domain for the residential sector. The indicators built for the cluster analysis are all at the country level, while the ex-post cluster analysis is also based on bilateral export flows. The country-pair and total export flows are taken from the UN-COMTRADE database and cover the class 775 of SITC Rev.3: Household-type electrical and non-electrical equipment, n.e.s. (Household-type laundry equipment, refrigerators and food freezers, Dishwashing machines, Shavers and hair clippers, Electromechanical and Electrothermic domestic appliances). Such data allow building three indicators. First, coherently with the innovation performance dimension, we the EE trade Balassa index. In line with the EE patent Balassa index, the EE trade Balassa indicator is formulated as follows:

$$EE\_Exp\_Balassa_{i,t} = \frac{Export\_EE_{\,i,t}/Export\_MAN_{\,i,t}}{Export\_EE_{EU,t}/Export\_MAN_{\,EU,t}} \quad (8)$$

In this case, we consider the ratio between the country and EU in terms of the relationship between the export flows in the EE residential sector identified and the overall export flows in manufacturing sectors.

In addition, we also include an EE trade specialization index as the share of trade in EE with respect to trade in manufacturing ($Export\_EE_{\,i,t}/Export\_MAN_{\,i,t}$) and the ratio between the share of country export in EE and the GDP share with respect to EU:

$$EE\_Export\_GDP_{i,t} = \frac{Export\_EE_{\,i,t}/Export\_EE_{\,EU,t}}{GDP_{i,t}/GDP_{\,EU,t}} \quad (9)$$

3.2. Principal components and cluster analysis

In order to classify EU countries in homogeneous groups on the basis of the previously described dimensions, we perform a cluster analysis. This procedure seeks “to uncover groups in data” (Everitt et al., 2001, p. 5). In other words, it identifies groups of units that are similar to each other within the group, though they differ from units that belong to the remaining groups. In order to have a representative picture of the current EU characteristics, we perform the analysis on the last period of our dataset taking data as three-year average values (2010-2012). Before applying the cluster analysis, we perform a preliminary principal component analysis (PCA) on the original dataset to avoid potential correlations between variables in the cluster procedure, given that several indicators in the same dimension rely on similar variables.[12] PCA is a technique that replaces the original variables by

[12] See Tables B2 and B3 in Appendix B.

a smaller number of derived variables, the principal components (PCs), which are linear combinations of the original variables (Jolliffe, 2005). In doing so, it reduces the dimensionality of datasets by extracting only the information that is essential for representing the variance of the phenomena. In this regard, in order to select the number of PCs to be retained, we follow the Kaiser criterion, according to which the components to be selected are those with eigenvalues greater than 1 (Hsieh et al., 2004; Kaiser, 1960). Accordingly, we select 6 PCs to which we apply the cluster analysis. It is worth noting that this number of components explains 85% of the cumulative variance, thus respecting also the alternative selection criterion that, as illustrated by Jolliffe (2002), consists of selecting the number of components that explains an established variance threshold level.[13] This level should be in the range 70–90%.

Following the approach adopted by Costantini et al. (2016), the cluster analysis is conducted in two steps. The first one is a hierarchical cluster analysis to determine the optimal number of clusters. The second step consists of using the number of clusters obtained in the first step to inform a non-hierarchical clustering process.

As for the first step of the cluster analysis, the hierarchical clustering process consists of four phases (Johnson, 1967): (i) to allocate each item in a distinct cluster so that there are N clusters; (ii) to identify the closest (most similar) pair of clusters and unify them into a single one, obtaining N-1 clusters; (iii) to compute distances (similarities) between the new cluster and each of the old clusters; (iv) to run again phases (ii) and (iii) until the delivery of one single cluster for all items (size N). Alternative hierarchical methods exist, depending on the way distances are computed in phase three. The method used in this analysis is the single linkage, according to which the distance between one cluster and another is equal to the smallest distance from any member of one cluster to any member of the other cluster. This is computed in terms of the Euclidean distance, which is the square root of the sum of squares of the differences between the coordinates of the points. Once the entire process is completed and the hierarchical tree is obtained, it is necessary to choose the optimal number of clusters (k). To this purpose, the Duda–Hart test is conducted (Duda and Hart, 1973) and interpreted according to Cao et al. (2008). This test gives as a result a three-columns matrix: the first column indicates the number of clusters, the second column provides the corresponding Duda–Hart Je(2)/Je(1) index stopping-rule,[14] whereas the third one shows the pseudo-T-squared values. From the comparison of these two values, it emerges that the best number of clusters is four,[15] as it has a high Duda–Hart Je(2)/ Je(1) value (0.88) associated with a low pseudo- T-squared value (1.65).[16]

This is the number of clusters implemented in the second step of the cluster analysis, namely a non-hierarchical k-means clustering in which the number of groups must be pre-determined. This method

[13] See Table B4 and Figure B1 in Appendix B.
[14] The Duda–Hart Je(2)/Je(1) index is the ratio between the total within sum of squared distances about the centroids of the clusters for the two-cluster solution (Je(2)) and the within sum of squared distances about the centroid when only one cluster is present (Je(1)).
[15] Four is found to be the best number of clusters even by applying alternative hierarchical methods (e.g. centroid, complete linkage and median linkage methods)
[16] See Table B5 in Appendix B.

aims to reduce to minimum the sum of the distances of each item from the centroid of its cluster, thus the intra-cluster variance (MacQueen, 1967).[17] At the end of the process, the final composition of the four clusters is achieved.

3.3. Post-cluster analysis

The different country-groups obtained by the PCA and the cluster procedures are then analysed by applying the original indicators used for the PCA and two additional indicators describing the intra-cluster characteristics considering the bilateral export flows and the absolute distance in the regulatory space, respectively. First, we consider the intra-cluster export share of energy commodities in the residential sector of each country *i* with all *c-1* countries belonging to same cluster:

$$EE\_Exp\_Share_{i,t} = \frac{\sum_{j=1}^{c-1} Export\_EE_{\,i,j,t}}{Export\_EE_{i,EU,t}} \tag{10}$$

where *j* indicates countries belonging to the same cluster of country *i* and *c* the number of countries included in the cluster.

Then we introduce the concept of intra-cluster policy balance similarity. In line with Costantini et al. (2017), it is calculated considering the policy balance distance between each *i-th* country and the other *j* countries belonging to the same cluster as:

$$Pol\_Bal\_Sim_{\,i,t} = \frac{1}{c-1}\sum_{j=1}^{c-1}\left|Pol\_Balance_{i,t} - Pol\_Balance_{j,t}\right|^{-1} \tag{11}$$

The higher the value, the closer the similarity of each *i-th* country with respect to the others belonging to the same cluster.[18]

The adoption of these indicators, additional to those used for the cluster analysis, allows better detecting if and to what extent the different channels described in the complex analytical framework can be highlighted by the empirical evidence. The combination of the information on domestic country features with that of bilateral relationship represents a first step in understanding if co-evolving dynamics occurred in this specific technological domain.

4. Results

According to the three-step analysis described in Section 3, the 19 EU countries selected in the dataset can be pooled into four groups, where Table 2 describes the final composition of each. Cluster 1 consists of three countries (Finland, Ireland and UK); Cluster 4 includes both central and northern EU

[17] The k-means algorithm consists of four phases: i) to determine the centroids; ii) to calculate the distance between cluster centroid to each object and assign each object to a cluster based on the minimum distance; iii) to compute the new centroid of each group based on the new memberships; iv) to run again phases two and three until the assignments no longer change.

[18] In eq. (11), we apply an average value instead of a sum in order to obtain a measure independent from the number of countries composing each cluster.

countries, while Clusters 2 and 3 have a common geographic feature, since they gather Mediterranean and East European countries, respectively.

Table 2 - Clusters' composition

Cluster 1	Cluster 2	Cluster 3	Cluster 4
Finland	Greece	Czech Republic	Austria
Ireland	Spain	Estonia	Belgium
UK	France	Hungary	Germany
	Italy	Poland	Denmark
	Portugal	Slovak Republic	Netherlands
			Sweden

In order to investigate the characteristics of each cluster, Table 3 describes them according to the selected variables representing the four dimensions.

Starting with Cluster 1, it is formed by countries with a relatively high national energy efficiency but a negative performance in terms of increase in EE w.r.t. the previous period (t-5). The same performance can be found for the specific residential sector, meaning that the achievement of high standards is difficult to be improved over time.

As for Clusters 1 and 2, they include the most energy-dependent EU countries. Consequently, in both cases we can see the greatest efforts in EE especially through the implementation of the highest number of policies and the efforts in innovations. What differentiate the two clusters the most is the policy mix composition and the innovation patterns. As for the first point, while Cluster 1 is the most technology-push oriented with the lowest level of balance, Cluster 2 has one of the most balanced policy mix (slightly demand-pull oriented). With regard to innovation, as already mentioned both clusters include big innovators. However, Cluster 1 is characterized by the lowest degree of specialization in EE innovation as well as the lowest performance in terms of trade competitiveness in EE commodities.

As for Eastern EU countries (Cluster 3), they are the weakest in terms of overall energy efficiency system. Indeed, they have the lowest level of energy efficiency and a very high residential energy consumption. They are also those that implement the lowest number of policies (comprehensiveness) but highly balanced, and invest the least in innovation. Nevertheless, they register the best performance in terms of trade.

On the contrary, Cluster 4 groups the most innovator EU countries, in terms of both number of patents and EE specialization, whose efforts in innovation do not translate into advantages in terms of trade, despite a low degree of energy dependency. As for the policy dimension, countries belonging to Cluster 4 register the most unbalanced policy mix demand-pull oriented.

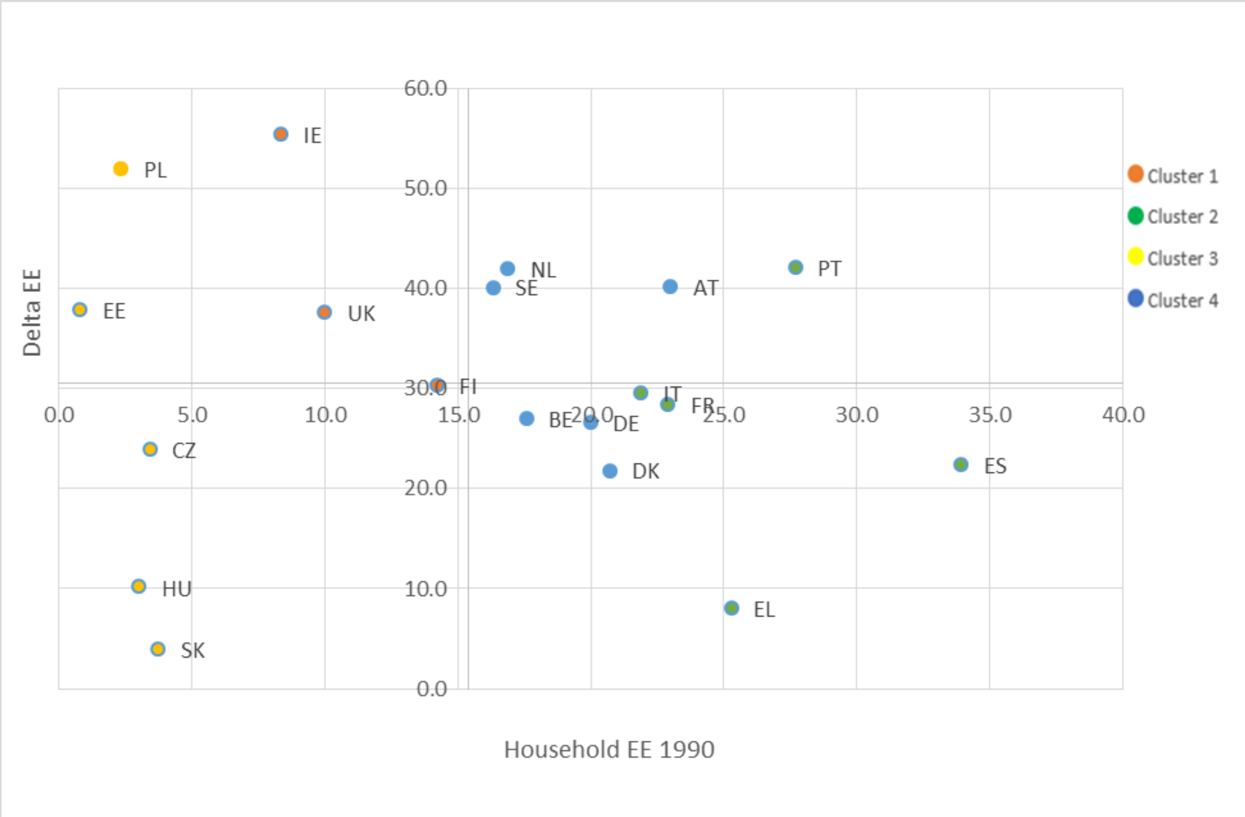
Table 3 - Variables used in cluster analysis (2010-2012 average)

	Cluster1	Cluster2	Cluster3	Cluster4
Energy				
National EE index (Mln Euro per toe)	12.3	12.1	6.1	12.4
Change in national EE w.r.t. t-5(%)	-0.03	0.04	0.15	0.04
Energy imports (% of energy use)	57.12	68.22	37.23	38.69
Residential energy consumption (% of tot. ener. cons.)	0.26	0.23	0.30	0.25
Residential energy consumption p.c. (Ktoe)	0.77	0.45	0.58	0.75
Average Annual Temperature (C°)	6.78	14.21	8.45	7.89
Household EE index (Mln Euro per toe)	23.75	33.01	11.72	24.17
Change in household EE w.r.t. t-5 (%)	-0.06	0.03	0.20	0.04
Innovation				
EE Patent Stock p.c. (Nr. per 1000 people)	0.75	0.36	0.07	1.88
EE Patent Stock Balassa Index (Index)	0.70	1.03	1.14	1.15
EE Patent Stock Specialization (%)	0.07	0.11	0.12	0.12
Policy				
Demand-pull (Euro)	0.15	0.23	0.20	0.33
Technology-push (Mln Euro)	0.38	0.05	0.06	0.12
Policy balance (Index)	-0.23	0.17	0.14	0.21
Comprehensiveness (Nr.)	8.10	10.03	2.37	7.60
Soft & Systemic instruments (Nr.)	0.35	0.39	0.38	0.47
Competitiveness				
EE Export Balassa Index (Index)	0.30	1.18	1.55	0.78
EE Export Specialization (%)	0.27	1.06	1.39	0.70
EE Export to GDP (Index)	1.62	4.75	28.89	13.61

The composition of clusters and their characteristics help describing the current situation. A further step would be to analyze how countries get to this composition by conducting a descriptive analysis on the main variables in order to compare the present with the first period under scrutiny. In this regard, it is useful to start this analysis with a description of the evolution of the energy efficiency variable. Accordingly, Figure 2 compares the “Household energy efficiency index” in 1990 with the change in energy efficiency (Delta EE) between the initial period and the final one (2012).

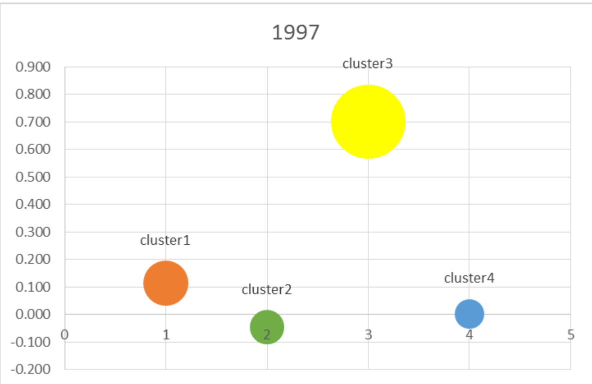
As we can see, the distinction between the four clusters is well defined. Countries belonging to Cluster 2 were the most energy efficient in the initial period (in part helped by high temperatures) while they register a change in EE close to the EU average in 2012 (with the exception of Greece that registers lower energy efficiency gains). Cluster 4 countries started in line with the EU mean and they still are. The same can be observed for Cluster 1, with the exception of Ireland that registers the highest improvement in energy efficiency. Finally, Cluster 3 countries are those that had the worst energy efficiency performance in the initial period. As for the change in EE, unlike the previous case, we see pronounced differences between countries belonging to this cluster, from Poland registering high changes in EE to Slovak Republic, which is the country with the lowest improvement in energy efficiency. These internal differences, in addition to the initial bad performances, make Cluster 3 a very interesting case study in terms of energy efficiency.

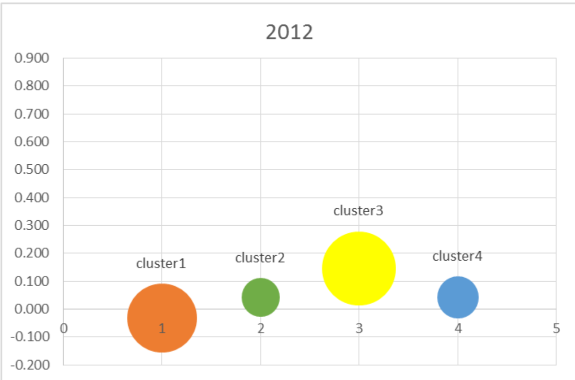
Figure 2 – Change in household energy efficiency in 2012 w.r.t. 1990



If we look at the change in national energy efficiency, we see that Cluster 3 is the one with the highest improvements in 1997 with respect to 1992, mainly due to the large economic growth experienced by East European countries in those years. In addition, their initial bad EE performance has contributed to achieve larger improvement, also due to the implementation of new instruments and measures to foster EE. Over the years, this dynamic decreases up to the last period under scrutiny in which we can see an alignment with the other clusters (Figures 3 and 4).

Figures 3 and 4 – Change in national energy efficiency w.r.t. t-5 in 1997 and 2012





Note: The diameter of each circle is given by the standard deviation within each cluster. The larger the diameter, the more the intra-cluster differences.

Let us now look at the Innovation dimension. In order to investigate whether innovation has had an impact in terms of trade performances, Figures 5 and 6 compare the level of EE patents with trade specialization in the initial period and in 2012, respectively. As for the innovation dimension, the specialization measure is given by the Balassa Index.

It emerges that during '90s, European countries were characterized by a similar (low) level of EE innovation, associated to a low level of EE trade specialization. An exception is represented by Italy, which registered the highest trade specialization in EE commodities, although scarce performances in innovation. Indeed, it could benefit from a cost-competitiveness, as well as from a long tradition in the production of electrical appliances. Over the years, the picture has changed and today some more defined groups emerge.

Indeed, if we focus on current situation (Figure 6), we see that there are some countries, in particular those belonging to Cluster 4, which are the leaders in EE innovation. However, this does not contribute in improving their trade performances. Conversely, Eastern EU countries are those with the highest competitive advantages in terms of trade in EE commodities, in spite of very scarce levels of innovation. As illustrated also in Figures 7 and 8, this situation has evolved over time, with a shift of leadership in terms of trade specialization between Cluster 2 and Cluster 3.

Figure 5 – Relation between EE patents per capita and EE Export Balassa Index (1997)

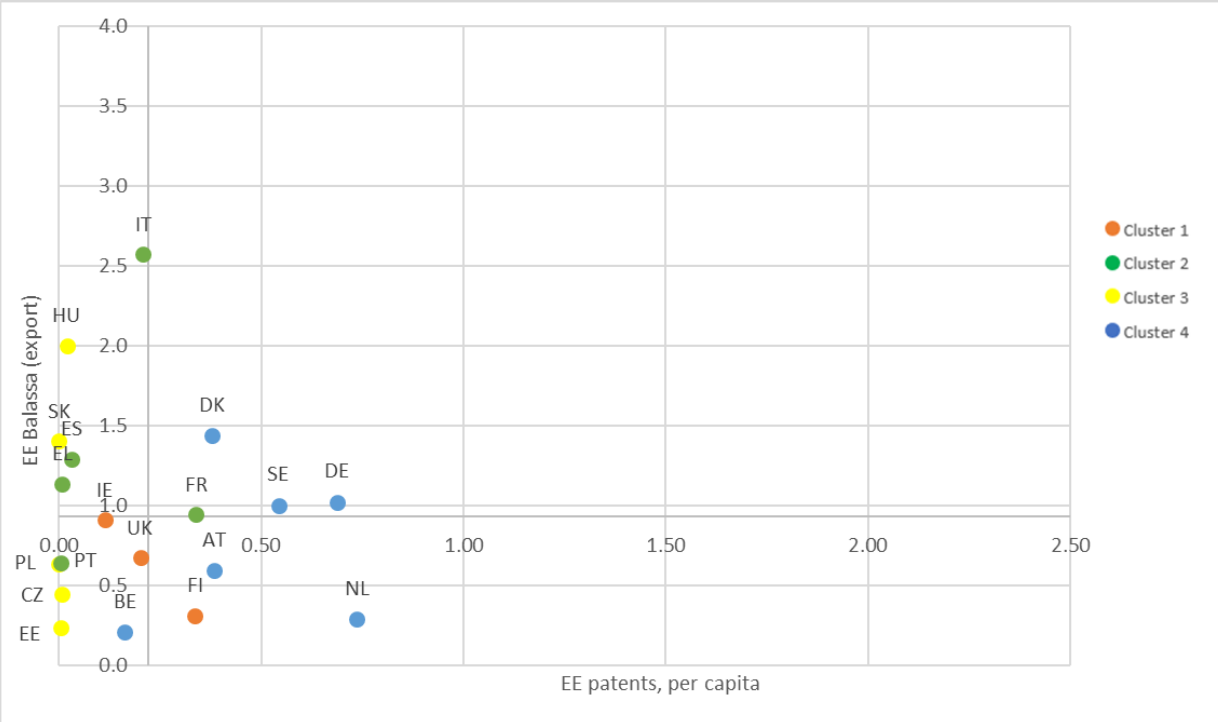
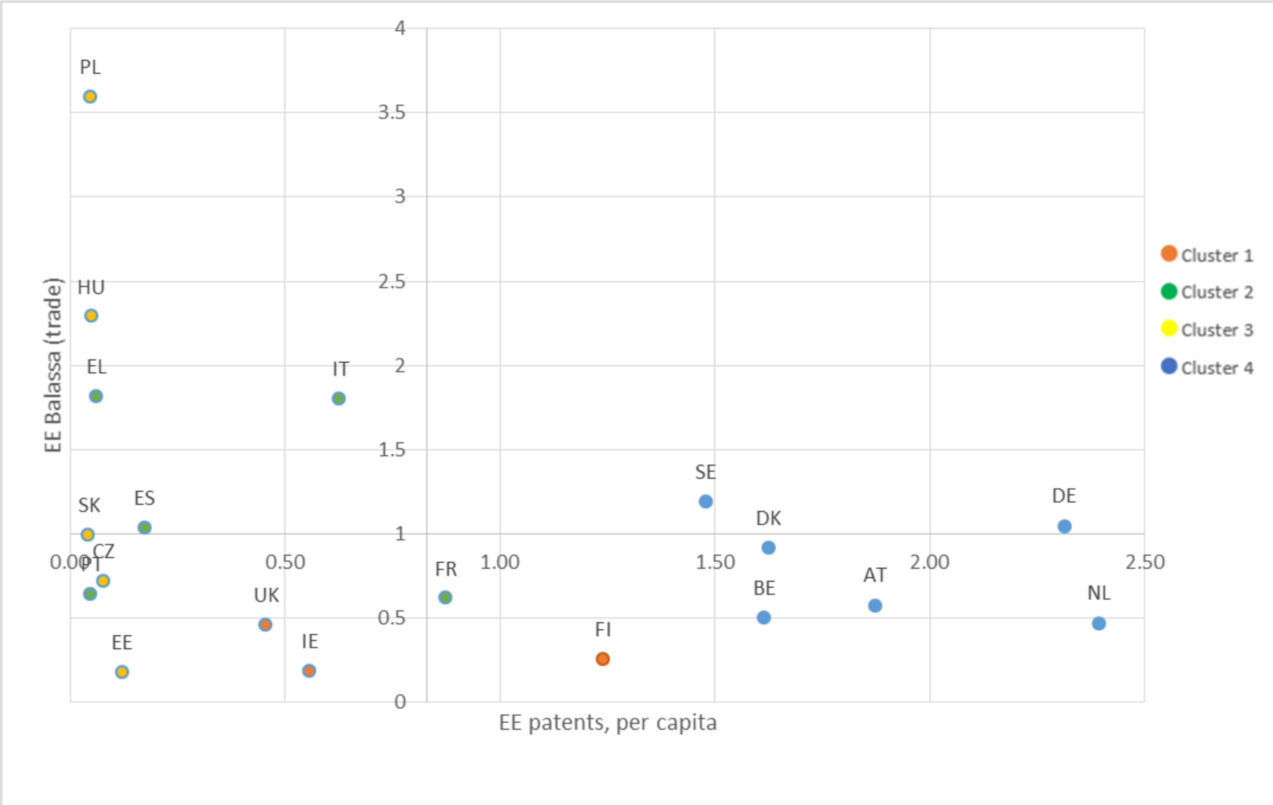
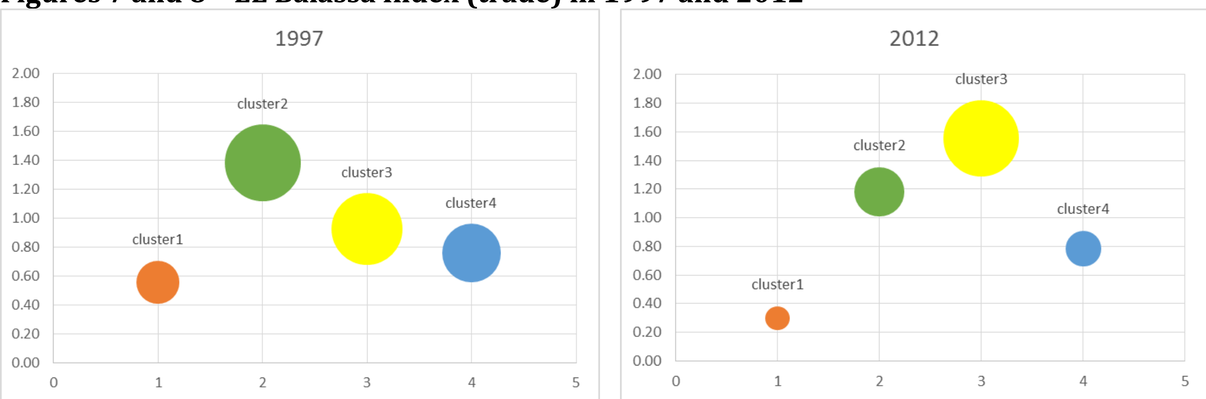


Figure 6 – Relation between EE patents per capita and EE Balassa Index (2012)



Figures 7 and 8 – EE Balassa Index (trade) in 1997 and 2012



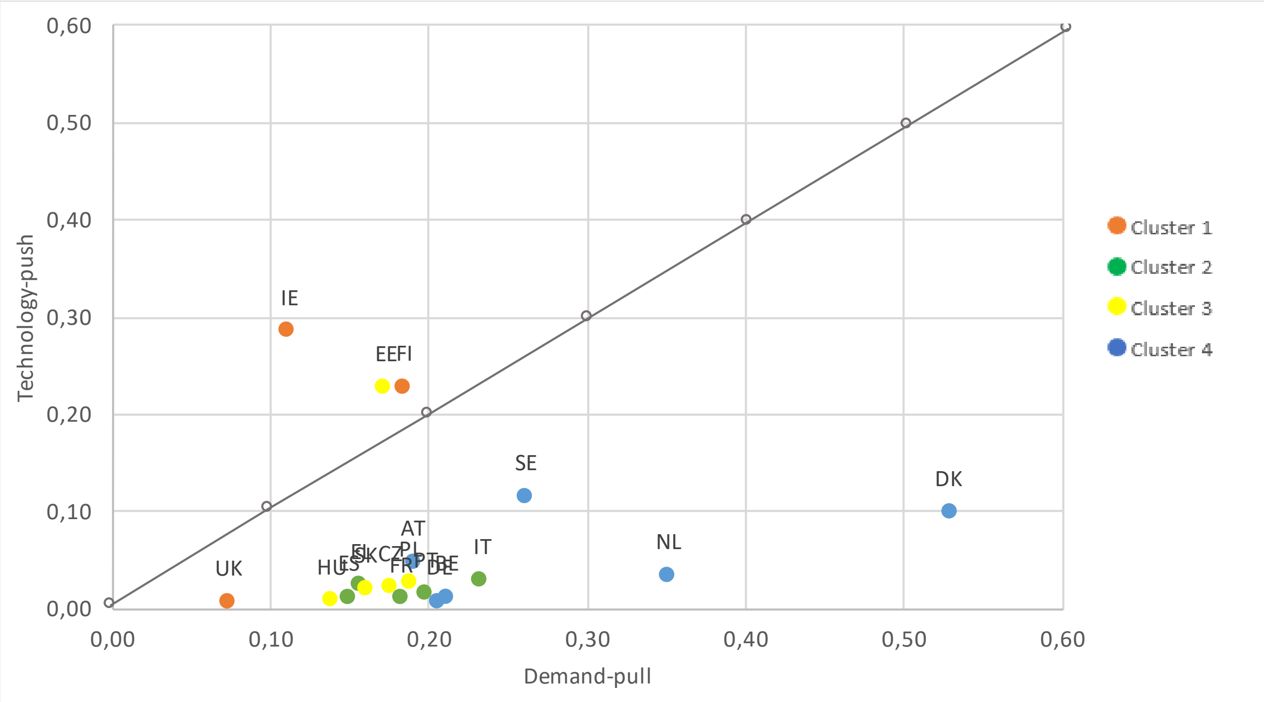
Note: The diameter of each circle is given by the standard deviation within each cluster. The larger the diameter, the more the intra-cluster differences.

This dynamic has been mainly driven by two countries, namely Italy and Poland. During 90s, Italy was the leader in terms of exports in EE commodities. Then, it gradually started to lose its competitive advantages (from 30% w.r.t. EU trade in 1997 to 15.5% in 2012) while Poland registered relevant improvements with respect to trade performances in EE commodities (from 0.76% in 1997 to 15% in 2012), even without a particular effort in terms of innovation. It is also worth noting that Poland and Cluster 3 in general, registered a general improvement in terms of manufacturing trade performances but to a lesser extent than trade performances in EE commodities. This suggests a propensity of eastern countries towards a process of specialization in this domain.[19] As for Cluster 1 countries, they generally maintain their position with respect to the previous period, registering values below the EU average for both dimensions. The current situation then suggests the existence of value chains: a part of Europe (mainly Cluster 4 countries) contributes to innovating and providing new technologies, while another part (especially Cluster 3) implements them to produce and then export final commodities.

Finally, it is worth having a closer look at France, which tends to reduce its performances over the years, reaching a position well below the EU average in 2012. This is mainly because it is on track with respect to abatement targets and it does not sustain high energy costs, due to its use of nuclear. Accordingly, while other countries need EE innovation efforts to contain energy costs, France does not have urgent needs to innovate.

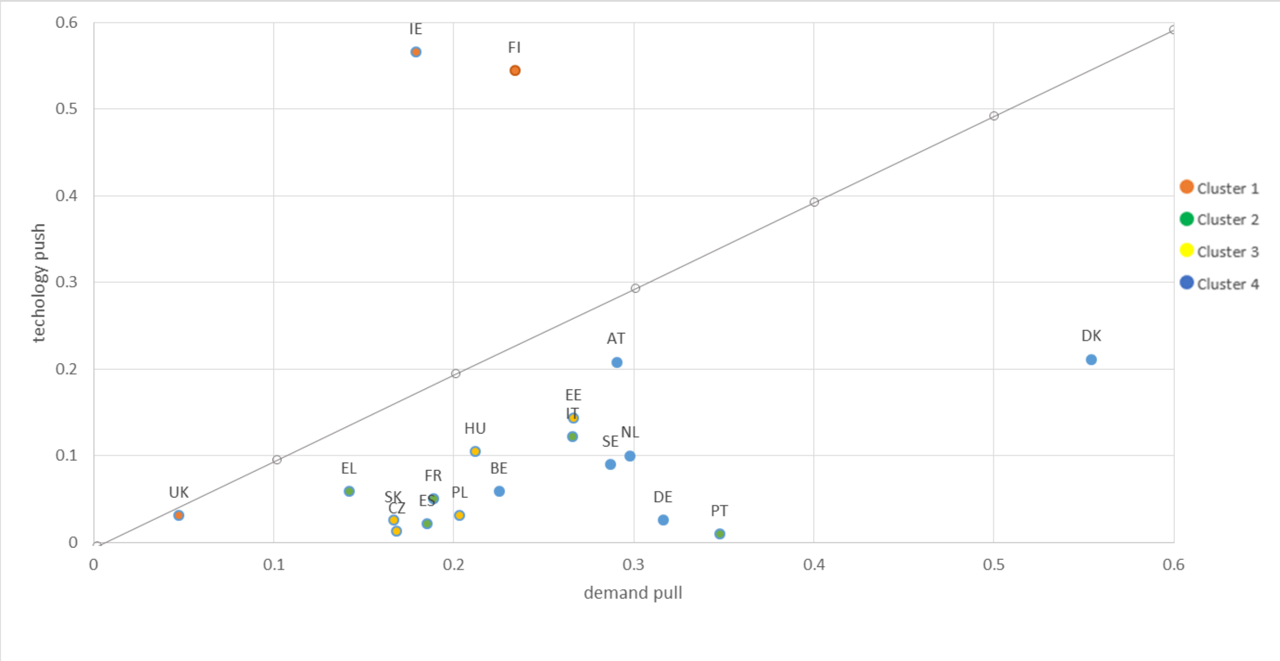
As for the Policy dimension, Figures 9 and 10 describe the composition of policy mix by comparing demand-pull and technology push measures in the two period under scrutiny. In both cases, almost all EU countries locate under the bisector, meaning that most of EU countries are more demand pull-oriented. In 2012, the only exceptions are Ireland and Finland, which have a very high unbalanced policy mix towards technology push measures. It was the same even in the past, although the preference of Cluster 1 countries for technology push was not so pronounced.

Figures 9 – Demand-pull w.r.t. Technology-push (1997)



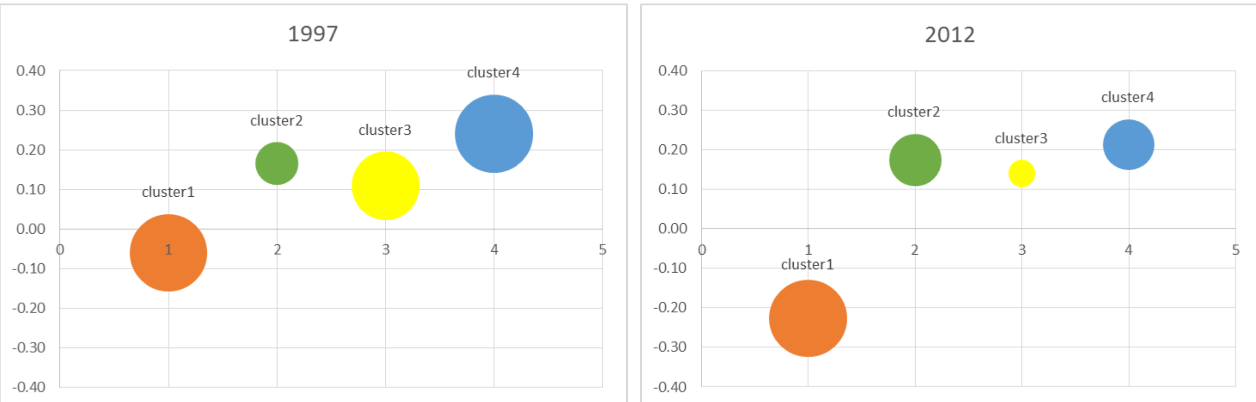
[19] See Table C1 in Appendix C.

Figures 10 – Demand-pull w.r.t. Technology-push (2012)



Moreover, all intra-clusters differences decrease over time, especially with regard to Cluster 3, as we can see by comparing Figures 11 and 12, which show the domestic policy balance. In other words, the fact that the intra-cluster standard deviation decreases over time (i.e. the dimension of the bubbles from Figures 11 to 12 reduces) means that countries belonging to the same cluster have become more similar in terms of policy mix structure.

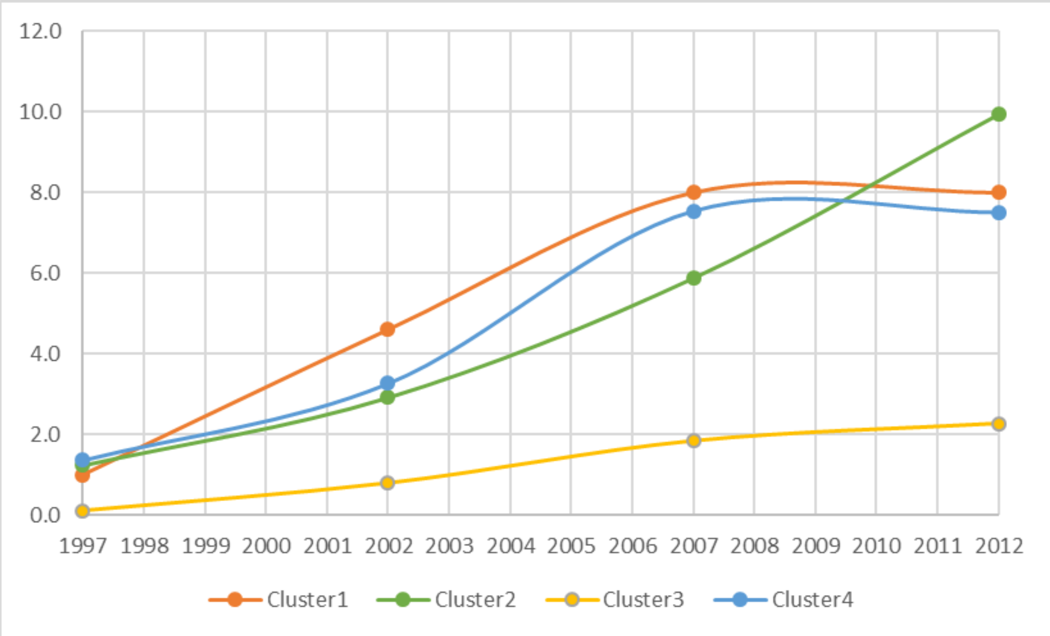
Figures 11 and 12 – Domestic balance in 1997 and 2012



Note: Domestic balance is the difference between demand-pull and domestic-push measures. Accordingly, negative values indicate technology-push oriented policy mixes.
The diameter of each circle is given by the standard deviation within each cluster. The larger the diameter, the more the intra-cluster differences.

During the considered period, many policies have been implemented by each country in order to improve its energy efficiency system. In particular, the attention towards this kind of policies started in about the year 1997 and has been increasing since then. Figure 13 shows the number of policies implemented by each cluster over time.

Figure 13 – Comprehensiveness



Firstly, we observe that Cluster 3 is the one that implements the lowest number of policies. Secondly, it is worth noting that while Cluster 2 registers an upward trend, both Cluster 1 and Cluster 4 have a trend reversal in 2007, when they reach about eight implemented policies. This recalls what highlighted in Costantini et al. (2017), according to which "there might be a threshold level beyond which the number of policy instruments contemporaneously implemented becomes excessive, with an increasing risk of conflicting interactions leading to negative effects in terms of innovation performance".

As already mentioned, the implementation of policies to foster eco-innovation also influence trade performances and dynamics. In this regard, it is worth looking at the interactions between countries in terms of both bilateral trade and policy similarity. Accordingly, in order to have a better picture of these dynamics, let us strat with Table 4, which shows the export share of each country towards each cluster.

In 1997, countries belonging to Cluster 3 had very strong bilateral trade relationships with Cluster 4. In particular, more than 70% of Poland's exports were directed towards this cluster. As already highlighted, Cluster 4 is composed by the most performing countries. Therefore, this relationship has contributed to boosting Cluster 3 countries to improve their performances and their technological specialization in EE innovation over the years. Indeed, in 2012 they are the most competitive, doing better than other countries, especially with respect to those that, on the contrary, have registered a loss of competitiveness (Cluster 2). Furthermore, from Table 4 it emerges that in 2012 Cluster 2 has also become the main trade partner of Cluster 3 countries. In other words, while Cluster 3 has experienced an improvement in terms of trade in energy efficiency commodities, Cluster 2, who was the leader in 1997, not only has drastically reduced its exports, but has also started to import these commodities from eastern countries (especially Poland).

Table 4 – Export in EE commodities share of each country towards each Cluster

	Cluster 1		Cluster 2		Cluster 3		Cluster 4	
Reporter	1997	2012	1997	2012	1997	2012	1997	2012
FI	2.34%	4.69%	3.48%	9.91%	21.56%	10.56%	72.63%	74.84%
IE	39.16%	68.54%	22.65%	5.83%	0.93%	1.33%	37.27%	27.40%
UK	17.38%	43.33%	35.46%	22.32%	3.78%	3.31%	43.38%	31.03%
EL	2.30%	7.08%	22.50%	38.71%	11.06%	4.68%	64.28%	49.62%
ES	10.94%	8.28%	50.48%	45.31%	4.02%	7.29%	34.55%	39.11%
FR	14.13%	7.55%	25.64%	27.40%	1.52%	8.51%	58.71%	56.55%
IT	17.78%	14.65%	31.40%	32.97%	9.05%	10.68%	41.76%	41.71%
PT	5.48%	3.25%	68.05%	50.46%	0.08%	3.63%	26.39%	42.72%
CZ	5.22%	4.14%	11.72%	11.65%	27.81%	21.01%	55.25%	63.21%
EE	47.43%	71.12%	1.54%	4.06%	2.72%	3.14%	50.29%	22.86%
HU	10.31%	7.25%	23.20%	24.14%	5.51%	22.19%	60.98%	46.42%
PL	4.03%	14.10%	15.75%	32.54%	8.91%	7.92%	71.35%	45.45%
SK	2.34%	3.35%	20.33%	24.82%	60.23%	44.38%	17.10%	27.45%
AT	9.22%	1.39%	15.44%	18.58%	23.11%	20.16%	52.23%	59.87%
BE	7.01%	4.56%	45.28%	62.98%	0.89%	2.34%	46.81%	30.12%
DE	11.43%	10.72%	34.91%	33.40%	6.03%	12.47%	47.62%	43.41%
DK	24.44%	17.82%	11.71%	8.75%	4.28%	3.60%	59.58%	69.82%
NL	6.70%	8.73%	21.99%	13.83%	2.71%	8.27%	68.61%	69.17%
SE	22.62%	34.28%	31.56%	7.77%	8.38%	7.24%	37.45%	50.71%

Note: Values highlighted in grey represent the intra-cluster trade.

Let us now look at the intra-cluster relationships. In this regard, we look at bilateral trade data and we compare them with policy balance information. Accordingly, Table 5 compares the two indicators defined in equations 9 and 10, namely the intra-cluster export share and the intra-cluster balance similarity, in 1997 and 2012, respectively.

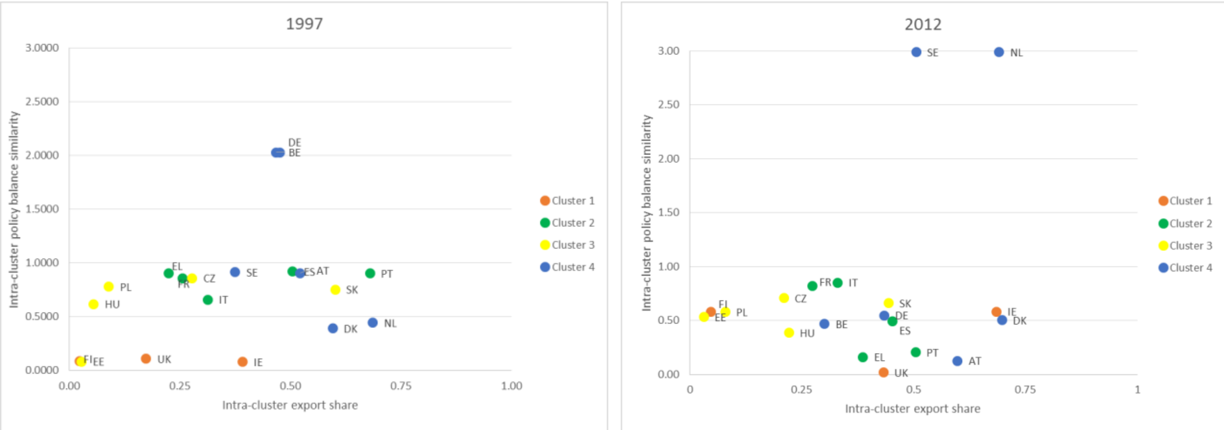
In both periods we see that, on average, Cluster 4 is the most similar in terms of balance even if it has the largest internal variation. Conversly, Cluster 1 is made of countries with the lowest level of intra-cluster balance similarity, followed by Cluster 3 and Cluster 2, as illustrated in Figures 14 and 15.[20]

[20] For further details see Table C2 in Appendix C.

Table 5 – Intra-cluster policy balance similarity and export share (1997 and 2012)

	1997		2012	
	Balance similarity	**Intra-cluster trade**	**Balance similarity**	**Intra-cluster trade**
Cluster 1	0.09	0.20	0.39	0.39
Intra-cluster st.dev.	*0.02*	*0.19*	*0.33*	*0.32*
Cluster 2	0.85	0.40	0.51	0.39
Intra-cluster st.dev.	*0.11*	*0.19*	*0.33*	*0.09*
Cluster 3	0.62	0.21	0.57	0.20
Intra-cluster st.dev.	*0.31*	*0.24*	*0.12*	*0.16*
Cluster 4	1.12	0.52	1.27	0.54
Intra-cluster st.dev.	*0.74*	*0.11*	*1.34*	*0.16*

Figures 14 and 15 – Intra-cluster export share w.r.t. intra-cluster balance similarity (1997 and 2012)



Moreover, in addition to a high level of balance similarity, Cluster 4 is characterized by a high intra-cluster export share. This suggests the existence of intra-cluster relationships leading to positive knowledge spillovers and, consequently, to a high propensity to innovate. Indeed, as illustrated in Figure 5 and Figure 6, Cluster 4 groups the big European innovators.

Furthermore, by comparing the two periods, it is worth noting that Clusters 1 and 4 improve their balance similarity but with an increase in the internal variation. On the contrary, Cluster 3 registers a reduction in the balance similarity index, but in 2012 the internal variation decreases compared to the previous period. However, the intra-cluster export share remains very low. In other words, Eastern European countries tend to have trade relationships with countries belonging to other clusters.

5. Conclusions

This paper provides a descriptive analysis of EU countries in order to measure some significant characteristics of the energy efficiency system and map European countries in terms of four dimension (policy, trade, energy and innovation dynamics) over the past twenty years. By applying a cluster analysis, we pool EU countries into four groups, each with specific characteristics. Then, by analyzing and comparing them also in a dynamic setting, we observe the multiple interactions between the several aspects under scrutiny.

As for the policy mix composition, from the analysis emerges that almost all EU countries composing our sample are demand-pull oriented, with the only exceptions of Ireland and Finland, which have a very high unbalanced policy mix towards technology-push measures.

Among the most interesting results, there is the evidence that there is not a direct relation between the degree of eco-innovation (in terms of EE patents) of a country and its degree of trade specialization in that field. Indeed, the most specialized countries in trade in EE commodities are those that register the lowest level of innovation (i.e. Eastern EU countries). This suggests the existence of value chains so that a part of Europe (mainly Cluster 4, e.g. Austria, Belgium, Germany, Denmark, Netherlands and Sweden) contributes to innovating and providing new technologies, while another part of Europe (mainly Eastern European countries) implements them to produce and export final commodities.

The last part of the paper aims to analyze the intra-cluster relationships. In particular, two main aspects are taken into account: the intra-cluster balance similarity and the intra-cluster export share.

Cluster 4 is found to be the most similar in terms of policy balance and the one with the highest intra-cluster trade share, while Eastern countries are those with the lowest one. Accordingly, we proceed into the analysis by investigating the trade relationship of each country with each cluster over the years in order to shed light on the dynamics arising in the trade of energy efficiency commodities among Europe.

Finally, from this analysis two main policy implications arise. Firstly, the implementation of policies for EE purposes emerges as a key factor to improve energy performances of countries. However, there is a threshold level, here found as equal to about eight policies, beyond which some negative interaction effects may occur as a result of policy fragmentation. The second policy implication is related to positive spillover effects that might arise between countries characterized by a similar policy balance and by a high level of bilateral trade.

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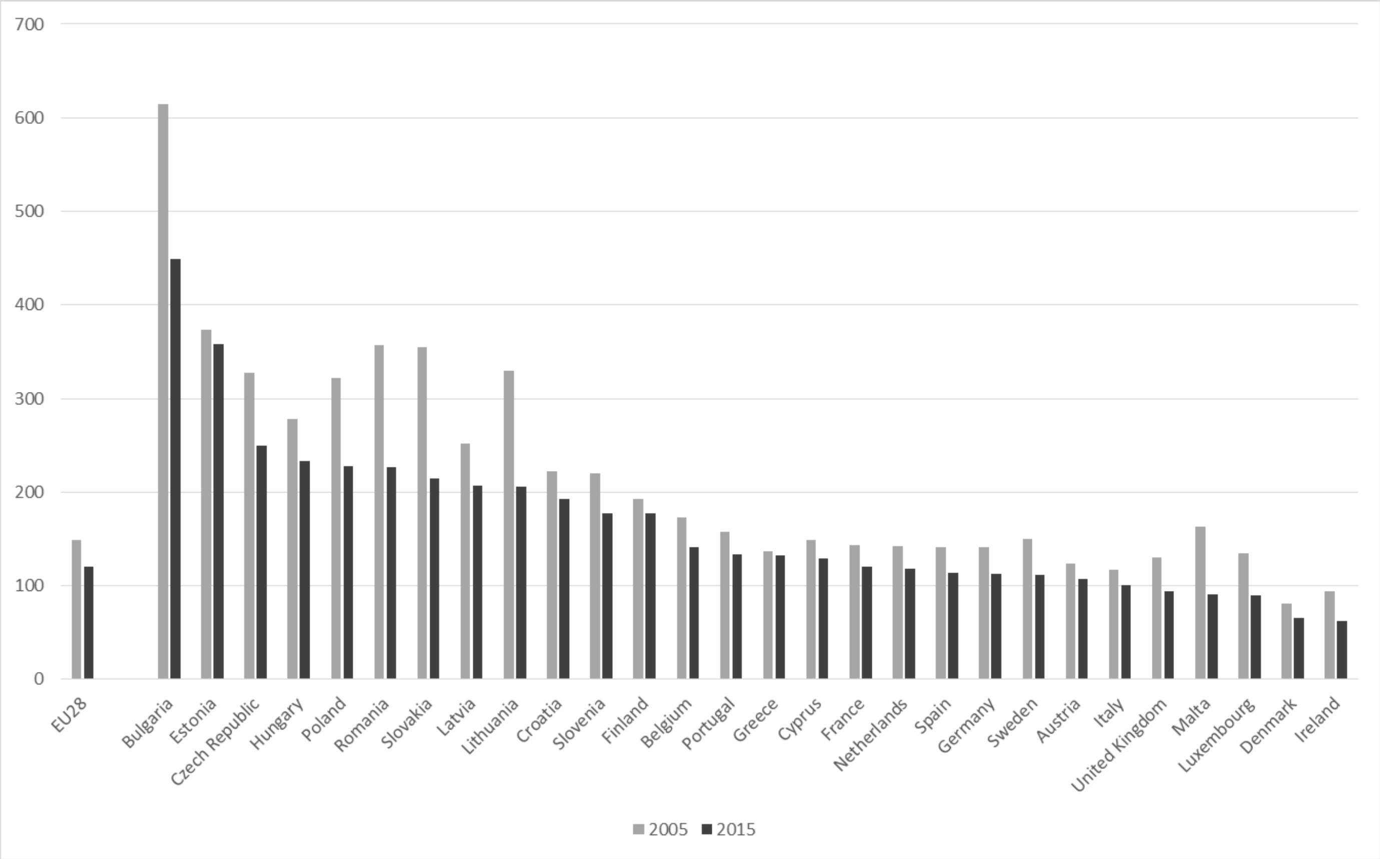
Appendix A

Figure A1 – Energy intensity of the economy, 2005 and 2015 (kg of oil equivalent per 1000 EUR of GDP)



Source: Eurostat (http://ec.europa.eu/eurostat/statistics-explained/index.php/Consumption_of_energy)

Table A1 - Share of renewables in gross final energy consumption, 2004-2015 and 2020

Country	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2020 Target
EU28	8.5	9	9.5	10.4	11	12.4	12.9	13.2	14.4	15.2	16.1	16.7	20
Belgium	1.9	2.3	2.6	3.1	3.6	4.7	5.7	6.3	7.2	7.5	8	7.9	13
Bulgaria	9.4	9.4	9.6	9.2	10.5	12.1	14.1	14.3	16	19	18	18.2	16
Czech Rep	6.8	7.1	7.4	8	8.6	9.9	10.5	11	12.8	13.8	15.1	15.1	13
Denmark	14.9	16	16.3	17.8	18.6	20	22.1	23.5	25.7	27.4	29.3	30.8	30
Germany	5.8	6.7	7.7	9.1	8.6	9.9	10.5	11.4	12.1	12.4	13.8	14.6	18
Estonia	18.4	17.5	16.1	17.1	18.9	23	24.6	25.5	25.8	25.6	26.3	28.6	25
Ireland	2.4	2.9	3.1	3.6	4.1	5.1	5.6	6.6	7.2	7.7	8.7	9.2	16
Greece	6.9	7	7.2	8.2	8	8.5	9.8	10.9	13.5	15	15.3	15.4	18
Spain	8.3	8.4	9.2	9.7	10.8	13	13.8	13.2	14.3	15.3	16.1	16.2	20
France	9.4	9.5	9.3	10.1	11.1	12.1	12.5	11.1	13.4	14.1	14.7	15.2	23
Croatia	23.5	23.8	22.7	22.2	22	23.6	25.1	25.4	26.8	28	27.9	29	20
Italy	6.3	7.5	8.3	9.8	11.5	12.8	13	12.9	15.4	16.7	17.1	17.5	17
Cyprus	3.1	3.1	3.3	4	5.1	5.6	6	6	6.8	8.1	8.9	9.4	13
Latvia	32.8	32.3	31.1	29.6	29.8	34.3	30.4	33.5	35.7	37.1	38.7	37.6	40
Lithuania	17.2	16.8	16.9	16.5	17.8	19.8	19.6	19.9	21.4	22.7	23.6	25.8	23
Luxembourg	0.9	1.4	1.5	2.7	2.8	2.9	2.9	2.9	3.1	3.5	4.5	5	11
Hungary	4.4	4.5	5.1	5.9	6.5	8	12.8	14	15.5	16.2	14.6	14.5	13
Malta	0.1	0.2	0.2	0.2	0.2	0.2	1	1.9	2.8	3.7	4.7	5	10
Netherlands	2.1	2.5	2.8	3.3	3.6	4.3	3.9	4.5	4.7	4.8	5.5	5.8	14
Austria	22.6	23.9	25.4	27.2	28.1	29.9	30.4	30.6	31.4	32.3	32.8	33	34
Poland	6.9	6.9	6.9	6.9	7.7	8.7	9.3	10.3	10.9	11.4	11.5	11.8	15
Portugal	19.2	19.5	20.8	21.9	23	24.4	24.2	24.6	24.6	25.7	27	28	31
Romania	16.3	17.3	17.1	18.3	20.5	22.7	23.4	21.4	22.8	23.9	24.8	24.8	24
Slovenia	16.1	16	15.6	15.6	15	20.1	20.4	20.3	20.8	22.4	21.5	22	25
Slovakia	6.4	6.4	6.6	7.8	7.7	9.4	9.1	10.3	10.4	10.1	11.7	12.9	14
Finland	29.2	28.8	30	29.6	31.3	31.3	32.4	32.8	34.4	36.7	38.7	39.3	38
Sweden	38.7	40.6	42.7	44.2	45.3	48.2	47.2	48.7	51.1	52	52.5	53.9	49
UK	1.1	1.3	1.5	1.8	2.7	3.3	3.7	4.2	4.6	5.7	7.1	8.2	15

Source: Eurostat (http://ec.europa.eu/eurostat/product?code=t2020_31&language=en&mode=view)

Appendix B

Table B1 – List of variables included in cluster analysis

Dimension	Variable	Definition	Source
Policy	Comprehensiveness	Number of policies (as in eq. 4)	IEA
	Demand pull	Ratio between the energy taxation levy on the total cost of energy consumption as in eq. 1	Our elaboration on Eurostat data
	Technology push	Stock of public gross R&D expenditures in energy efficiency (Euro 2010) as in eq. 2	Our elaboration on IEA data
	Domestic balance	Balance between demand-pull and technology-push policies as in eq. 3	Our elaboration on Eurostat and IEA data
	Soft & Systemic	Ratio between qualitative policies classified as EE soft and systemic instruments (as in eq. 5) and comprehensiveness	Our elaboration on IEA data
Competitiveness	EE Balassa Index	Degree of specialization of energy efficiency trade as in eq. 8	Our elaboration on UN Comtrade data
	EE Trade specialization	Share of trade in energy efficiency w.r.t. trade in manufacturing	Our elaboration on UN Comtrade data
	EE Trade w.r.t GDP	Ratio between national trade in energy efficiency share and GDP share w.r.t. EU	Our elaboration on UN Comtrade and World Bank data
Energy	National energy efficiency index	Ratio between GDP and total energy consumption	Our elaboration on World Bank and EUROSTAT data
	Change in national energy efficiency	Change in national energy efficiency w.r.t. t-5	Our elaboration on World Bank and EUROSTAT data
	Energy imports	Energy imports (% of energy use)	World Bank (from IEA data)
	Residential energy consumption	Share of residential energy consumption w.r.t. total energy consumption	Our elaboration on Eurostat data
	Residential Energy consumption, per capita	Ratio between residential energy consumption and population (ktoe)	Our elaboration on Eurostat and World Bank data
	Temperature	Mean Annual temp. (Celsius)	World Bank
	Household energy efficiency index	Ratio between household consumption and residential energy consumption	Our elaboration on EUROSTAT data
	Change in household energy intensity	Change in household energy consumption per unit of output w.r.t. t-5	Our elaboration on EUROSTAT data
Innovation	EE Patents, per capita	Ratio between the stock of patents in energy efficiency (as in eq. 6) and population	Our elaboration on OECD PATSTAT and World Bank data
	EE Patent Balassa Index	Degree of specialization of patents in energy efficiency as in eq. 7	Our elaboration on OECD PATSTAT data
	EE Patent specialization	Share of patents in energy efficiency w.r.t. total patents	Our elaboration on OECD PATSTAT data

Table B2 – Dataset description

Variable	Obs	Mean	Std. Dev.	Min	Max
Comprehensiveness	19	6.94	3.82	0.10	14.10
Demand pull	19	0.24	0.10	0.05	0.55
Technology push	19	0.13	0.16	0.01	0.57
Domestic balance	19	0.11	0.18	-0.39	0.34
Soft & Systemic	19	0.41	0.19	0.00	0.91
EE Balassa Index	19	1.01	0.85	0.18	3.60
EE Trade specialization	19	0.01	0.01	0.00	0.03
EE Trade w.r.t GDP	19	13.41	16.26	0.06	59.84
National energy efficiency index (Mln)	19	10.7	3.4	5.7	16.5
Change in national energy efficiency	19	0.06	0.08	-0.11	0.26
Energy imports	19	48.99	27.21	-14.50	88.25
Residential energy consumption	19	0.26	0.05	0.16	0.34
Residential Energy consumption, per capita	19	0.63	0.18	0.27	1.01
Temperature	19	9.53	3.85	1.70	16.09
Household energy efficiency index	19	23.16	8.92	8.67	41.02
Change in household energy intensity	19	-0.07	0.06	-0.21	-0.01
EE Patents, per capita	19	0.83	0.83	0.04	2.39
EE Patent Balassa Index	19	1.04	0.31	0.53	1.62
EE Patent specialization	19	0.11	0.03	0.06	0.17

Table B3 – Correlation

	Compr	Demand pull	Technology push	Domestic balance	Soft & Systemic	EE Balassa Index	EE Trade spec.	EE Trade w.r.t GDP	National EE index	Change in national EE
Compr	1									
Demand pull	0.0249	1								
Technology push	0.0165	0.1112	1							
Domestic balance	-0.0005	0.4699	-0.825	1						
Soft & Systemic	0.1941	0.1834	0.0088	0.0965	1					
EE Balassa Index	-0.4149	-0.0707	-0.3514	0.2719	-0.6095	1				
EE Trade spec	-0.416	-0.0706	-0.3512	0.2718	-0.6105	1	1			
EE Trade w.r.t GDP	-0.3992	-0.0699	-0.2431	0.1761	-0.1788	0.3662	0.3649	1		
National EE index	0.6601	0.2707	0.1754	-0.0019	0.1928	-0.3114	-0.3119	-0.496	1	
Change in national EE	-0.4351	0.0258	-0.2909	0.273	-0.1351	0.2103	0.2111	0.4451	-0.653	1
Energy imports	0.4407	-0.3801	0.1181	-0.3211	-0.0774	0.0164	0.015	-0.0098	0.0555	-0.2072
Residential energy consumption	-0.5266	-0.0569	-0.0301	-0.0056	-0.0212	0.3773	0.3773	0.3647	-0.1347	0.0243
Residential Energy consumption, per capita	-0.1427	0.2592	0.5233	-0.3174	0.0229	-0.3233	-0.322	-0.0113	0.0952	-0.1106
Temperature	0.2733	-0.1261	-0.4505	0.3285	0.0489	0.2035	0.2016	0.0253	0.2214	-0.1794
Household EE index	0.795	0.1194	-0.1002	0.1569	0.1118	-0.2527	-0.2535	-0.5572	0.6735	-0.4998
Change in household energy intensity	-0.4239	0.1573	-0.2896	0.3467	-0.2053	0.4611	0.4616	0.2153	-0.6077	0.5469
EE Patents, per capita	0.2492	0.4988	0.1774	0.1261	0.1752	-0.3305	-0.3308	-0.1501	0.4522	-0.3229
EE Patent Balassa Index	-0.3212	0.0173	-0.3891	0.3555	0.1268	0.2309	0.2307	0.0805	-0.2002	0.2354
EE Patent spec	-0.321	0.0174	-0.3892	0.3556	0.1263	0.2312	0.2309	0.0806	-0.1998	0.2351

Table B3 – Correlation (continued)

	Energy imports	Residential energy consumption	Residential Energy consumption, per capita	Temperature	Household EE index	Change in household energy intensity	EE Patents, per capita	EE Patent Balassa Index	EE Patent specialization
Compr									
Demand pull									
Technology push									
Domestic balance									
Soft & Systemic									
EE Balassa Index									
EE Trade spec									
EE Trade w.r.t GDP									
National EE index									
Change in national EE									
Energy imports	1								
Residential energy consumption	-0.4603	1							
Residential Energy consumption, per capita	-0.4364	0.2639	1						
Temperature	0.4531	-0.1572	-0.814	1					
Household EE index	0.4338	-0.6394	-0.4288	0.5834	1				
Change in household energy intensity	-0.1078	0.0687	-0.2388	0.0845	-0.2732	1			
EE Patents, per capita	-0.1882	-0.2072	0.6106	-0.3496	0.1264	-0.259	1		
EE Patent Balassa Index	0.0687	-0.0218	-0.2138	0.2454	-0.0852	0.3015	0.0773	1	
EE Patent spec	0.0687	-0.0219	-0.2139	0.2458	-0.0848	0.3014	0.0774	1	1

Table B4 – Principal Component Analysis (PCA)

Component	Eigenvalue	Difference	Proportion	Cumulative
Comp1	5.280	1.563	0.278	0.278
Comp2	3.717	1.140	0.196	0.474
Comp3	2.578	0.789	0.136	0.609
Comp4	1.789	0.368	0.094	0.703
Comp5	1.420	0.153	0.075	0.778
Comp6	1.268	0.378	0.067	0.845
Comp7	0.890	0.159	0.047	0.892
Comp8	0.731	0.325	0.039	0.930
Comp9	0.406	0.081	0.021	0.952
Comp10	0.325	0.056	0.017	0.969
Comp11	0.269	0.131	0.014	0.983
Comp12	0.138	0.053	0.007	0.990
Comp13	0.086	0.034	0.005	0.995
Comp14	0.052	0.011	0.003	0.997
Comp15	0.040	0.029	0.002	0.999
Comp16	0.011	0.011	0.001	1
Comp17	0	0	0	1
Comp18	0	0	0	1
Comp19	0	.	0	1

Figure B1 – Eigenvalues after PCA

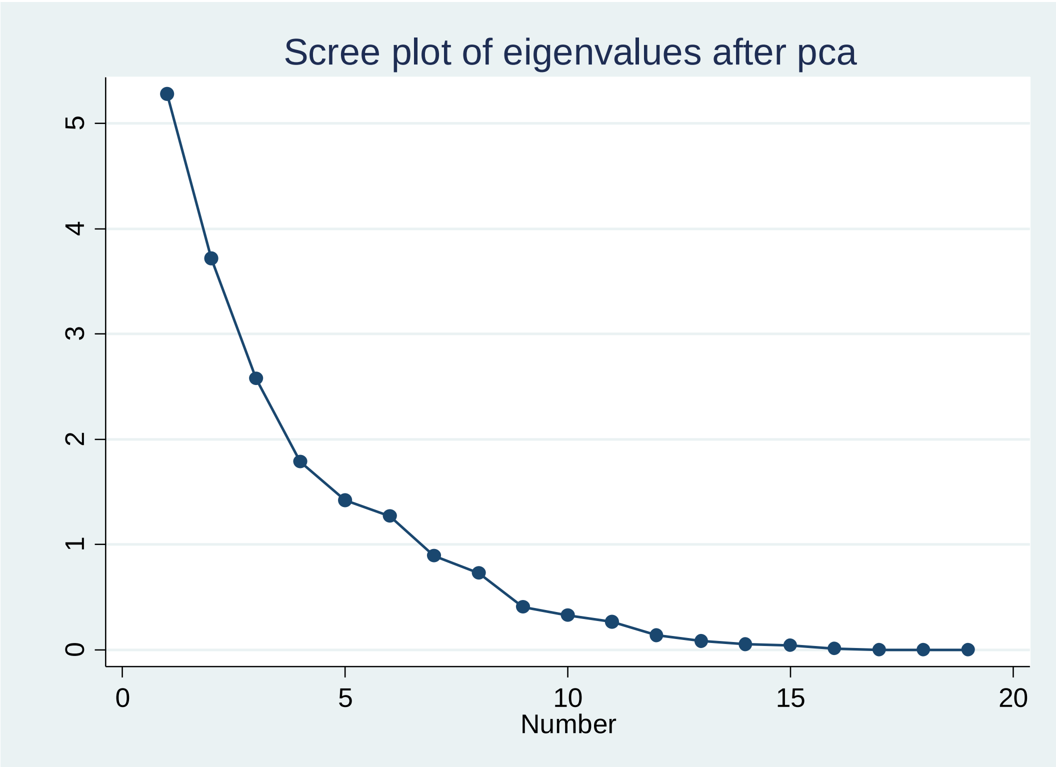


Table B5 – Duda-Hart test

	Duda/Hart	
Number of clusters	**Je(2)/Je(1)**	**Pseudo T-squared**
1	0.8855	2.2
2	0.8462	2.91
3	0.772	4.43
4	0.8791	1.65
5	0.2754	2.63
6	0.8012	2.73
7	0	.
8	0.8218	2.17
9	0.8499	1.59
10	0.6697	3.95
11	0.7075	2.48
12	0.511	4.79
13	0.52	2.77
14	0.484	2.13
15	0.322	2.11

Appendix C

Table C1 – Export share with respect to EU19

		EE trade (w.r.t. EU)		Trade in manufacturing (w.r.t. EU)	
Reporter	**Cluster**	**1997**	**2012**	**1997**	**2012**
Finland	1	0.55%	0.28%	1.81%	1.10%
Ireland	1	2.13%	0.43%	2.36%	2.36%
United Kingdom	1	7.02%	2.84%	10.49%	6.19%
Greece	2	0.34%	0.35%	0.30%	0.19%
Spain	2	6.55%	5.42%	5.09%	5.24%
France	2	12.29%	6.23%	13.08%	10.10%
Italy	2	29.61%	15.48%	11.54%	8.59%
Portugal	2	0.97%	0.83%	1.52%	1.30%
Czech Republic	3	0.61%	3.11%	1.37%	4.35%
Estonia	3	0.02%	0.04%	0.08%	0.22%
Hungary	3	1.49%	5.54%	0.76%	2.42%
Poland	3	0.76%	14.91%	1.21%	4.15%
Slovak Republic	3	0.73%	2.05%	0.53%	2.06%
Austria	4	2.00%	1.87%	3.35%	3.25%
Belgium	4	1.91%	4.62%	9.12%	9.19%
Germany	4	24.71%	26.93%	24.17%	25.74%
Denmark	4	2.52%	1.40%	1.75%	1.53%
Netherlands	4	2.41%	4.40%	8.11%	9.27%
Sweden	4	3.38%	3.27%	3.38%	2.75%

Table C2 – Intra-cluster policy balance similarity and export share (1997 and 2012)

		1997		2012	
Reporter	**Cluster**	**Balance similarity**	**intra-cluster trade**	**Balance similarity**	**intra-cluster trade**
Finland	1	0.09	0.02	0.58	0.05
Ireland	1	0.08	0.39	0.58	0.69
United Kingdom	1	0.11	0.17	0.02	0.43
Cluster 1		*0.09*	*0.20*	*0.39*	*0.39*
Intra-cluster st.dev.		*0.02*	*0.19*	*0.33*	*0.32*
Greece	2	0.90	0.22	0.16	0.39
Spain	2	0.92	0.50	0.49	0.45
France	2	0.86	0.26	0.82	0.27
Italy	2	0.66	0.31	0.85	0.33
Portugal	2	0.91	0.68	0.21	0.50
Cluster 2		*0.85*	*0.40*	*0.51*	*0.39*
Intra-cluster st.dev.		*0.11*	*0.19*	*0.33*	*0.09*
Czech Republic	3	0.86	0.28	0.71	0.21
Estonia	3	0.08	0.03	0.53	0.03
Hungary	3	0.62	0.06	0.39	0.22
Poland	3	0.78	0.09	0.58	0.08
Slovak Republic	3	0.75	0.60	0.66	0.44
Cluster 3		*0.62*	*0.21*	*0.57*	*0.20*
Intra-cluster st.dev.		*0.31*	*0.24*	*0.12*	*0.16*
Austria	4	0.91	0.52	0.13	0.60
Belgium	4	2.03	0.47	0.47	0.30
Germany	4	2.03	0.48	0.55	0.43
Denmark	4	0.39	0.60	0.50	0.70
Netherlands	4	0.45	0.69	2.99	0.69
Sweden	4	0.92	0.37	2.99	0.51
Cluster 4		*1.12*	*0.52*	*1.27*	*0.54*
Intra-cluster st.dev.		*0.74*	*0.11*	*1.34*	*0.16*