Trajectories for energy transition in the countries of the European Union over the period 2000-2015: a multidimensional approach

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Abstract

Environmental issues have become a major concern for policymakers faced with the threat of global warming. An ambitious plan “The European Climate Energy Package” drives trajectories of European countries in three directions: reducing greenhouse gas emissions (GHG), increasing the share of renewable energy and improving energy efficiency. Considering the three targets together and using multidimensional data analysis methods constitutes the originality of the article, the methodology used makes it possible to propose temporal and spatial typologies of the energy transition of European countries over the period 2000–2015. Results show evidence of a gradual transition over three sub-periods towards a more environmentally conscious economy. Results highlight the backwardness of the great Western European countries in achieving the goals assigned to them. Finally, discriminant analyses suggest that *policy mix design* and *innovation system* are the key drivers of the energy transition over the sub-period 2011–2015. However, they do not contribute to discriminate the contrasted performances between countries on the same sub-period.

1. Introduction

How to maintain a certain level of economic development while preserving environmental resources is a key question regarding sustainable development?[1] That is why policymakers since the 1990’s, faced with the threat of global warming, see reducing energy consumption, limiting the use of fossil fuels, and promoting the development of low-carbon energies as essential. This requires a radical technological transformation of the global energy system, and the rapid establishment of policies to encourage concerted and coordinated efforts to integrate global ecological concerns into local and national policies. At the Paris Climate Conference (COP21) in December 2015, 195 countries adopted the world’s first ever universal and legally binding climate agreement. The agreement sets a long-term goal of keeping global average temperature rise below 2°C above pre-industrial levels and pursuing efforts to limit it to 1.5°C. In fact, to reach this goal, each country is free to fix its own objectives and numerous countries have chosen efforts of reduction of greenhouse gas emissions with a reference level fixed at the year of the agreement (2015). The European Union has become the first region in the world to commit to much more ambitious goals. The adoption of the Climate Energy Package at the European Council of 12 December 2008 set out an action plan to enable the EU to achieve three objectives for the year 2020 that constitute, in this contribution, the three variables retained to measure the Energy Transition (ET) in Europe, over the period 2000-2015:

(i) reduce greenhouse gas emissions (GHG) by 20% compared to 1990 levels;

(ii) increase the share of renewable energy to 20%, and

(iii)reduce energy consumption by 20% by 2020 compared to projections. This latter objective is well known as the 20% energy efficiency target.[2]

This plan was reinforced in 2014 and in 2018 with the adoption of the EU 2030 Framework for Climate and Energy Policies, which sets even more ambitious targets, namely: (i) a reduction in greenhouse gas emissions of 40%, (ii) an increase in EU energy of renewable sources to 32%, and (iii) an indicative target of 32,5% energy efficiency. These objectives are binding at the European level.[3]

Beyond these three climate targets, the EU's energy policy has three main objectives jointly intended to reconcile sustainability, security of supply and competitiveness. The EU Energy Strategy aims to ensure a reliable energy supply for EU countries by (i) increasing EU energy security, (ii) reducing dependence on energy imports, and (iii) contributing to achieving a European Energy Union. New technologies and energy efficiency measures should create new industrial sectors, boost jobs, foster growth and make Europe more competitive. Europe's ambition is to be the worldwide leader in developing the technologies required to tackle climate change.

Although all countries in the European Union face the same energy and environmental challenges, the energy systems and their performances vary greatly from one country to another. They depend widely on the structural characteristics of countries such as national energy endowments, demographics, geography, climate, past national energy policies and historical development [1-4]. Taking into account national characteristics is therefore essential in order to understand the progress made and to achieve the objectives set by the EU for 2020 and 2030.

In this paper, we examine the trajectories of the ET in the 28 EU countries over the period 2000-2015. The approach adopted rests on a combined use of multidimensional evolutionary data analyses that take into account characteristics of countries in terms of the three variables related to the 2020 Climate Energy Package targets. These methods allow developing temporal and spatial typologies of the energy transition. This evolutionary analysis is especially designed to study individuals (i.e. countries) characterized by a number of groups of the same variable (i.e. the components) measured at each different moment in time.

The purpose of this article is twofold.

First, we propose descriptive analyses to better understand the performance of the 28 EU member countries in terms of energy transition over the period 2000-2015. We consider the dynamics of the energy transition pursued by the European Union and we establish a typology of the 28 EU member countries. Then we focus on the countries' trajectories over the period 2000-2015.

Second, our purpose is to explain and characterize synthetically the temporal and spatial heterogeneities of the EU in terms of energy transition. To this end, we use discriminant models to explore the links between typologies and a set of explanatory variables related to national techno-economic characteristics. In line with the literature cited above, we consider four explanatory themes: *economic performance*, *trade performance*, *policy mix design* and *innovation system*. For each theme, we select several representative variables. Understanding how these variables affect national performance towards sustainability can allow identifying the levers and obstacles to the energy transition; it is a major concern for policymakers.

To our knowledge, few studies to date have simultaneously considered the three targets of the energy transition as applied to all EU countries in a dynamic perspective. We can mention Costantini et al. (2020) [5] who used a multivariate framework to analyze energy efficiency in the residential sector of 19 EU countries. Our proposal is different and more exhaustive. The originality of the contribution also lies in the diversity of the thematic variables considered. It is also an important manner to see how a supranational institution like Europe is able to implement good policies and incentives among its members to achieve the challenge of Global Warming. In a sense, the European Union exemplifies the necessary cooperation that may drive all countries faced to this vital issue. Because European countries have highly specific characteristics, all the three different targets have been adapted to each case.

The paper is organized as follows. Section 2 focuses on national characteristics and main drivers of energy transition. The data and methodology are described in Section 3. Section 4 presents main results and related comments, while Section 5 summarizes our findings and provides policy recommendations.

Footnotes

[1] "Degrowth", which de facto reduces the environmental footprint, is not a viable solution because it increases social inequalities, as does current growth, but would, for the poorest countries, lead to an unbearable increase of absolute poverty.

[2] The EU has pledged to attain a primary energy consumption of no more than 1,483 million tonnes of oil equivalent (Mtoe) and a final energy consumption of no more than 1,086 Mtoe by 2020.

[3] The targets on carbon emissions and the share of renewable energy in energy consumption were translated into national targets, which depend on national wealth, on the starting situation of the different countries in terms of renewable energy production, and on the capacity to increase it.

2. National Characteristics And Drivers Of Energy Transition

The energy balance sheets of each EU Member State depend largely on their geographical location, energy policy, the structure of the energy system, the availability of energy resources for primary energy production, and the structure and development of the economy.

2.1 National characteristics

Fossil fuels continue to dominate the energy balance sheets largely because of a market failure that neglects the cost of their negative externalities [6-8]. In Malta, Cyprus, Luxembourg and Greece petroleum products account for more than half of domestic consumption. Natural gas has a share of over 30% in the Netherlands, Italy, United Kingdom and Hungary. Nuclear power is part of the domestic energy mix in 14 EU Member States, it is the major source of energy consumption in France, it accounted for more 40% in 2015. Nuclear source is also important in Sweden, Slovakia, Slovenia and Bulgaria. The most successful countries in terms of the development of RE are Sweden, Latvia, Finland and Austria, where RE covers more than 30% of the domestic energy consumption; on the other hand, RE accounts for less than 6% of energy consumption in the Netherlands and Malta.

Comprehensive studies on energy efficiency in EU countries are scare but agree on the existence of significant potential for energy savings varying substantially between countries [9, 10]. The EU has made substantial progress towards its energy efficiency objective. All but two Member States reduced primary energy consumption compared to 2005 by values ranging from 3.3% to 27.3%. In 2015, the EU consumed 10.7% less primary energy than in 2005. All the countries have improved their primary energy intensity in terms of GDP; this denotes a real effort in improving their efficiency notwithstanding the different structures of production.

Similar heterogeneity can be found in GHG emissions. Some countries have made significant efforts to reduce their GHG emissions, recording a reduction of at least -25% in ten years (Luxembourg, UK, Denmark, Malta, Italy, Spain and Sweden). Yet in 2015, there still remains a notable difference between the worst performing, i.e. Luxembourg, and the best performing, i.e. Sweden: Luxembourg in fact emitted 3.6 times more GHG per inhabitant. In more developed countries the contribution of nuclear power to electricity production has helped to reduce their GHG emissions (especially France, but also Belgium, Sweden, Finland, United Kingdom and Germany). Less developed countries like Bulgaria, Slovakia, Slovenia, Hungary have also developed their nuclear energy capacity, with the Czech Republic in particular having recently increased its share.

2.2 Drivers of energy transition

Let us now briefly survey the economic literature on the main drivers of energy transition according to four explanatory themes: economic performance, trade performance, policy mix design and innovation system.

Economic performance

An abundant literature [11-15] has established a positive link between economic growth and the use of renewable energy. Assuming that environmental quality is a normal good, the demand for environmental policies should increase with income. A higher income level means greater potential to bear high regulatory costs (which can result in both higher prices and higher taxes) and also more resources available to implement and promote sustainable environmental alternatives (and greater use of renewable energy). Several other arguments support this “optimistic” vision of growth [16, 17]:

(i) economic development and its corollary like the expansion of the tertiary sector reduce environmental impact;

(ii) the increase of the level of education and standard of living can lead to strong sensitivity to environmental concerns and changes in consumer behaviour;

((iii) and finally technical innovation and progress contribute actively to the development of clean-up techniques and the implementation of clean technologies support this “optimistic” vision of growth.

We therefore assume that national disparities in terms of economic performance and sectoral specialization can induce differentiated energy mixes and thus a contrasting development of renewable energy.

Trade performance

The pollution haven hypothesis [18] in case of carbon taxation, means the relocation of the production in the less environmentally responsible countries. It raises concerns about the effectiveness of regionally fragmented climate policies [19] (Arroyo-Currás et al. 2015). Under the assumption of the pollution haven hypothesis in case of carbon taxation, i.e. relocation of the production in the less environmentally responsible countries, the environmental policy leads to a loss of competitiveness and a deterioration of the terms of trade and moreover it is ineffective to mitigate climate change [18]. Similarly, an increase in the taxation of petroleum products in order to reduce fossil fuel consumption tends to reduce world oil prices and hence boost global demand and GHG emissions by non-virtuous countries. Furthermore, many countries show free-rider behaviours, causing others to bear the burden of climate change, which acts as a disincentive for them to mitigate their emissions. However, several authors have questioned this approach.

Porter [20] considered than well-designed environmental regulations can spur innovation by partially reducing or even fully offsetting the compliance costs associated with environmental regulations. Thus, a well-designed environmental policy can lead to a win-win result translating into productivity gains concomitant with environmental protection [20, 21]. Furthermore, according to the California effect [22], there is a positive virtuous cycle arising from the interactions between bilateral trade, environmental regulation and the diffusion of clean energy technologies: technology upgrading through trade integration and transfer along the value chain.

Policy mix design

Mitigating the effects of climate change requires urgent government actions to reduce carbon emissions. Voluntarist policies must be implemented to accompany the trajectories of the energy transition by promoting low-carbon technologies and increasing energy efficiency [6, 23, 24]. It is all the more important that subsidies for fossil fuels still exist [25, 26]. There are three main incentive mechanisms employed by governments to finance RE deployment: feed-in-tariffs, tax incentives, and tradable green certificates. The EU Emission Trading Scheme (ETS) was introduced in 2005 with the aim of addressing market failures by creating a market for GHG emission allowances, hence setting a price for carbon emissions reflecting the negative externalities associated with fossil-fuel-based electricity generation. To support the deployment of RE, a mix of different policy instruments was implemented by each member state, concerning regulatory policies, fiscal incentives as well as public financing [27]. For example, in the early 2000s most European Union countries set up a guaranteed purchase price mechanism aimed at promoting the development of renewable energy [28]. If feed-in tariffs and feed-in-premiums are the main support schemes for the deployment of renewable technologies in the EU electricity sector [29, 30], it has been increasingly recognised that a mix of policy instruments is needed to foster low-carbon transitions [31,32]. Furthermore, these instruments may change significantly over time and differ according to the country to address different national objectives and stages on innovation [33].

Innovation system

The transition from a fossil fuel economy to a sustainable, low-carbon economy requires the massive diffusion and deployment of low-carbon technologies. Fostering eco-innovation that is a key element of the transition by environmental regulation is therefore essential. However, an important peculiarity of eco-innovations is the double externality problem that reduces the incentive for firms to innovate [34]. Indeed, in addition to generating knowledge spillovers, eco-innovation also generates environmental spillovers. Usual free riders of knowledge externalities add benefit of environmental externalities in the adoption and diffusion phases of eco-innovation that prevent them to invest in eco-innovations. Finally, double externality problem leads to a reduction of the incentive to invest in eco-innovation because the private return on R&D in environmental technology is less than its social return. For Ghisetti and Rennings [35], on a survey data for German firms, energy efficiency innovations affect positively the firms' performance while innovations allowing the reduction of negative externalities (pollution: capture and storage of CO_2) have a negative impact on firm performance. Kruse [36] found a negative effect of green energy (efficiency and renewable energy) innovations on firms' performance.

These combined market failures underscore the need for environmental regulation. Many empirical studies have confirmed the key role of environmental regulation as a driver of eco-innovation [37-41]. It still rests difficult to redirect and accelerate technological change towards sustainability because it depends on the interactions of independent actors who have their own goals [42]. Moreover, relevant policies are difficult to implement. It is always a trade-off between flexibility and stability [43]. Flexibility because technological, social, or even geopolitical uncertainties need frequently to adapt environmental policies and stability because green entrepreneurship and venture capital must have at least a medium term visibility about the rules that are applied especially in terms of tariffs.

3. Data And Conceptual Framework

In this section, we describe the data. We present some summary statistics for the variables representing the three targets defined by the 2020 European Climate Energy Package. Then, we consider two types of additional variables. The first aims to provide additional information on national specificities in order to enrich the typologie of the 28 EU countries. The second concerns thematic variables likely to explain different profiles concerning the energy transition.

3.1 The three energy transition targets

Our proposal aims to establish the trajectories of the EU and its 28 countries with respect to the three energy transition objectives. We consider three comparable variables across countries, described in Table A1 in appendix, namely the Greenhouse Gas Emissions (GHGE), Primary Energy Intensity (PEI)[4], and the Share of Renewable Energy Consumption (SREC). These three active variables will hereafter be called the *three components of the energy transition* (ET). We use annual data extracted from Eurostat databases over the period 2000-2015.

To get an overview of the differences between the 28 EU countries, in Table 1 we present some summary descriptive statistics computed from the national averages of the three ET components of the EU over the period 2000-2015. There is indeed a quasi-linear evolution of the three components: SREC is increasing, while PEI and per capita GHGE are decreasing.

We observe strong variability in the variables related to the ET, revealing a strong heterogeneity between the 28 EU countries. The GHGE ranges from 5.369 tons of CO_2 equivalent per capita in Latvia to 26.162 tons of CO_2 equivalent per capita in Luxembourg. The PEI peaks at 0.541 tons of oil equivalent per thousand euros of GDP at 2010 market prices in Bulgaria against only 0.079 in Denmark. The SREC varies from 1.382% of the final consumption in Malta to 43.42% in Sweden. What is more, these variables also exhibit relatively high coefficients of variation, confirming the heterogeneity in ET performance across the 28 EU member countries. This suggests that there are various processes involved in implementing the energy transition in Europe.

3.2 Supplementary variables

We use a wide set of variables relevant to describe national characteristics in terms of energy balance sheets. Most of the data were expressed as a percentage of GDP or per capita, so as to be directly comparable across the 28 member countries. The others are expressed as percentages. These variables, described in Table A1 in appendix, provides additional information, which will help us to consolidate and enrich the interpretation of the classes of countries, so have been positioned as supplementary variables in the multidimensional analysis. They do not affect the calculations based upon the three active variables (the three components of the ET): they are not used to determine the principal component factors, but are positioned *a posteriori* in order to assess their degree of similarity with the active variables. In addition, it seems relevant to evaluate states' performance in relation to the objectives assigned to them.

To assess the progress made as regards the ET, we use variables representing deviations from the national targets set by the Climate Energy Package for 2020. We thus consider the three targets: greenhouse gas emissions measured in tonnes of CO2 equivalents, share of renewable energy in final energy consumption, and primary energy consumption. The first two targets were translated into national targets, which depend on national wealth, the starting situation of the different countries in terms of renewable energy production, and the capacity to increase it. The last target requires reducing primary energy consumption (PEC) by 20% by 2020 compared to projections. In order to compare country performance, we calculated distances to target for each ET components and expressed them as a percentage[5]. From these distance variables, we also built three qualitative variables, indicating whether the national objectives have been achieved.

3.3. Explanatory variables for data mining predictive methods

To explain and characterize synthetically the temporal and spatial heterogeneities of the EU in terms of energy transition, we can use different predictive techniques, discriminant analysis model [44, 45] or multinomial logistic or probit regression models [46]. In order to do that, we consider four explanatory themes: *economic performance*, *trade performance*, *policy mix design* and *innovation system*. For each theme, we selected several representative variables described in Table A2 in the appendix. To choose these variables, we have relied on the empirical literature cited in the previous section, but our choices are largely conditioned by data availability and resource constraints.

Figure 1 gives a conceptual framework overview of empirical approach. First, multidimensional analyses are used to build temporal and spatial typologies of the 28 EU countries relative to the three components of the

ET. Second, explanatory models, namely discriminant analyses, are used to identify the drivers of the ET accordingly to four explanatory themes. These themes are assumed to represent national characteristics.

Footnotes

[4] We chose a criteria of energy efficiency rather than the primary energy consumption in order to be able to compare the national performances.

[5] For example, the distance between the component X_t at year t and its 2020 target X_{2020}, is calculated by the formula: $[(X_t - X_{2020}) / X_{2020}] * 100$, where t = 2011, … , 2015, the five period years studied for the targets.

4. Empirical Results

We first present a temporal analysis of the ET of the EU over the period 2000-2015, and then propose a typology of the 28 member countries in relation to the three components of the ET. The additional variables described in the previous subsection will be used to enrich the description of the homogenous classes of EU countries.

4.1 Trajectory of the EU-28 energy transition

A methodological sequence of two data analysis methods [47, 48, 45] was used to group the sixteen years into homogeneous classes according to the ET components of the EU. More precisely, Hierarchical Ascendant Clustering (HAC) was used on the significant factors of the Principal Component Analysis (PCA) of annual components of the ET development.

The first two axes of dispersion of factors as revealed by the PCA form the first factorial plane, which summarizes more than 99.76% of the information regarding the evolution of the ET components of the EU over the period 2000-2015. Figure 2 illustrates representations of the components of the energy transition and years projected into the first factorial plane.

The first factorial axis opposes the early period 2000-2006, characterized by high PEI and GHGE, with the later period 2011-2015, characterized by a high SREC. Figure 2 shows the grouping of the closest years according to the first component: these groups are materialized by geometric shapes. Years with the same shape have common energy transition characteristics.

Using an HAC with the Ward criterion[6] allows us to distinguish three homogeneous sub-periods. Table 2 summarizes the main results and profiles of the EU energy transition over the three sub-periods selected from the cut in the three classes of the hierarchical tree.

The first period, comprising the six first years, 2000-2006, is characterized by high PEI, high GHGE, and low SREC.

The second class, which groups together the four succeeding years of the middle period, 2007-2010, is considered as a homogeneous class, which means that none of the three ET components on this sub-period differs significantly from the average of these components over the overall period. It can be considered as an adaptation phase, concomitant with the adoption of the climate energy package in 2008.

The ET characteristics of the last class, constituted by the last five years of the period, are opposed to those of the first class. This third class is characterised by a high share of RE in final consumption, lower energy intensity and lower GHG emissions per capita.

4.2 Energy transition of the 28 EU member countries

To better analyse and understand the evolution of the development of the ET of the 28 EU countries, we carried out an evolutionary data analysis on the three sub-periods.

The approach adopted relies on a combined use of exploratory methods of evolutionary data analysis that take into account the characteristics of the countries in terms of GHGE, PEI and SREC, as well as their evolution over each sub-period. According to the similarity of these three components, we can establish a typology of the 28 EU countries. The evolution of the countries is thus studied by a Multiple Factor Analysis (MFA), based on a weighted analysis of the principal components of all the data. The MFA [49-51] allows the simultaneous exploration of several multidimensional data tables, and it applies more particularly to time series data.

This evolutionary analysis is especially designed to study individuals (i.e. countries) characterized by a number of groups of the same variable (i.e. the components) measured at each different moment in time. The MFA highlights the common structure of a set of groups of ET components observed for the same 28 countries. The primary interest of this method is that it enables us to carry out a factor analysis in which the influence of the different groups of ET components is *a priori* equilibrated. An HAC was then used on the significant factors of the MFA in order to characterize homogeneous classes of countries relative to the evolution of the three ET components.

Table 3 summarizes the results of the three partitions of the EU-28 countries into four homogeneous classes as carried out over the three sub-periods, and provides the characterization of the classes[7].

Note first that even though the temporal evolution of the EU's ET development identified three homogeneous sub-periods with distinct profiles, the three evolutionary analyses of the 28 EU countries show a certain stability in country trajectories, with all typologies having four homogeneous classes and almost identical profiles and anti-profiles. With the exception of Slovenia, Denmark and Lithuania, which had different paths in terms of ET development, the other 25 countries had an almost identical course throughout the period 2000-2015.

The first class includes six countries over the entire period, namely Austria, Croatia, Finland, Latvia, Portugal and Sweden, and is also made up of Slovenia in the first sub-period, while Denmark and Lithuania join the class in the sub-period 2011-2015. A high share of RE in final energy consumption over the three sub-periods and low GHG emissions per capita over the 2000-2006 and 2011-2015 sub-period characterize the first class. This class gathers the most successful countries in terms of the ET. This class can be called the **virtuous class** for ET.

The energy balance sheets of countries in this class are characterized by significantly high shares of renewable energy and waste (non-renewable) and a small share of fossil and solid fuels in domestic energy consumption. Electricity generation from hydropower and renewable sources is rather high which contributes to a low level of GHGE. The share of solar photovoltaic in gross inland RE consumption is rather low.

In each year of the 2011-2015 period, distance to RE share target that is above the EU average, means that these countries have made greater efforts to meet or exceed their objectives and achieved their SREC target in 2012, 2014 and 2015. These eight countries were efficient throughout the 2011-2015 period in terms of reducing PEC, and achieved their PEC goal in 2012. With regard to the other two objectives, their performance is quite similar to the European average, with the exception of the year 2012 for which the PEC goal was reached.

The second class contains seven countries over the entire period 2000-2015: Romania, Slovakia, Poland, Hungary, Estonia, Czech Republic, Bulgaria. Lithuania also belongs to this class in the first two sub-periods only, while Slovenia joins in the sub-period 2011-2015. The characterization of the second class is stable over the three sub-periods. These countries have a PEI significantly higher than the average of the 28 EU countries. The other two components are no different from the EU averages. It is terms the **low energy efficiency class**. These are countries of the ancient eastern bloc, which still suffer from entrenched specialization in heavy industries driven by central planners. This results in a high level of PEI, i.e. a low efficacy in producing one unit of GDP.

This low energy efficiency comes also from the lower access to clean fuels and technologies for cooking. Having highly developed coal and nuclear energy sources, these countries are less dependent on energy imports. Indeed, the share of solid fuels in gross domestic consumption is significantly higher than the EU average. Coal and nuclear sources make a significant contribution to electricity production while the shares of natural gas and renewable (total and excluding hydroelectric) sources in electric power are rather low. The biomass and renewable waste sector provided an important share of RE consumption from 2011 to 2013, while the share of wind power lags behind the average of the EU countries.

Throughout the period, countries belonging to this class present a distance to their GHGE targets that is lower than the European average and made greater efforts to meet their RE consumption objectives in 2011. These countries, mainly developing countries, have made significant efforts to control their GHGs. Note that the targets assigned to them vary from + 4% for Slovenia to + 20% for Bulgaria. Countries in this class have generally achieved their GHG objectives in 2011 and 2012.

The third class contains eleven countries over all three sub-periods: Malta, Italy, Spain, France, Ireland, Greece, Germany, Cyprus, Belgium, United Kingdom and Netherlands. Denmark is also attached to this class in the first two sub-periods, while Slovenia is in it for the intermediate sub-period (2007-2010). The characterization of the class is stable over the period 2000-2015. This class gathers countries whose PEI and SREC are significantly below the respective averages of all the EU-28. We establish that the EU-28, projected *a posteriori* in each periodic analysis, is assigned to class 3 whatever the sub-period, meaning that the EU-28 has characteristics similar to those of class 3 with respect to the three components of the ET. We term it the **energy efficient class lagging behind in RE development**. These countries are diverse, gathering developed countries, which are relatively efficient in terms of production but not very aware and/or attentive to environmental concerns, and less developed countries (Malta, Greece and Cyprus) where the low PEI can be attributed to low industrialization.

These countries are the most energy efficient, but are also the most dependent on energy imports. They are highly dependent on fossil fuels, and in particular oil. Fossil fuel energy consumption and share of fossil fuel and oil (crude oil and petroleum products) in gross inland consumption are significantly higher than the average of the EU-28. Electricity production from fossil sources remains very high over the period 2011-2015, being mainly dependent on oil and gas sources. The shares of RE and hydroelectric in power generation are below the average for the EU-28. Compared to the EU average, the SREC is rather low in this class, this being explicable by the massive use of fossil fuels. However, this class is the leader in the development of new renewable sources: the shares of wind power, solar thermic and solar photovoltaic energy in the domestic consumption of RE are significantly higher than the European Union averages. On the other hand, biomass and renewable waste are less prominent in the RE energy mix.

In this class, the distances to targets are higher than the European averages for the three targets of the ET, reflecting insufficient efforts to achieve the objectives. In addition, we see that these countries never achieve their PEC objectives during the whole period and have not achieved their RE consumption objectives since 2012.

The fourth class consists solely of Luxembourg over the three sub-periods. Notably, Luxembourg is isolated in all the three sub-periods, differing from other EU countries over the three periods by having a significantly higher GHGE per capita than those of the EU over all three sub-periods, and a lower SREC from 2007. We name it the **non-virtuous class** as regards the energy transition. Contrary to results widely established in the literature (see supra), the positive link between economic growth and the use of renewable energy does not prevail in Luxembourg.

Since 2013, Luxembourg has been highly dependent on energy imports. Its characteristics are those of a rich country with both primary and final energy and electricity consumption per capita significantly higher than those of the EU population on average. The share of crude oil and petroleum products in gross domestic consumption has been high since 2013, and natural gas is widely used in electricity production. Note that Luxembourg is a small and densely populated country, with a high density of road freight and many “cross-border workers”, which contributes to its GHGE. In particular, fuel sales to non-residents have increased significantly, by 165% between 2000 and 2013.

Finally, Luxembourg, which seemed to be “the least virtuous” country, is still at the level of the European average in terms of distances to the objectives that have been set for it. This clearly indicates that, despite an unfavourable situation, Luxembourg has made considerable efforts to reach its objectives, albeit insufficient to achieve its three targets for 2020. It should be emphasized that over the whole period 2011-2015, Luxembourg has met its PEC objective.

The results we have revealed are not in line with the ambitions and commitments of the EU. Although progress has been made, we note that the EU Member States' performances fluctuate greatly from one year to the next, and that no major trend toward achieving the SREC and PEC goals is emerging. In particular, the large western countries in Class 3 are significantly behind in achieving their objectives, notably Belgium, France, Germany, the Netherlands and the United Kingdom, as well as Ireland with regard to the development of renewables and the reduction of primary energy consumption. Germany, Ireland and the Netherlands are also lagging behind in reducing GHG emissions.

4.3 Discriminating effects of themes on the trajectories of the energy transition of the 28 EU countries

As predictive model, we choose here Discriminant Analysis (DA) which is a modeling method of decision-making. DA is a multidimensional method; it allows one to highlight the links existing between a target qualitative variable which can help explain, in this case, the variable synthesis of energy transition into several modalities corresponding to the previously discussed classes (three classes for the temporal analysis and four for the spatial analysis) and a set of continuous explanatory variables relating to a homogeneous theme. Four explanatory themes were considered: *economic performance*, *trade performance*, *policy mix design* and *innovation system*.

The DA method is a special PCA; it produces discriminant factors which are linear combinations of the explanatory variables and establishes graphical representations on discriminant factorial planes making it possible to distinguish the classes, and then explain their respective positions[8].

It has two main objectives: the first is descriptive and consists in determining which of the explanatory variables are discriminating. The second objective is predictive or decision-making and is concerned with classifying new anonymous explanatory data in these known classes using the discriminant linear functions established previously. Our goal is a search to identify themes -homogeneous sets of explanatory variables -, which discriminate between the classes presented in sections 4.1 and 4.2.

4.3.1 Discriminant effect on the temporal typology

Table 4 below summarizes the main results of the four models of DA[9] according to each theme. For each theme, the explanatory variables that discriminate between and separate each of the energy transition sub-periods characterized by the HAC are mentioned.

All these models are globally significant. Indeed, for each model, the critical probability or p-value Pr> F of the Wilks'Lambda statistic is less than the significance level of 1%[10]. We can therefore conclude that *economic* and *trade performance,* policy *mix design* and *innovation system* themes have a significant effect on the three sub-periods of the EU energy transition.

Thus, among the three explanatory variables of the *economic performance* theme, only the GDP growth rate is not discriminating. The other two variables perfectly differentiate the three sub-periods of the energy transition of the 28 EU countries.

The first significant discriminating factor restates 81.38% of the discriminating power of the model. It separates and opposes the third period 2011-2015 characterized by a high unemployment rate and GDP per capita to the first period 2000-2006. As for the second discriminating factor (18.62%), it distinguishes the third period 2011-2015 characterized by a high unemployment rate, which opposes the second period 2007-2010[11].

Our results suggest that during the second period coinciding with the economic and financial crisis, the economic performance of the 28 EU countries did not have a significant impact on environmental performance. More generally, we find:

1) The *economic performance*'s model shows that the GDP growth rate of the EU28 over the period 2000-2015 does not induce significant effects on the trajectory for energy transition in the 28 EU countries. There seems to be a decoupling between economic growth and environmental performance measured from the three targets. The two other variables perfectly differentiate the three sub-period of the ET of the 28 EY countries.

2) Concerning the *trade performance*'s model, only the energy dependence is not discriminating. EU energy dependence has slightly increased over the period from 54.8 in 2000 to 56.1 in 2015. However, its evolution has not had any significant effects on the trajectories for energy transition in the 28 EU countries. On the other hand, the improvement in energy terms of trade over the 2011-2015 period, probably related to the development of RE, led to better environmental performance.

3) Regarding the model of discrimination according to the *policy mix design*, all the variables of this theme are discriminating. The first discriminating factor (90.74%) opposes the first period 2000-2006 characterized by a high rate of environmental taxes, to the third period 2011-2015, which is distinguished by a high rate of public research and development expenditure. The second discriminating factor (9.26%) separates the third period 2011-2015 characterized by high-energy taxes and environmental taxes and opposes it to the second period 2007-2010. These results show the effectiveness of the public policies adopted at European level to meet the 2020 climate targets; the energy taxes and public expenditure in R&D have strongly contributed to improve environmental performance over the period 2011-2015.

4) As for the three variables introduced into the *innovation system*'s model, all are discriminating and well separating the three periods. The discriminating factor (84.12%) opposes the third period 2011-2015 characterized by a high number of environmental, a high share of environmental technology patents and high R&D expenditure, to the first period 2000-2006. The preoccupation of global warning has oriented research and development towards environmental issues. The evolution of the innovation system is a significant driver of the European energy transition.

4.3.2 Discriminant effect on the spatial typology over the period 2011-2015

As we showed in section 4.1, the energy transition is on track for the 2011-2015 period that is why we focus our research on the drivers of the EU energy transition on this sub-period. We use DA[12] models to see how each of the four thematic makes it possible to distinguish different classes of EU countries grouped according to their energy transition performance. Table 5 presents the overall results of the discriminant analysis models for each theme. Note that only two models, *economic* and *trade performance* are significant and therefore discriminating. Indeed, the Wilks Lambda of these two models are less than the significance level of 5%. In contrary the *innovation system* and *policy mix design* have no effect on the energy transition development of the EU countries over the 2011-2015 sub-period.

Thus, for the 2011-2015 sub-period, among the three explanatory variables of the *economic performance* theme, GDP growth and unemployment rates are not discriminating. The first discriminating factor (72.61%) is statistically significant and opposes Luxembourg (class 4, non-virtuous class as regards the energy transition), characterized by a high GDP per capita, to the low energy efficiency class (class 2 grouping Eastern and Central European countries). So, national disparities in terms of standard of living induce contrasted environmental performances. This finding contradicts the results of [53, 16, 17], since we show that a high level of development does not necessarily lead to virtuous growth. Nevertheless, it should be noted that Luxembourg is a major transport node and has the highest road freight density in Europe. The share of CO_2 emissions from transport in total fuel consumption is the highest in Europe; it reached 66.8 % in 2015 compared to 31.1% for the European average. Furthermore, Luxembourg is also a small country with low relief, which considerably limits the development of RE.

In the *trade performance* model, only the energy dependence variable is discriminant with a significance level less than 5%. The first factor (75.24%) is significant and therefore discriminating. It opposes Luxembourg characterized by a high rate of energy dependence to class 2. Luxembourg has no domestic energy resource and is highly dependent on its energy imports, mainly oil and gas. On the other hand, the Central and Eastern European countries have developed national energy production based on coal and nuclear energy sources, so they are less dependent on energy imports.

DA models highlight that temporal and spatial determinants of the energy transition with respect to the three targets defined by the 2020 European Climate Energy Package differ. Indeed, while the four themes selected make it possible to discriminate the trajectory of the energy transition of the European Union over the period 2000-2015, only the themes relating to the economic and commercial performances explain the contrasted environmental performances of the countries over the period 2011-2015. More specifically, only two variables, namely GDP per capita and energy dependence are discriminant. *Policy mix design* and *innovation system* do not contribute to discriminate the four classes of the typology. Our findings provide strong evidence that *policy mix design* and *innovation system* have been particularly effective in promoting sustainable development in the last sub-period, but national differences regarding these two themes do not explain the contrasting results observed at the country level.

Footnotes

[6] Generalised Ward's Criteria, i.e. aggregation based on the criterion of the loss of minimal inertia.

[7] In order not to overload the article, we do not present the results related to illustrative variables but they are available on request.

[8] The DA is based on the normality of populations. The discriminant functions are linear if the matrices of variances and co-variances of these populations are equal; otherwise they are quadratic. All these conditions of application have been checked.

[9] The DA is based on the normality of populations. The discriminant functions are linear if the matrices of variances and co-variances of these populations are equal; otherwise they are quadratic. All these conditions of application have been checked.

[10] The value of Wilks' lambda varies between 0 and 1, the more it tends to 0, the best is the discrimination model (the class centers are well separated). A probability distribution of Fisher approximates the Wilks test statistic.

[11] Nevertheless, unemployment rates evolution is very different among European countries during the 2007-2017 period [52]. If Slovakia was at the top of the list of the highest unemployed countries before the crisis, it ranks eleventh in ten years. On the other hand, it is mainly the countries of Mediterranean Europe such as Greece, Spain, Cyprus or Italy, which are at the top of the ranking of the countries most affected by unemployment ten years later –France, is at the sixth positon-. Conversely, Germany (-56%), which has had its lowest unemployment rate since reunification at 5.7%, Hungary (-49%) and Poland are the three states to have known the biggest decline.

[12]DA is based on normality of the variables in the populations. The discriminant functions are linear if the matrices of variances and covariances of the variables are equal, otherwise they are quadratic. All these application conditions have been verified except for class 4.

5. Conclusion And Policy Implications

Over the past 25 years, Europeans have believed that their commitment to reducing GHG emissions would serve as a template for the rest of the world. We can notice the success of the European environmental policy, which is moving towards achieving the objectives set for 2020. Results show evidence of a gradual transition over three sub-periods towards a more environmentally conscious economy: reducing greenhouse gas emissions, developing renewable energy sources and improving energy efficiency. We identified four distinct types of energy transition profiles over the three sub-periods, and point out a stability in EU28 member country trajectories with a few exceptions.

Yet the performance of the EU Member States varies considerably from one year to the next. Major Western European countries, namely Belgium, France, Germany, the United Kingdom, Netherlands and Ireland, are lagging behind in achieving their goals for developing renewable energy and reducing primary energy consumption.

The high rate of public R&D expenditure combined with high energy and environmental taxes has strongly contributed to improving the EU28’s environmental performance over the period 2011-2015. However, *policy mix design* and *innovation systems* do not contribute to discriminate the contrasted performances between countries on the same sub-period.

While it is indisputable that European environmental policy has led countries to make efforts in the right direction, we find that in many countries the results are starkly insufficient compared to the objectives set. What is more, in 2015 European countries appeared to begin to disengage from the process. The most recent data show that CO_2 emissions from fossil fuel combustion have been increasing since 2015 [54, 55]. Questions may therefore be raised regarding the motivations of States to implement the measures necessary to fight against climate change. The looseness of effort of the biggest polluters, namely Canada, Australia and the United States could partially explain the European disengagement: Europe, as virtuous as it is, cannot fight against climate change alone.

From our results, three policy recommendations can be made to promote the energy transition and strengthen Europe's leading position.

First, investing in research and innovation must be the EU's priority to fight against global warming. Europe must take advantage of the disengagement of the US to outperform its competitors in clean energy innovation. The EU needs to invest massively in renewables to reduce their cost and ensure a wide diffusion. At the same time, investments in improving energy efficiency need to be boosted as they are the most cost-effective way to achieve the EU's climate goals.

Second, there is the need of active public policies that make possible to meet climate change commitments. Therefore, mobilizing investment in low-carbon technologies, especially in renewable energy production, is essential. Our findings suggest that both support for investment, research and development, and the introduction of energy and environmental taxes have been the drivers of the energy transition. EU must pursue its efforts to ensure its leadership in green technologies, but must prevent negative impacts of its environmental policy, both on firm's competitiveness and on the energy vulnerability of low-income households.

Third, mobilizing investment from the private sector will be essential to meet climate change goals. The European Commission presented in December 2019 a new Green Deal for Europe, which aims for carbon neutrality by 2050[13]. Governments have to find ways to make efficient use of available public funding to mobilise much larger private capital. Funding and public support mechanisms must set on a sustainable path in order to provide a clear and understandable framework that promotes green investments. Green finance is today considered as a major leverage to support the European Green Deal and guide private investment to the transition to a climate neutral economy. According to Berrou [56] green securities are still "a drop in ocean" regarding the huge need of fundings -around 550 billion of dollars are necessary each year in Europe to achieve a net-zero greenhouse gas economy at the 2050 horizon-.

In a context of massive indebtedness of states and high degree of uncertainty on energy prices induced by the Covid-19, the development of the energy transition and renewable energies may be threatened in the short term. Indeed, the drop in the price of oil, coal and natural gas induced by Covid-19 may favor the use of fossil sources. On the other hand, the Covid-19 crisis has highlighted the need to relocate production systems, which could accelerate the decentralization of the national energy systems, and therefore promote the development of local renewable energies.

In any event, climate change urgently requires a profound transformation of the European carbon pricing system, both emission allowances[14] and taxes related to CO_2 emissions. In the case of unilateral policy, such as the European environmental policy, a tax or quota system undermines the competitiveness of targeted companies. For companies able to relocate their production, this leads to a carbon and jobs leakage towards countries less environmentally responsible. It seems far more efficient to introduce a tax on products, which would be proportional to the carbon footprint. Nordhaus [57] establishes that a regime with small trade penalties on non-participants, what we may call a Climate Club, can induce a large stable coalition with high levels of GHG abatements. Springmann et al. [58] show that there is substantial global climate change mitigation potential for emissions pricing for food commodities. Consequently, in the absence of a binding global agreement, European commitments will fail to be honoured without taxing imported products or imposing trade sanctions on participants who do not comply with European environmental standards. It is why EU is on the way to introduce a tax on products. Yet, challenges are high, some branches of industry may choose to relocate because of the loss in competitiveness, some countries may apply retaliatory measures in the frame of World Organization of Commerce. In a global context dominated by the proliferation of trade disputes between the United States and China, Europe must give its voice by imposing a simple rule: given the climate emergency, it is now necessary to subordinate the freedom of the trade to binding climatic standards. A first step has just been taken, on March 10, 2021, the European Parliament approved by an overwhelming majority the creation of a carbon tax at the border aimed at protecting EU companies against imports from countries with less stringent standards climate policies.

Footnotes

[13] According to the European Commission, to achieve carbon neutrality, Europe must make an investment effort in its energy system in the range of 175 to 290 billion euros per year.
[14] Note that the functioning of the European Emissions Trading Scheme (EU ETS), a pillar of the EU's climate change policy, is not satisfactory. The EU ETS has for years been characterized by endemic over-allocation, while the high volatility of the price of CO_2 does not provide enough visibility for companies to invest in energy efficiency. From this point of view, a fixed tax defined via a multi-year plan would be more effective. After an increase of GHG of 1,7% in 2017, Europe has nevertheless recorded a good result in 2018 with a decrease of 2,5% of its emissions

Declarations

Authors' Contributions:

Patricia Renou-Maissant: Conceptualization, data preparation, validation, the writing, review and editing, and project administration.

Rafik Abdesselam: data preparation and cleaning, methodology, formal analysis, the writing.

Jean Bonnet: Conceptualization, data preparation, the writing, review and editing.

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Tables

Table 1: Summary statistics of the three ET components of the EU-28 countries

Variables	Frequency	Mean	Minimum	Maximum	Standard deviation	Coefficient of Variation (%)
GHGE[a]	28	10.644	5.369	26.162	4.149	38.98
PEI[b]	28	0.192	0.079	0.541	0.105	54.69
SREC [c]	28	14.930	1.382	43.420	11.087	74.26

[a] Tons of CO_2 equivalent per capita

[b] Tons of Oil equivalent per unit of GDP

[c] Percentage of final total energy consumption

Table 2: Summary of EU energy transition profiles by sub-period

	Beginning of period	Mid-period	End of period
Duration	7 years	4 years	5 years
Years	2000 to 2006	2007 to 2010	2011 to 2015
Profile	+ PEI + GHGE	homogeneous profile	+ SREC
Anti-Profile	- SREC		- PEI - GHGE

Table 3: Energy transition trajectories of the 28 EU members over the three sub-periods

		Beginning of period 2000 - 2006		Sub-period 2007 - 2010		End of period 2011 - 2015
	+ GHGE + PEI - SREC	EU-28		EU-28	+ SREC - GHGE - PEI	EU-28
Class 1	+ SREC 00 to 06 - GHGE 00	Austria Croatia Finland Latvia Portugal Sweden Slovenia	+ SREC 07 to 10	Austria Croatia Finland Latvia Portugal Sweden	+ SREC 11 to 15 - GHGE 12,14,15	Austria Croatia Finland Latvia Portugal Sweden Denmark Lithuania
Class 2	+ PEI 00 to 06	Romania Slovakia Poland Hungary Estonia Czech Republic Bulgaria Lithuania	+ PEI 07 to 10	Romania Slovakia Poland Hungary Estonia Czech Republic Bulgaria Lithuania	+ PEI 11 to 15	Romania Slovakia Poland Hungary Estonia Czech Republic Bulgaria Slovenia
Class 3	- PEI 00 to 06 - SREC 00 to 06	Malta Italy Spain France Ireland Greece Germany Cyprus United Kingdom Netherlands Belgium Denmark *EU-28	- PEI 07 to 10 - SREC 07 to 10	Malta Italy Spain France Ireland Greece Germany Cyprus United Kingdom Netherlands Belgium Denmark Slovenia *EU-28	- PEI 11 to 15 - SREC 11 to 15	Malta Italy Spain France Ireland Greece Germany Cyprus United Kingdom Netherlands Belgium *EU-28
Class 4	+ GHGE 00 to 06	Luxembourg	+ GHGE 07 to 10 - SREC 07 to 10	Luxembourg	+ GHGE 11 to 15 - SREC 11 to 15	Luxembourg

Table 4: Temporal discriminant analyzes according to the four themes

Economic performance			
Complete model: 3 explanatory variables Multivariate Statistics and Approximations F			
Statistic	**Value**	**F Value**	**Pr > F**
Wilks' Lambda	0.3786	10.67	**0.0018****
Variable	**R-Square**	**F-Value**	**Pr > F**
GDP	0.6214	10.67	**0.0018****
GDPGR	0.3186	3.04	0.0826
UN	0.5565	8.15	**0.0051****
Misclassification rate[1]: 0%			

Policy mix design			
Complete model: 3 explanatory variables Multivariate Statistics and Approximations F			
Statistic	**Value**	**F Value**	**Pr > F**
Wilks' Lambda	0.0549	11.98	**<.0001****
Variable	**R-Square**	**F-Value**	**Pr > F**
ENT	0.4963	6.40	**0.0116***
ENVT	0.5793	8.95	**0.0036****
PR&D	0.8816	48.42	**<.0001****
Misclassification rate: 0%			

Trade performance			
Complete model: 4 explanatory variables Multivariate Statistics and Approximations F			
Statistic	**Value**	**F Value**	**Pr > F**
Wilks' Lambda	0.0633	7.43	**0.0001****
Variable	**R-Square**	**F-Value**	**Pr > F**
EDEP	0.2260	1.90	0.1891
TRADE	0.7124	16.10	**0.0003****
ETRADE	0.6744	13.46	**0.0007****
HTEX	0.7993	25.88	**<.0001****
Misclassification rate: 0%			

Innovation system			
Complete model: 4 explanatory variables Multivariate Statistics and Approximations F			
Statistic	**Value**	**F Value**	**Pr > F**
Wilks' Lambda	0.0322	16.77	**<.0001****
Variable	**R-Square**	**F-Value**	**Pr > F**
PAT	0.8131	28.29	**<.0001****
SPAT	0.8067	27.12	**<.0001****
R&D	0.9034	60.80	**<.0001****
Misclassification rate: 0%			

Significance level a ; **a £ 1% ; *a Î]1% ; 5%]

[1] The misclassification rate is given to judge the predictive quality of the model.

Table 5: Spatial discriminant analyzes according to the four themes over the sub-period 2011-2015

Economic performance 2011-2015			
Complete model: 3 explanatory variables Multivariate Statistics and Approximations F			
Statistic	**Value**	**F Value**	**Pr > F**
Wilks' Lambda	0.2483	4.61	**0.0002****
Variable	**R-Square**	**F-Value**	**Pr > F**
GDP	0.6609	15.59	**<.0001****
GDPGR	0.0532	0.45	0.7200
UN	0.0770	0.67	0.5801
Misclassification rate: 28.57%			

Policy mix design 2011-2015			
Complete model: 3 explanatory variables Multivariate Statistics and Approximations F			
Statistic	**Value**	**F Value**	**Pr > F**
Wilks' Lambda	0.8210	1.74	0.1848
Variable	**R-Square**	**F-Value**	**Pr > F**
ENT	0.0938	0.83	0.4917
ENVT	0.0356	0.30	0.8282
PR&D	0.1790	1.74	0.1848
Misclassification rate: - %			

Trade performance 2011-2015			
Complete model: 4 explanatory variables Multivariate Statistics and Approximations F			
Statistic	**Value**	**F Value**	**Pr > F**
Wilks' Lambda	0.3811	2.05	**0.0364***
Variable	**R-Square**	**F-Value**	**Pr > F**
EDEP	0.4029	5.40	**0.0055****
TRADE	0.0452	0.38	0.7692
ETRADE	0.2081	2.10	0.1264
HTEX	0.2391	2.51	0.0825
Misclassification rate: 32.14%			

Innovation system 2011-2015			
Complete model: 4 explanatory variables Multivariate Statistics and Approximations F			
Statistic	**Value**	**F Value**	**Pr > F**
Wilks' Lambda	0.5472	1.19	0.3120
Variable	**R-Square**	**F-Value**	**Pr > F**
PAT	0.1843	1.81	0.1727
SPAT	0.0888	0.78	0.5171
EPBI	0.0835	0.73	0.5448
R&D	0.1108	1.00	0.4112
Misclassification rate: - %			

Significance level a ; **a £ 1% ; *a Î]1% ; 5%]

Figures

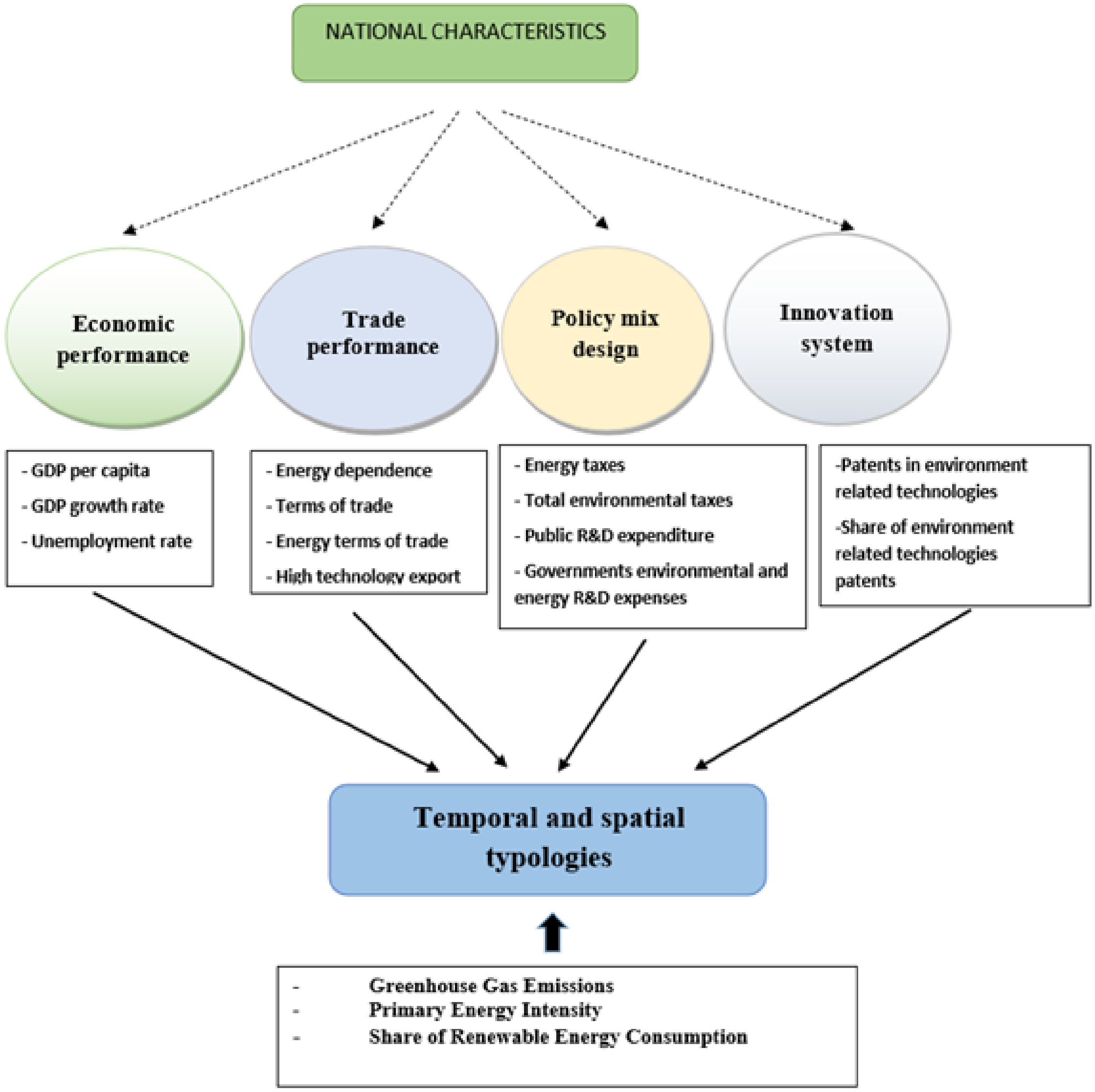

Figure 1

Methodology overview

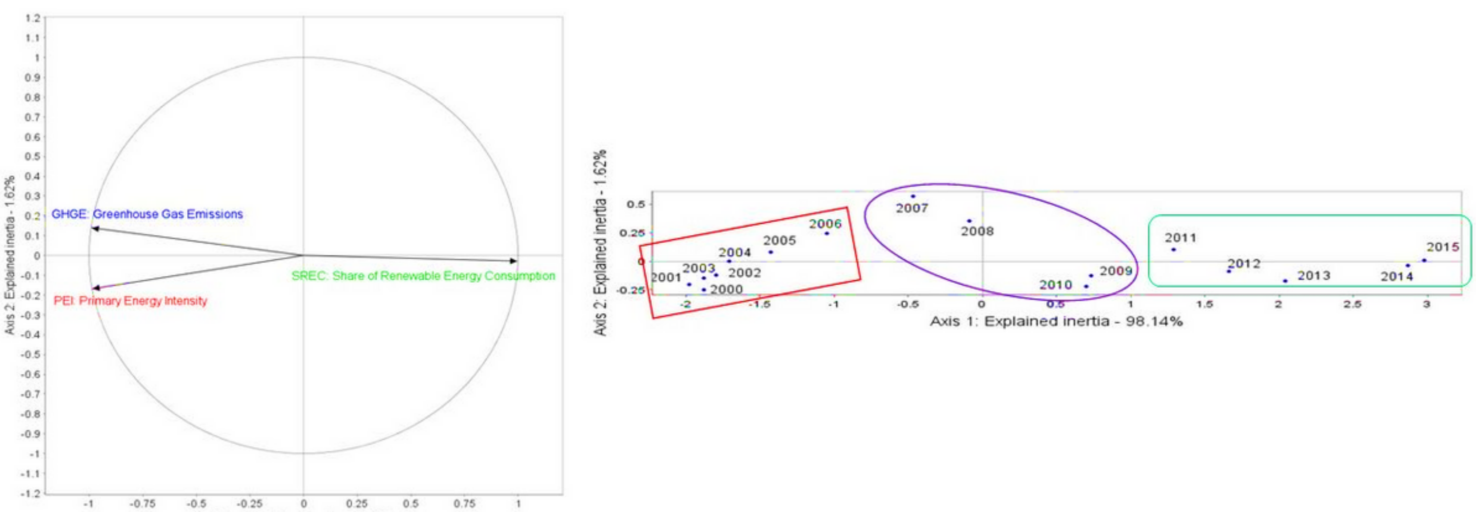

Figure 2

Representations of ET components and years in the first principal plane of the PCA