



Trajectories for Energy Transition in EU-28 Countries over the Period 2000–2019: a Multidimensional Approach

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Abstract

Environmental issues have become a major concern for policymakers faced with the threat of global warming. The European Climate Energy Package is an ambitious plan which drives the trajectories of European countries in three directions: reducing greenhouse gas emissions, increasing the share of renewable energy and improving energy efficiency. This article is original in that it considers the three targets together using multidimensional data analysis methods, a methodology which makes it possible to propose temporal and spatial typologies for the energy transition of European countries over the period 2000–2019. Results show evidence of a gradual transition over three sub-periods towards a more environmentally conscious economy. Four distinct types of energy transition profiles are identified, highlighting the contrasting performances of EU Members in terms of energy transition. In particular, some economically more advanced countries, namely Germany, Ireland, Belgium, Luxembourg and the Netherlands, are lagging in achieving their targets. Finally, discriminant analyses suggest that *economic performance*, *trade performance*, *innovation system* and *policy mix design* have been particularly effective in promoting energy transition over the period 2000–2019, while only *innovation system* helps to explain the contrasting results observed at country level over that time.

Keywords Energy transition · European Union · Multidimensional data analysis

JEL C38 · O33 · Q48 · Q55

1 Introduction

Eighty-one percent of the world's energy was still supplied by fossil fuels in 2018. Global Greenhouse Gas (GHG) emissions rose through 2019, and more than 770 million people around the world still lack access to electricity [1]. How to maintain a certain level of economic development while preserving environmental resources is a key question of sustainable development.¹ This is why policymakers since the 1990s, faced with the threat of global warming, have considered it essential to reduce energy consumption, limit the use

of fossil fuels and promote the development of low-carbon energy. This requires a radical technological transformation of the global energy system, and the rapid implementation of policies that encourage concerted and coordinated efforts to integrate global environmental concerns into local and national policies. At the Paris Climate Conference (COP21) in December 2015, 195 countries adopted the first-ever universal, legally binding global climate agreement. This agreement sets a long-term goal of keeping the increase in global average temperature below 2 °C above pre-industrial levels and continuing efforts to limit it to 1.5 °C. Each country is free to set its own targets to reach this goal, and many countries have chosen to reduce their greenhouse gas emissions with a reference level set in the year of the agreement (2015).

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

The European Union has become the first region in the world to commit to much more ambitious targets. The adoption of the climate-energy package at the European Council of 12 December 2008 defined an action plan to enable the EU to achieve three objectives by 2020, which in this contribution constitute the three variables chosen to measure the energy transition (ET) in Europe over the period 2000–2019:

- (i) reduce greenhouse gas emissions 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 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 of renewable sources in EU energy to 32% and (iii) an indicative target of 32.5% energy efficiency. These objectives are binding at the European level.³

More recently, the European Climate Law adopted in June 2021 affirms the EU's pledge of becoming the first carbon-neutral continent by 2050 and revises upwards the GHG reduction target for 2030, from 40 to 55%.

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 on structural characteristics of countries such as national energy endowments, demographics, geography, climate, past national energy policies and

historical development [2–5]. Considering national characteristics is therefore essential in order to understand the progress that has been made so far, and in order 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 2000–2019. 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 us to develop temporal and spatial typologies for the energy transition. This evolutionary analysis is especially designed to study individuals (i.e. countries) characterized by a number of groups of the same variables (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 the energy transition over the period 2000–2019. 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 2000–2019. In this, we follow Hafner and Raimondi, who observe that energy is a 'shared competence' between European institutions and national governments, and that 'Member States were not keen to leave such a strategic topic exclusively to the EU's responsibility. Therefore, despite the announcements and declarations, it can be said that there are different speeds for the EU energy transition among Member States and different results' [6] p. 382.

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, with 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 as regards sustainability can allow an identification of the levers and obstacles to the energy transition, something which is a major concern for policymakers.

To our knowledge, few studies to date have considered the three energy transition objectives simultaneously as applied to all EU countries and in a dynamic perspective. Our analysis differs from analyses carried out by international organizations in several respects. We propose a multidimensional evolutionary analysis over a long period covering the 28 EU countries. Our objective is to analyse the trajectories of the countries and to propose temporal and spatial typologies in order to identify on the one hand the dynamics of the

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.

transition, and on the other hand the similarities and dissimilarities of the national trajectories. In this sense, it differs from the analyses carried out by the IEA for individual countries [7] and for the purposes of the EU annual reports [8]. These studies offer a univariate analysis of criteria, they are not part of a long-term dynamic analysis and they provide an annual assessment of the actual progress towards Europe's climate and energy goals. The approach taken by the World Energy Forum [1] is also very different, being based on the construction of an Energy Transition Index (ETI) to track energy transitions at the country level. This index covers 40 indicators from 115 countries. It rates countries on the performance of their energy systems, as well as their readiness to transition to a secure, sustainable, affordable and reliable energy future. We may, in this connection, cite Costantini et al. [9] who used a multivariate framework to analyse energy efficiency in the residential sector of 19 EU countries, but our proposal is different and more exhaustive. The originality of the contribution lies in the diversity of the variables considered, and it is also an important way to see how a supranational institution like Europe is able to implement incentives and good policies among its members so as to address the challenge of global warming. In a sense, the European Union presents an example of the cooperation which will be necessary for all countries if they are to face this vital issue. Since the European countries each have specific characteristics, the three different objectives have been adapted to each case, and we follow the efforts made by each class of countries over the period 2014–2019.

According to the EEA report [10], the EU has achieved its three climate and energy targets for 2020. However, these targets have been achieved against the backdrop of the COVID-19 crisis, which weighed heavily on activity, sharply reducing energy consumption and GHG emissions. In addition, the report underlines a strong disparity between countries in terms of meeting their energy and climate targets. While the targets have been set collectively for the EU, each country is required to participate in the effort individually and to achieve its own targets. These findings raise questions about the will and capacity of European countries to meet the present and future targets assigned to them. As such, a comprehensive assessment of national energy transition performance is still needed. In this paper, the concept of ET is assessed on the basis of three energy climate targets with the aim of providing an evaluation framework for empirically comparing the performance of the 28 EU members. The findings make it possible to identify the strengths and weaknesses of the countries in the implementation of ET. This approach provides the bases for a systematic monitoring of ET policies at the national scale.

The paper is organized as follows. Section 2 focuses on national characteristics and main drivers of energy transition. The conceptual framework and data are described in

Section 3. Section 4 presents main results and related comments, while Section 5 summarizes our findings and provides policy recommendations.

2 National Characteristics and Drivers of Energy Transition

'Growing CO₂ emissions is a problem for the entire world, rather than the issue of any individual nation, since no country can confront such global challenges alone.' [11], p. 1046. This observation is doubtless incontestable, yet countries do have their own specificities. This section provides a brief overview of the main fundamentals of the national specificities of European energy systems that could induce different trajectories for the energy transition. The main drivers of the energy transition are also presented in the light of the literature. National specificities related to *economic performance*, *trade performance*, *policy mix design* and *innovation system* can explain contrasting performances in the energy transition process.

2.1 National Characteristics

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. As a result, there are significant differences in the use of fossil fuels, renewables, energy intensity and CO₂ emissions between countries. The energy balance sheet of the EU28 has been deeply modified in the last 20 years, with a decline in the share of solid fuels and an increase in renewable energy and natural gas. However, fossil fuels continue to dominate the energy balance sheets (their share falling from 79% in 2000 to 71% in 2019) largely because of a market failure that neglects the cost of their negative externalities [12–14] and because of hysteresis. Due to centuries of industrial development, fossil fuels have enormous structural advantages, making them more mature than sustainable alternatives such as wind, solar and biogas energy. Moreover, fossil fuel resources are still largely sufficient, and the price of non-environmental energies remains far cheaper than most renewable energies (RE). The value of fossil fuel subsidies is still high and progress towards phasing them out has been slow [15]. A recent study in the 11 largest EU economies (representing 83% of EU greenhouse gas emissions) records that European countries spent more than €112 billion per year for the period 2014–2016 to subsidize the production and consumption of oil, gas or coal, including through tax breaks for diesel [16].

In 2019, the share of solid fossil fuels in the domestic consumption was 10.4% for the EU28 but above 15% in

most Eastern European countries (Bulgaria, Czech Republic, Poland, Slovenia, Slovakia) as well as in Germany. Oil and petroleum products represent nearly 37% of the inland consumption of the EU28 and continue to be the main energy source for the European economy. In Malta, Cyprus, Luxembourg, Greece and Ireland, petroleum products account for more than half of domestic consumption. Natural gas is the second largest source of energy in the EU-28, accounting for 24% of European consumption in 2019, but with strong disparities between countries. Its share is over 30% in the Netherlands, Italy, the UK, Hungary and Ireland, while it is almost zero in Cyprus, Malta and Sweden.

The share of nuclear energy was relatively stable over the period 2000–2019, decreasing slightly from 14.5 to 13%. Nuclear power is part of the domestic energy mix in 14 EU Member States, and is the major source of energy consumption in France, wherein it accounted for more 40% in 2019. It is also important in Sweden and Finland, as well as in most Eastern European countries (Bulgaria, Czech Republic, Hungary, Slovenia, Slovakia).

RE represented 15% of the European energy mix in 2019, compared to about 6% in 2000. The most successful countries in terms of the development of RE are Sweden, Latvia, Finland, Estonia, Austria, Denmark and Portugal, where RE covers more than 30% of the domestic energy consumption; on the other hand, RE accounts for less than 10% of energy consumption in Belgium, Luxembourg, the Netherlands and Malta.

Despite these profound changes in the energy mix, the EU still relies heavily on energy imports, especially from non-EU countries. The dependency rate on energy imports for the EU as a whole was 61% in 2019, whereas it was just 56% in 2000. In 2019 this rate ranged from over 90% in Malta, Cyprus and Luxembourg to 5% in Estonia. The main supplier of energy to the EU is Russia, which supplies 41.1% of natural gas imports, 26.9% of crude oil imports and 46.7% of solid fuel imports.

The EU has made substantial progress towards its energy efficiency objective. In 2019, the EU consumed 10.8% less primary energy than in 2005. Comprehensive studies on energy efficiency in EU countries are scarce but agree on the existence of significant potential for energy savings, varying substantially between countries [17, 18]. The primary energy intensity of the EU28 in terms of GDP decreased by 28% over the period 2000–2019; this denotes a real effort by countries to improve their efficiency notwithstanding the different structures of production. Eastern European countries have recorded the highest rates of decrease, but their energy intensities remain higher than those of the other European countries.

Similar heterogeneity can be found in GHG emissions. Some countries have made significant efforts to reduce their GHG emissions, recording a reduction of more than 30%

in 20 years (Denmark, Ireland, Malta, Sweden, the UK). In 2019, a notable difference remains between the worst performing country, i.e. Luxembourg, and the best performing, i.e. Sweden: Luxembourg has emitted 3.9 times more GHG emissions per capita.

Industrial structure may also explain some of the high GHG emission figures among the less developed Eastern Bloc countries, such as Bulgaria, Estonia or the Czech Republic. On the other hand, a low level of development explains the low level of GHG emissions per capita in countries such as Romania or Croatia, while in some more developed countries the high contribution of nuclear power and/or RE to electricity production (Sweden, France) results in a low level of emissions.

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.

2.2.1 Economic Performance

An abundant literature [19–23] has established a positive link between economic growth and the use of renewable energy [24–27]. 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 [28, 29]:

- (i) economic development and its corollaries, such as 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 [30, 31];
- (iii) and finally, technical innovation and progress contribute actively to the development of clean-up techniques, and the implementation of clean technologies supports this ‘optimistic’ vision of growth [32–34].

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

2.2.2 Trade Performance

The ‘pollution haven’ hypothesis [35] in the case of carbon taxation refers to the relocation of production in less environmentally responsible countries. This raises concerns about the effectiveness of regionally fragmented climate policies [36]. The pollution haven hypothesis assumes that environmental policy leads to a loss of competitiveness and a deterioration of the terms of trade, and is moreover ineffective to mitigate climate change [35]. 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. Foreign Direct Investments (FDI) from multinational firms may also spread greener technology in the host country, this being referred to as the ‘pollution-halo’ hypothesis [37]. They may also, through a scale effect, induce an increase in CO₂ emissions in some developed countries, despite the high level of their environmental regulations. Porter [38] considered that 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 [38, 39]. Furthermore, according to the ‘California effect’ [40], there is a positive virtuous cycle arising from the interactions between bilateral trade, environmental regulation and the diffusion of clean energy technologies: this foresees technology upgrading through trade integration and transfer along the value chain [41].

In the case of unilateral policy, such as with 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 job leakage towards countries that are less environmentally responsible. It seems far more efficient to introduce a tax on products, which would be proportional to the carbon footprint. Nordhaus [42] establishes that a regime with small trade penalties on non-participants, which we may call a Climate Club, can induce a large stable coalition with high levels of GHG emissions abatements. Springmann et al. [43] 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. This is why the EU is on the way to introducing

a carbon border tax on products [44]. Yet the proposed carbon border tax, presented by Brussels as a ‘contribution to reducing global emissions’, has been described as a ‘protectionist’ and ‘discriminatory’ measure by several emerging countries. Russia, China, Turkey, Ukraine, India and Brazil will be the most affected by this tax, which should initially apply to imports of fertilizer, steel, aluminium, electricity and cement. It ‘could redirect trade flows to countries where production is less polluting, but will have little effect on global warming’, according to UNCTAD. According to the EU, ‘this mechanism will also help reduce the risk of carbon leakage by encouraging producers in non-EU countries to green their production processes’ [45].

2.2.3 Policy Mix Design

For a long time, many policy recommendations have ignored carbon lock-in, which may have limited their potential for successful implementation [46]. Techno-institutional complexes have emerged through a path-dependent process of increasing returns to scale. This explains why existing technologies capable of minimizing climate-enhancing emissions did not diffuse rapidly, even if they were cost-effective. Alongside the effect of lobbying [47], this explains why subsidies for fossil fuels still exist [48, 49]. Mitigating the effects of climate change requires urgent government actions to reduce carbon emissions. Policies must be implemented to accompany the trajectories of the energy transition by promoting low-carbon technologies and increasing energy efficiency [12, 50, 51]. There are four main incentive mechanisms employed by governments to finance RE deployment: feed-in-tariffs, tax incentives, tradable green certificates and investment subsidies. The EU Emissions Trading Scheme (ETS) was introduced in 2005 to address market failures by creating a market for GHG emission allowances, thereby putting a price on carbon emissions that reflects the negative externalities associated with fossil fuel-based electricity generation, but also with heat production and highly polluting industries such as cement, aluminium and steel. However, the generous allocation of pollution certificates has long reduced the effective incentive to switch to greener production. The price of carbon emissions is set to rise, in pursuit of greater efficiency [45]. Carbon prices have more than doubled since the beginning of 2021, peaking at € 74.12 per tonne on November 25, after world leaders signed off a new agreement aiming to reduce the use of fossil fuels at the COP26. To support the deployment of RE, a mix of different policy instruments was implemented by each member state, concerning regulatory policies and fiscal incentives as well as public financing [52]. 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 [53]. While feed-in tariffs and

feed-in-premiums are the main support schemes for the deployment of renewable technologies in the EU electricity sector [54, 55], it has been increasingly recognized that a mix of policy instruments is needed to foster low-carbon transitions [56, 57]. Furthermore, these instruments may change significantly over time and differ according to countries' different national objectives and stages of innovation [58].

2.2.4 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, a key element of the transition as mediated by environmental regulation, is therefore essential. According to a European Commission report [59], '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'. However, an important peculiarity of eco-innovation is the double externality problem that reduces the incentive for firms to innovate [60]: it 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. Ghisetti and Rennings [61] showed, from survey data for German firms, that energy efficiency innovations positively affect firms' performances while innovations allowing the reduction of negative externalities (pollution, capture and storage of CO₂) have a negative impact on firms' performance. Kruse [62] 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 [63–67]. It remains difficult to redirect and accelerate technological change towards sustainability because it still depends on the interactions of independent actors who have their own goals [68]. Moreover, relevant policies are difficult to implement. There is always a trade-off between flexibility and stability [69]: flexibility because technological, social or even geopolitical uncertainties mean environmental policies frequently need to be adapted, and stability because green entrepreneurship and venture capital must have at least medium-term visibility concerning the rules that are applied, especially in terms of tariffs.

It can be noted that Europe is becoming the most innovative region in the world in low-carbon energy (LCE) technologies over the period 2010–2019, with 28% of patents

granted according to a recent study by the European Patent Office and the International Energy Agency [70]. After a decline between 2014 and 2016, the latest data shows 3 years of growth in International Patent Families (IPFs) in LCE technology, while IPFs on fossil fuels reached their maximum in 2015. Innovation in cross-cutting technologies such as batteries, hydrogen and smart grids, and carbon capture, utilization and storage (CCUS) have been the drivers of LCE growth since 2017, as they are enablers of ET. In contrast, patents related to renewable energy technologies (such as wind, solar, geothermal or hydro) and other energy supply technologies have been declining since 2012 after a decade of strong growth. Europe is particularly specialized in renewable energy (solar thermal, ocean) and end-use innovations—electric vehicles, road transport and railways. With 25% of all IPFs in the field of LCE since 2010, Japan has remained very close to Europe during the analysis period, followed by the USA at some distance in the third place (with 20% of all IPFs). Japan is a world leader in batteries and hydrogen, while the USA has a technological advantage in low-carbon combustion. The Republic of Korea (10% of all IPFs) and the People's Republic of China (8% of all IPFs) remain modest centres of innovation in LCE technologies, with a specialty in batteries, ICT and solar photovoltaic technology for Korea, and ICT and railways for China. In a recent paper Bonnet et al. [71] show that intense competition and strategic behaviour coexist in the filing and acquisition of patents registered in the EPO Worldwide Patent Statistical Database (PATSTAT) database between 1992 and 2014, in the field of RE—i.e. wind (onshore and offshore), solar photovoltaics, biofuels, fuel from waste, geothermal, solar thermal and hydropower (excluding hydropower dam technologies). Leadership in renewable energy technologies is measured by the number of inventions patented by the five main international patent offices, weighted by claims.⁴ Germany is the leader in this field, followed by the USA, Japan, South Korea and France. The latter three countries have been increasing their number of patents recently, but France files less than one-fourth of the number of patents filed by Germany.

3 Conceptual Framework and Data

This section provides details about the methodological approach and data analysis techniques, and gives a description of the data used in the study.

⁴ US Office (USPTO), Japanese Office (JPO), European Office (EPO), Korean Office (KIPO) and Chinese Office (SIPO). A high number of claims in a patent application examination document correspond to a high-value invention, as examiners will concede high market power in exchange for the expected long-term benefit to the company from the invention.

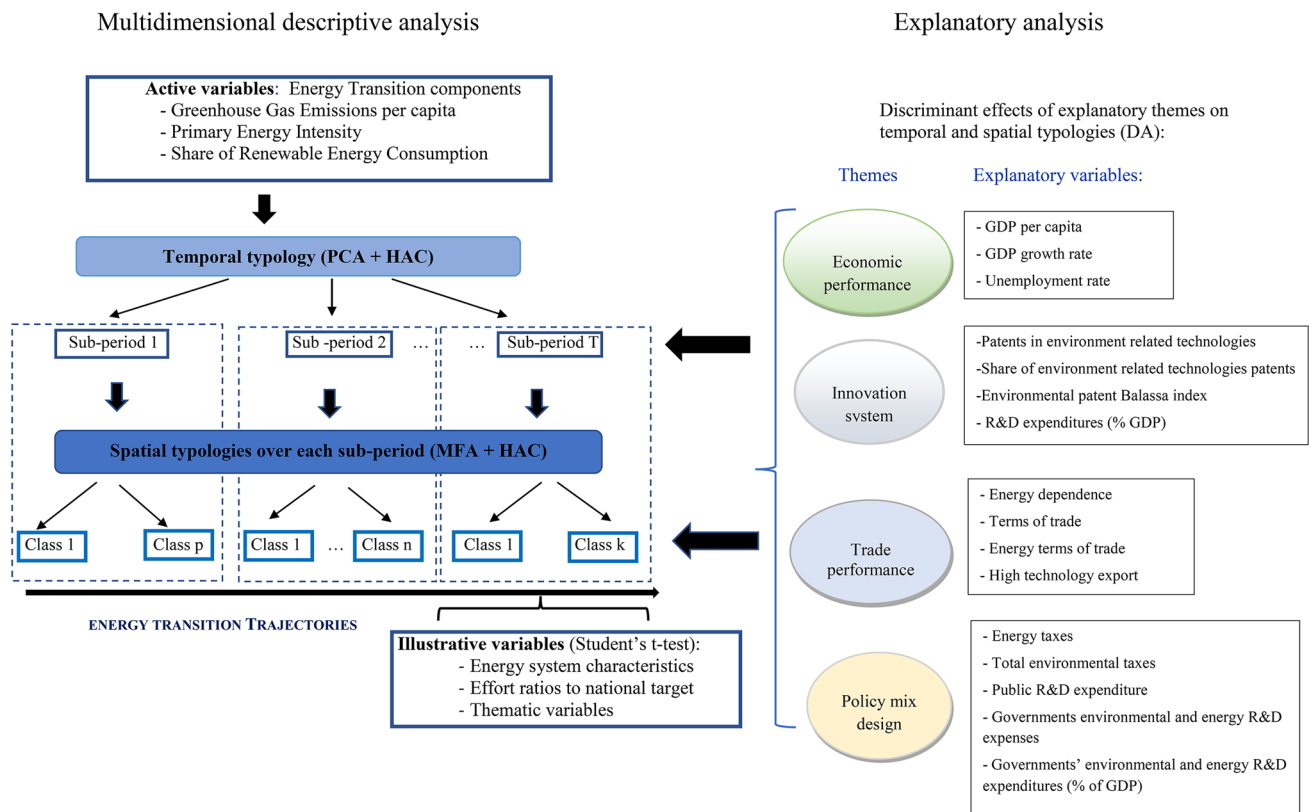


Fig. 1 Methodology overview

The analysis is built in several stages. Figure 1 gives a conceptual framework overview of the empirical approach. First, multidimensional analyses are used to build temporal and spatial typologies of the 28 EU countries relative to the three objectives of the ET. Second, explanatory models, namely discriminant analyses, are used to identify the drivers of the ET according to explanatory themes. These themes are assumed to represent national characteristics.

3.1 Multidimensional Descriptive Analysis

Our proposal aims to establish the trajectories of the EU and its 28 countries with respect to the three ET objectives. We consider three comparable variables across countries, described in Table 6 in the Appendix, namely the greenhouse gas emissions per capita (GHGC), primary energy intensity (PEI) and the share of renewable energy consumption (SREC). We chose a criterion of energy efficiency rather than primary energy consumption in order to be able to compare the national performances. Indeed, there is a strong heterogeneity between the countries of the European Union in terms of both population and GDP.⁵ We have chosen

these indicators with the aim of tracing the trajectories of the energy transition of the countries of the European Union over the period 2000–2019. These indicators highlight the adaptation of national energy systems to address environmental concerns over a period of 20 years. They also make it possible to measure the progress made following the adoption of the Climate and Energy Package adopted at the end of 2008.

These three active variables will hereafter be called the *three components of the energy transition*. They are used to build temporal and spatial typologies of the ET and to analyse the trajectories of the European countries over the period 2000–2019.

3.1.1 Data

We use annual data extracted from Eurostat databases over the period 2000–2019.

Figure 2 shows the evolution of the three ET components of the EU over the period 2000–2019. There is indeed a quasi-linear evolution of the three components: SREC is increasing, while PEI and GHGC are decreasing.

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 2000–2019.

⁵ In 2019, Germany accounted for 16.17% of the population and 20.25% of the GDP of the EU28, while Malta accounted for only 0.10% of the population and 0.08% of GDP.

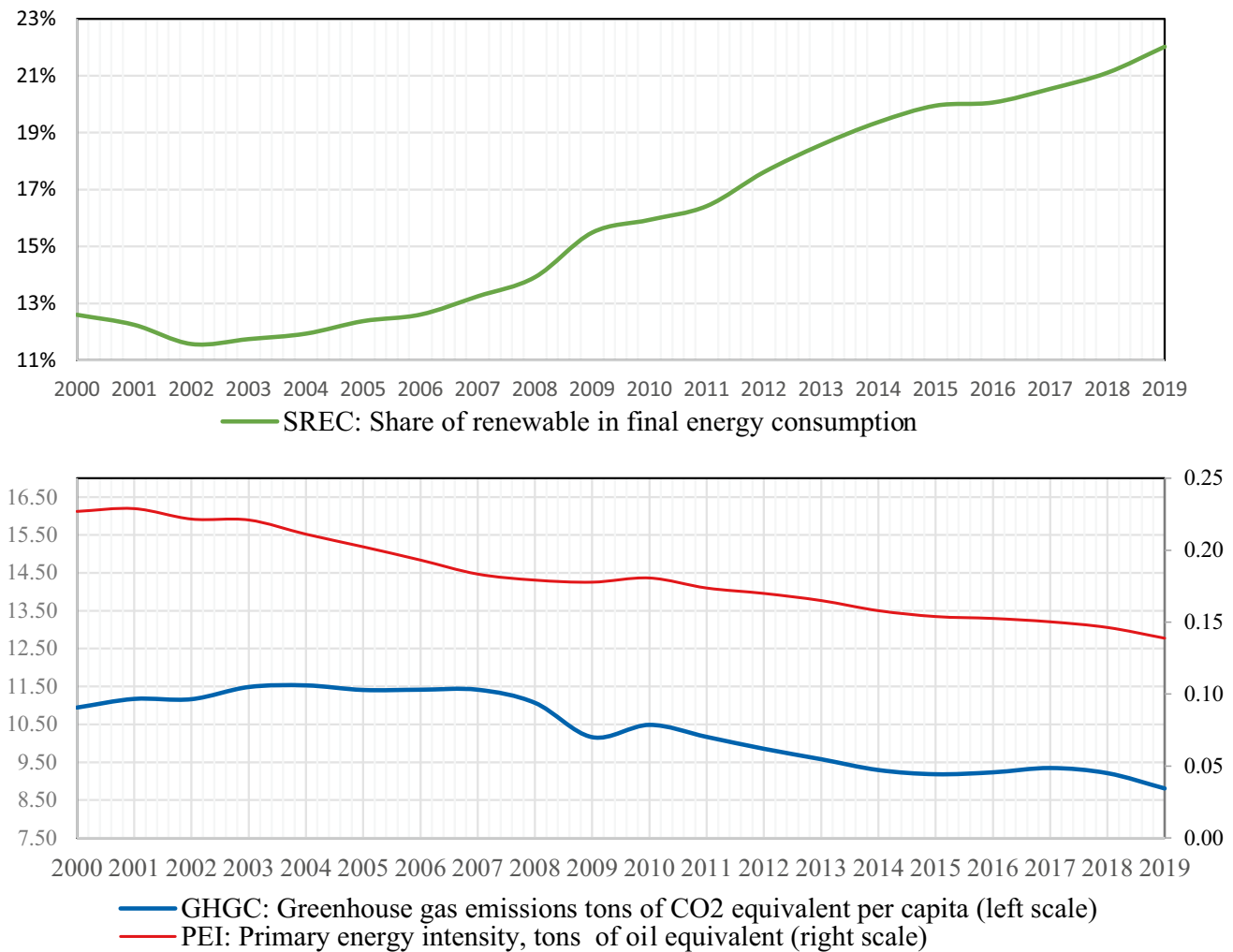


Fig. 2 Average evolution of the three ET components of the EU-28

We observe strong variability in the variables related to the ET, revealing a strong heterogeneity between the 28 EU countries. On average, over the period 2000–2019 the GHGC ranges from 5.325 tonnes of CO₂ equivalent per capita in Latvia to 24.994 tonnes of CO₂ equivalent per capita in Luxembourg. The PEI peaks at 0.496 tonnes of oil equivalent per thousand euros of GDP at 2010 market prices in

Bulgaria against only 0.075 in Denmark. The SREC varies from 2.8% of the final consumption in Malta to 46.2% 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 ET in Europe.

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

Variables	Frequency	Mean	Minimum	Maximum	Standard deviation	Coefficient of variation (%)
GHGC ^a	28	10.346	5.325	24.995	3.894	37.64
PEI ^b	28	0.182	0.075	0.496	0.091	50.15
SREC ^c	28	15.932	2.797	46.193	10.756	67.51

^aTonnes of CO₂ equivalent per capita

^bTonnes of oil equivalent per 1000 € of GDP

^cPercentage of final total energy consumption

3.1.2 Temporal Typology of the ET

We first implement a temporal analysis of the ET of the EU over the period 2000–2019, studying the annual evolution of the three ET components of the EU. In this analysis, years play the role of ‘individuals’ and annual components the role of the ‘variables’.

A methodological sequence of two data analysis methods [72–74] was used to group the 20 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. This methodological linking of a factorial analysis and clustering method constitutes an instrument for statistical observation and structural analysis of multidimensional data.

This analysis allows us to identify several sub-periods corresponding to different stages of the energy transition in the EU.

3.1.3 Spatial Typologies and Trajectories of the ET

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 sub-periods.

The approach adopted relies on a combined use of exploratory methods of evolutionary data analysis that consider the characteristics of the countries in terms of GHGC, 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 [75–77] 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 variables (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. This balance is necessary because the groups of variables always differ according to the structure of the variables, namely their interrelationships. It provides us with representations of countries and ET components that can be interpreted according to the usual PCA. 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.

Then we focus on the countries’ trajectories over the period 2000–2019 using the spatial typologies carried out over each sub-period. We are interested in the evolution of the characterization of the classes as well as in the trajectories of the countries in these classes.

Finally, in order to consolidate and enrich the interpretation of the classes of countries, we consider supplementary (illustrative) variables that provide additional information. These variables 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): these variables are therefore not taken into account in the construction of the principal component factors, but are positioned a posteriori in order to assess their degree of similarity with the active variables. To do this, each illustrative variable has been subjected to a *t*-test, also known as Student’s *t* distribution, to determine whether there is a significant difference between the means of this variable in the class and overall, and that for all the classes of the typology.⁶

Illustrative variables are described in Table 7 in the Appendix.

We consider a large set of relevant variables describing national characteristics in terms of energy balances as well as the drivers of energy transition. These refer to the four themes *economic performance*, *commercial performance*, *policy mix design* and *innovation system*, and are called thematic variables. 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.

Finally, 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 (GHG), share of renewable energy in final energy consumption (SREC) and primary energy consumption (PEC). 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 effort ratios to national target defined as:

$$EF_X_t = \frac{(X_t - X_{2020})}{X_{2020}} \cdot 100, \text{ where the year } t = 2009, \dots, 2019, \text{ and the variable } X = \text{GHG, SREC, PEC}$$

⁶ T-test is a parametric test; data is assumed to follow a normal distribution, both within classes as well as overall, since the sample size for comparing means is small.

These ratios are calculated for each ET component to the target over the period 2009–2019, since the objectives were set in 2007 and enacted in legislation in 2009. These variables can therefore only be used at the end of the period studied in the article. They are expressed as a percentage and can therefore be compared between countries. For the share of renewable energy in final energy consumption, a positive (negative) ratio means that the country has exceeded (failed to meet) its target. On the contrary, for greenhouse gas emissions and primary energy consumption, a negative (positive) ratio means that the country has exceeded (failed to meet) its target.

3.2 Explanatory Analysis

To explain and characterize synthetically the temporal and spatial heterogeneities of the EU in terms of energy transition, we can use different predictive techniques, a discriminant analysis model [72, 78], or multinomial logistic or probit regression models [73]. We choose to implement discriminant analysis (DA), which is a modelling method for decision-making. DA is a multidimensional method; it allows to highlight the possible links existing between qualitative target variable to be explained and a set of explanatory quantitative variables; in this case, we explore the links between the predefined typology (temporal or spatial) and all the variables of one or the four themes presented in Table 7 in the Appendix. Discriminant factor analysis is a descriptive and explanatory method, applying to qualitative data on which a typology or partition is already defined. The aim of this method, like PCA, is to reduce the number of dimensions of the data, by finding factorial axes according to which the classes are best separated.

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.⁷ 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 into these known classes using the discriminant linear functions established previously. Our goal is to identify themes—homogeneous sets of explanatory variables—which discriminate between the temporal and spatial classes previously determined.

Four explanatory themes were considered: *economic performance*, *trade performance*, *policy mix design* and *innovation system*. For each theme, we selected several representative variables described in Table 7 in the Appendix. To choose these explanatory 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.

4 Empirical Results

We first present a temporal analysis of the ET of the EU over the period 2000–2019. Then we propose a typology of the EU-28 member countries over each of the identified sub-periods in order to study the trajectories of the 28 EU countries. Finally, we implement discriminant analyses to identify the drivers of the energy transition.

4.1 Trajectory of the EU-28 Energy Transition

Figure 3 shows that the two first factors of the PCA explain 95.48% and 4.24%, respectively of the total variance, and account for 99.72% of the information regarding the evolution of the ET components of the EU over the period 2000–2019. It also 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 2000–2008, characterized by high PEI and GHGC, with the later period 2014–2019, characterized by a high SREC. The middle sub-period 2008–2013 is homogeneous, which means that over this 5-year sub-period, the values of the three ET components do not differ from the averages of these components calculated over all the 28 countries of the European Union. Figure 3 shows the grouping of the closest years according to the first component: these groups are represented by geometric shapes. Years with the same shape have common energy transition characteristics.

Using an HAC with the Ward criterion⁸ 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, Fig. 4 given in the Appendix.

The first period, comprising the nine first years, 2000–2008, is characterized by high PEI, high GHGC and low SREC.

⁷ 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.

⁸ Generalised Ward's Criteria, i.e. aggregation based on the criterion of the loss of minimal inertia.

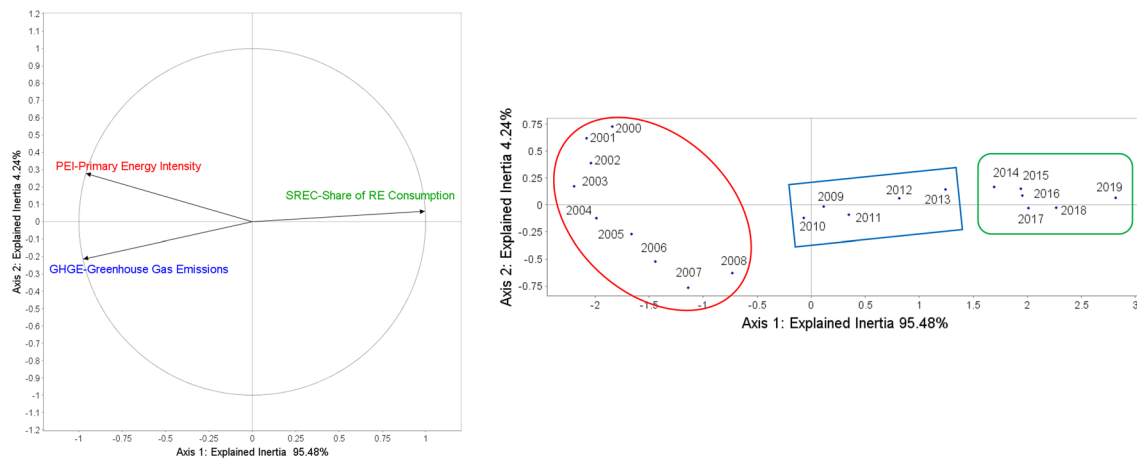


Fig. 3 Representations of ET components and years in the first principal plane of the PCA

The second class, which groups together the five succeeding years of the middle period, 2009–2013, 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 6 years of the period, are opposed to those of the first class. This third class is characterized by a high share of RE in final consumption, lower energy intensity and lower GHG emissions per capita. The energy transition is underway.

Due to high public concern about global warming, people are more likely to consider GHGCs as an important target. As Hafner and Raimondi have remarked, ‘In 2018, the GHG emissions across the EU have reduced by 23.2% below 1990 levels; thus, the EU was on track to meet its upcoming target by 2020.’ [6]. COP26 records that by 2020, the EU had reduced its emissions by 25% from 1990 levels. At the same time, meeting the energy efficiency target appeared to

be increasingly difficult, and 2014 projections already indicated that the target would not be met. Both primary and final energy consumption levels increased steadily during the 2014–2017 period [79]. Eurostat data (January 2020) shows that in 2018, primary energy consumption was 5.8% above the 2020 targets, while final energy consumption was 3.5% above those targets [80]. In 2019, renewable energy represented 19.7% of energy consumed in the EU27, only 0.3% short of the 2020 target of 20%.

4.2 Energy Transition of the 28 EU Member Countries

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 (Fig. 5 in the Appendix), and provides the characterization of the classes. This table presents the energy transition trajectories in the European Union countries for the period 2000–2019. First, we comment on the trajectories. Then we present in detail the

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

	Beginning of period	Mid-period	End of period
Duration	9 years	5 years	6 years
Years	2000 to 2008	2009 to 2013	2014 to 2019
Profile	+ PEI + GHGC	homogeneous profile	+ SREC
Anti-Profile	- SREC		- PEI - GHGC

The variables presented in the table are significant at the 0.05 level. The sign ‘-’ (respectively ‘+’) indicates a significantly lower level (respectively higher) of the variable in the class considered compared to the average of the 28 countries.

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

	Beginning of period 2000 - 2008		Sub-period 2009 - 2013		End of period 2014 - 2019	
	+ GHGC + PEI - SREC	EU-28		EU-28	+ SREC - GHGC - PEI	EU-28
Class 1	+ SREC 00 to 08 - GHGC 00	Austria Croatia Finland Latvia Portugal Sweden Slovenia	+ SREC 09 to 13 - GHGC 09 to 13	Austria Croatia Finland Latvia Portugal Sweden Slovenia Hungary Romania Lithuania	+ SREC 14 to 19 - PEI 18,19	Austria Croatia Finland Latvia Portugal Sweden Denmark
Class 2	+ PEI 00 to 08	Bulgaria Czechia Estonia Poland Hungary Romania Lithuania Slovakia	+ PEI 09 to 13	Bulgaria Czechia Estonia Poland	- GHGC 14 to 19	Malta Italy Spain France Greece U-Kingdom Slovenia Hungary Romania Lithuania Slovakia *EU-28
Class 3	- PEI 00 to 08 - SREC 00 to 08	Germany Cyprus Ireland Netherlands Belgium Malta Italy Spain France Greece U-Kingdom Denmark *EU-28	- PEI 09 to 13 - SREC 09 to 13	Germany Cyprus Ireland Netherlands Belgium Malta Italy Spain France Greece U-Kingdom Denmark Slovakia *EU-28	+ GHGC 14 to 19 + PEI 18,19 - SREC 14 to 19	Germany Cyprus Ireland Netherlands Belgium Czechia Poland Luxembourg
Class 4	+ GHGC 00 to 08	Luxembourg	+ GHGC 09 to 13	Luxembourg	+ PEI 14 to 17	Bulgaria Estonia

The variables presented in the table are significant at the 0.05 level. A sign ‘-’ (respectively ‘+’) indicates a significantly lower level (respectively higher) of the variable in the class considered compared to the average of the 28 countries. The years for which the variables are significant are specified following the names of the variables. The colors indicate a particular trajectory for a country or similar trajectories for groups of countries. It's a simple way to visualize models. These trajectories are discussed in the text.

typology of the last period as well as the results concerning the illustrative variables.⁹

First of all, it should be noted that although the temporal analysis 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: (i) the three typologies have four homogeneous classes, and (ii) over the first two sub-periods the profiles and anti-profiles are identical. The first class is characterized by a higher share of renewable energy than the European average and a significantly lower level of GHG emissions. The countries belonging to the second class have a PEI significantly higher than the average of the 28 EU countries. The third class gathers countries whose PEI and SREC are significantly below the respective averages of all the EU28, while class 4 has a level of GHG emissions that is significantly higher than the average.

As regards the countries, we note the strong stability of classes 3 and 4 over the first two sub-periods. Class 3 includes 12 countries in the first sub-period (Germany, Cyprus, Ireland, Netherlands, Belgium, Malta, Italy, Spain, France, Greece, the UK and Denmark) representing 82.67% of GDP and 73.14% of the population of the EU-28. Slovakia joins this class in the second sub-period.¹⁰ Luxembourg is isolated in class 4 over the first two sub-periods, representing 0.36% of GDP and 0.12% of the population of the EU-28. In the first sub-period, class 2 gathers 8 low-energy-efficiency countries (Bulgaria, Czech Republic, Estonia, Poland, Hungary, Romania, Lithuania and Slovakia) representing 8.10% of GDP and 18.36% of the EU-28 population. These countries belong to the former Eastern Bloc (with a majuscule), which still suffers from an entrenched specialization in heavy industries under the impulse of central planners. However, we observe that four eastern countries, namely Hungary, Romania and Lithuania, move from class 2 to class 1 over the second sub-period. This trajectory reflects an improvement in their situation with respect to the three components of the energy transition. Class 1 consists of 7 countries (Austria, Croatia, Finland, Latvia, Portugal, Sweden and Slovenia) over the first period and accounts for 8.87% of GDP and 8.38% of the population of the EU-28.

The last sub-period is characterized by significant changes in both characterization and class composition. Several interesting results can be highlighted.

We observe an opposition between classes 1 and 2 on the one hand and classes 3 and 4 on the other. The countries

belonging to the classes 1 and 2 are more virtuous since they are characterized by a higher share of renewable energy, a lower energy intensity and a lower level of emissions compared to the EU-28 average. On the other hand, classes 3 and 4 show deteriorated performances related to the three ET components.

We establish that the EU-28, projected a posteriori in each periodic analysis, is assigned to class 3 over the first two sub-periods and then to class 2 over the last sub-period. This means that the EU-28 has similar characteristics to class 3 over the period 2000–2013, i.e. PEI and SREC are significantly below the respective averages of all the EU-28.

Let us consider more specifically the description and interpretation of the classes over the 2014–2019 sub-period (see Table 9 in appendix).

The first class consists of seven countries, namely Austria, Croatia, Finland, Latvia, Portugal, Sweden and Denmark. It represents 10.51% of GDP and 9.10% of the population of the EU-28. A high share of RE in final energy consumption and a low PEI 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. Austria, Croatia, Finland, Latvia, Portugal and Sweden have a common trajectory and belong to the most virtuous class (class 1) over the three sub-periods, so these countries have consolidated their position. Denmark has moved from class 3 in the first two sub-periods to class 1 in the 2014–2019 period. It has made very significant progress in terms of the development of RE, with the share of renewables rising from 29.3% in 2014 to 35.41% in 2019. Note that in 2019, 4 countries in class 1, namely Sweden, Finland, Denmark and Austria, appear in the top 6 of the ranking made by the World Economic Forum, based on the score of the ETI [1].

In this class, renewable and biofuels sources as well as hydroelectric sources represent a high part of the energy and electricity mixes, while fossil fuels contribute little.

The significant thematic variables in class 1 mainly concern the innovation system and the policy mix design. The class of *virtuous countries* has a high level of research and development expenditure for the whole period 2014–2019 and total government budget allocations for R&D for the years 2014 to 2018 and a low level of governments environmental protection expenditures in %age of GDP. Patents in environment-related technologies per million inhabitants are high for 2014–2017.

For each year of the 2014–2019 period, EF_SREC is significantly positive, which means that these countries have made increased efforts and exceeded their objectives. Figure 6 in the Appendix shows that on average, the countries of this class exceeded their target by 8.79%. With regards to the other two objectives, their performances are quite similar to the European average.

⁹ In order not to overload the article, we do not present the results related to illustrative variables for the two first periods, but they are available on request.

¹⁰ The weight of the classes in terms of GDP and population is presented in Table 8 in the Appendix.

The second class contains eleven countries: Malta, Italy, Spain, France, Greece, the UK, Slovenia, Hungary, Romania, Lithuania and Slovakia. It accounts for 53.79% of GDP and 56.77% of the population of the EU-28. This class gathers countries whose GHGC are significantly lower than the EU-28 average, i.e. countries that are on the path to decarbonizing their economies. Note that five Eastern countries have joined this class, having made considerable efforts to control their GHG emissions. This class can be called *the lowest GHG emitting*.

Some countries, namely Malta, Italy, Spain, France, Greece and the UK, joined class 2 over the last period, escaping class 3. They have caught up with the European average in terms of RE development and have significantly reduced their GHG emissions. These results validate the claim by Hafner and Raimondi that ‘One of the key challenges to a successful energy transition is the political commitment and will in Member States’ ([6], p. 382). For example, Italy and the UK have seen an increased trend toward renewable energy transition with two different approaches (Italy is more state-driven through feed-in programs, while the UK is more market-driven).

These countries have a rather low energy consumption, the primary and final energy consumptions per capita being clearly lower than the European average. They also present a low level of electricity production from renewables and biofuels sources and a low share of non-renewable wastes in gross available energy. The final electricity consumption per capita is significantly lower than the European average.

The significant thematic variables in class 2 are identical to those in class 1 and mainly concern the innovation system and the policy mix. *The lowest-GHG-emitting class* has a low level of total government budget allocations for R&D, of patents in environment-related technologies per million inhabitants 2014–2016 and of GDP/inhabitants 2018–2019. The government’s environmental protection expenditures is high for 2014–2016.

Regarding the effort rates, the countries in this class are particularly efficient in terms of GHG emissions, since on average their emissions are 20.72% below their objectives (Fig. 6 in the Appendix). For the other two objectives, their performance is not significantly different from the European average.

The third class gathers eight countries (Germany, Cyprus, Ireland, Netherlands, Belgium, Czechia, Poland and Luxembourg) representing 35.23% of GDP and 32.51% of the population of the EU-28. These economies are characterized by high levels of GHGC and PEI and a low level of SREC compared to the average population. All the three ET variables are poor, so this class can be described as the class of *Europe’s poor performers* in terms of ET.

Germany, Cyprus, Ireland, the Netherlands and Belgium, taking advantage of their high level of development,

showed a low PEI over the first two sub-periods, but show poor results in the last period with respect to the three ET components. Some a priori virtuous choices can have bad consequences. For example, while Germany has moved away from nuclear, large-scale deployment of RE has not led to significant emissions reductions, due to the intermittency of wind or solar power, and the dependence on coal-fired power generation [81]. Germany’s efforts to reduce CO₂ have been weakened by the combination of two trends—low coal costs and CO₂ prices—which has resulted in its not moving away from coal.

Luxembourg and two Eastern countries, the Czech Republic and Poland, join class 3 in the last period. Luxembourg is a small and densely populated country, with a high density of road freight and many ‘cross-border workers’, which contributes to its high level of GHGC. The coal industry employs thousands of Polish citizens, which is the reason for Poland’s strong opposition to the EU’s climate neutrality goal. In 2018 electricity generation was dominated by coal, which accounted for 78.1% [6]. Yet we can notice the recent increasing role of natural gas in the Polish energy mix and its openness to phasing out coal following COP 26.

These countries have a rather high energy use, the primary and final energy consumptions per capita being significantly higher than the European average. They still rely heavily on fossil fuels, whose share in the gross available energy and electricity production remains very high. On average in these countries, the share of renewable energies and biofuels in gross available energy is below the European average. The share of hydro power in gross inland renewable energy consumption is significantly lower than the European average, while the share of wind power is above the European average.

The significant thematic variables in class 3 concern both economic and trade performance. This class, which we may label *Europe’s poor performers*, has a high level of GDP/inhabitant and a low level of energy terms of trade measured as the ratio of energy exports (Mtoe) to energy imports (Mtoe) for 2018–2019.

We find that the rates of effort in this class for the three targets and virtually all the years are markedly insufficient. The performance of these countries is significantly lower than the European average. Concerning the SREC and PEC targets, this class failed to meet its objectives. On average over the period 2014–2019, the share of RE is 24.83% below the target and for the PEC 3.54% above (Fig. 6 in the Appendix). As far as GHG emissions are concerned, the countries in this class have achieved their target but are clearly lagging behind the other classes.

The fourth class, entitled the *low energy efficiency* class, includes Bulgaria and Estonia, two former Eastern European countries with PEI significantly above the EU average for the years 2014 to 2017. Nevertheless, it should be noted

that the performance of this class is not significantly different from the EU averages in terms of RE development and GHG emissions. Moreover, for the years 2018 and 2019 the energy intensity is similar to that of the EU average. This class accounts for 0.45% of GDP and 1.62% of the population of the EU-28.

The share of renewables and biofuels in gross available energy is rather high for the years 2017–2019. This class also records a low level of energy dependence and energy productivity. The share of biofuels in gross inland renewable energy consumption is above the European average for the years 2018 and 2019.

The significant thematic variables in class 4 are about innovation system and trade performance. The *low energy efficiency* class has a low level of energy dependence measured as energy imports in % of energy uses, a high level of energy terms of trade measured as the ratio of energy exports (Mtoe) to energy import (Mtoe) for 2017–2019 and, for 2014 to 2017, a high level of share of environment-related technologies patents in total patents (%) and environmental patent Balassa index. These results reflect a strong specialization in environmental technologies.

This class presents a significant effort to develop SREC from 2017 (Fig. 6 in the Appendix). Bulgaria and Estonia have made considerable efforts and exceeded their objectives by 18.52% over the 2014–2019 period. In 2019, the share of RE in final energy consumption reached 21.56% in Bulgaria and 31.89% in Estonia, far exceeding their respective targets of 16% and 25%.

The introduction of illustrative variables representative of the rate of effort provided by the countries in relation to their national objectives over the last period shows a strong consistency between the classification made using the three active variables of the energy transition and the performance of the countries related to their national targets; thus, this result seems to validate the choice made concerning the explanatory variables to study the trajectories of the countries. It appears that the classes correctly describe the process of energy transition. This result is not surprising because the active variables are strongly conditioned by national specificities (level of development and energy systems), and national targets have been defined to take into account national specificities and the capacities of each country to reach the targets. Our results validate the relevance of the national targets as they have been defined, but we can nevertheless ask ourselves whether these targets defined for 2020 were sufficiently ambitious.

Our results confirm the conclusions of the EEA report [10], according to which ‘Over the recent years, trends have indicated a steady path towards achieving the 2020 greenhouse gas emission reductions, the likely achievement of the renewable energy targets and difficulties in reducing energy consumption quickly enough to reach the level

envisioned for 2020’. They show that an energy transition process is well underway over the 2000–2019 period, and that the 2014–2019 sub-period in particular is characterized by a significant reduction in greenhouse gas emissions, an increase in the share of renewable energies in the energy mix and an improvement in energy efficiency. Since 2014, EU-28 emissions have consistently remained below the EU’s 20% reduction target for 2020, and we see that all four classes did better than their target (Fig. 6 in the Appendix). When it comes to renewable energy, only the first and fourth classes did better than their target. Regarding the improvement of energy efficiency, only class 3 did not achieve its objective. Although progress has been made, we note that the EU Member States’ performances fluctuate greatly from year to year, especially with regard to the PEC, and from country to country. We highlight that the performance of EU Member States is very disparate. In particular, some economically more advanced developed countries, namely Germany, Ireland, Belgium, the Netherlands and Luxembourg, are lagging far behind in achieving their three objectives. However, overall the overachievement of national targets in some countries offsets underperformance in others (EEA report, 2021) [82].

4.3 Discriminating Effects of Themes on the Trajectories of the Energy Transition of the 28 EU Countries

We consider four themes, namely *economic performance*, *trade performance*, *policy mix design* and *innovation system*, and we seek to identify the themes—homogeneous sets of explanatory variables—which discriminate between the classes presented in Sect. 4.1 and 4.2 (three classes for temporal analysis and four for spatial analysis).

4.3.1 Discriminant Effect on the Temporal Typology

Table 4 summarizes the main results of the four models of DA 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 significant. Indeed, for each model, the critical probability or p -value ($\Pr > F$) of the Wilks’ lambda statistic¹¹ is less than the significance level of 1%.

¹¹ The value of Wilks’ lambda varies between 0 and 1, and the more it tends to 0, the better is the discrimination model (the class centers are well separated). A probability distribution of Fisher approximates the Wilks test statistic.

Table 4 Temporal discriminant analyses over the full period 2000–2019 according to the four themes

Economic performance 2000-2019				Innovation system 2000-2019			
Complete model: 3 explanatory variables Multivariate Statistics and Approximations F				Complete model: 4 explanatory variables Multivariate Statistics and Approximations F			
Statistic	Value	F Value	Pr > F	Statistic	Value	F Value	Pr > F
Wilks' Lambda	0.4065	12.41	0.0005**	Wilks' Lambda	0.1387	46.59	<.0001**
Variable	R-Square	F-Value	Pr > F	Variable	R-Square	F-Value	Pr > F
GDP	0.5935	12.41	0.0005**	SPAT	0.4275	5.60	0.0152*
GDPGR	0.5346	9.76	0.0015**	EPBI	0.1736	1.58	0.2393
UN	0.3790	5.19	0.0174*	PAT	0.5363	8.67	0.0031**
Misclassification rate ¹ : 0%				R&D	0.8613	46.59	<.0001**
Significance level α ; ** $\alpha \leq 1\%$; * $\alpha \in]1\% ; 5\%$				Misclassification rate: 0%			

Trade performance 2000-2019				Policy mix design 2000-2019 ²			
Complete model: 4 explanatory variables Multivariate Statistics and Approximations F				Complete model: 4 explanatory variables Multivariate Statistics and Approximations F			
Statistic	Value	F Value	Pr > F	Statistic	Value	F Value	Pr > F
Wilks' Lambda	0.1295	57.13	<.0001**	Wilks' Lambda	0.2496	25.55	<.0001**
Variable	R-Square	F-Value	Pr > F	Variable	R-Square	F-Value	Pr > F
EDEP	0.0892	0.83	0.4521	GEPE	0.2696	3.14	0.0692
TRADE	0.8705	57.13	<.0001**	ENVT	0.1392	1.37	0.2797
ETRADE	0.8642	54.08	<.0001**	ENT	0.5835	11.91	0.0006**
HTEX	0.3829	5.27	0.0165*	GR&D	0.7504	25.55	<.0001**
Misclassification rate: 0%				Misclassification rate: 0%			

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

²Only four variables are available for the temporal analysis, the GEER&R variable was removed due to a lack of data for the period 2000–2003

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.

- 1) The *economic performance* model shows that the three explanatory variables introduced over the period 2000–2019 induce significant effects on the ET trajectory in the 28 EU countries. The first significant discriminating factor restores 90.53% of the discriminating power of the model. It opposes and separates at best the first sub-period 2000–2008 characterized by a high GDP growth rate (GDPGR) to the second sub-period 2009–2013 characterized by a high unemployment rate (UN). It opposes also the first to the third sub-period 2014–2019 characterized by a high GDP per capita (GDP). The second discriminating factor (9.47%) distinguishes the second sub-period 2009–2013 characterized by high unemploy-

ment¹², from the third sub-period 2014–2019, characterized by a high GDP per capita (GDP) rates¹³.

Our results suggest that during the second period, coinciding with the economic and financial crises, the

¹² Nevertheless, the evolution of the unemployment rate is very different among European countries during the 2007–2017 period [83]. While Slovakia was at the top of the list of the highest unemployed countries before the crisis, it ranks eleventh ten years later. 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 position. 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.

¹³ Graphical representations for this theme are presented in Fig. 7 in the Appendix. For the other DA, graphical representations are available upon request.

economic performance of the 28 EU countries did not have a significant impact on environmental performance.

- 2) Regarding the four variables introduced in the *innovation system* model, the EPBI (Environmental Patent Balassa Index) is not discriminating, while all the others are discriminating and separate the three sub-periods well. The significant discriminating factor (91.43%) pits the second sub-period 2009–2013 along with the third sub-period 2014–2019 (characterized by a high number of environmental patents per million inhabitants, a high share of environmental technology patents and high R&D expenditure in % of GDP), against the first sub-period 2000–2008. The global warning concern has directed research and development towards environmental issues. The evolution of the innovation system is an important driver of the European energy transition.
- 3) As regards the *trade performance* model, only the dependence on EDEP energy imports is not discriminating. The EU's energy dependency has increased slightly over the period, from 53.9 in 2000 to 59.1 in 2019. However, its evolution did not have significant

effects on the ET trajectories in the 28 EU countries. In contrast, the improvement in energy terms of trade from 0.316 in the first sub-period 2000–2008, 0.345 in the second sub-period 2009–2013, to 0.379 in the last sub-period 2014–2019, probably related to the development of RE, has led to a better environmental performance.

- 4) Regarding the model of discrimination according to the *policy mix design*, it is significant as a whole, but two variables, government environmental protection expenditures (GEPE) and total environmental taxes (ENTV), are not discriminating. The significant first factor (97.16%) opposes the second sub-period 2009–2013 and the third sub-period 2014–2019 (characterized by a high rate of energy taxes (ENT) and a high rate of public research and development expenditure (GR&D)), to the first sub-period 2000–2008. 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 (including RE promotion schemes) have strongly contributed to improving environmental performance over the period 2009–2019.

Table 5 Spatial discriminant analyses over the sub-period 2014–2019 according to the four themes

Economic performance 2014-2019			
Complete model: 3 explanatory variables Multivariate Statistics and Approximations F			
Statistic	Value	F Value	Pr > F
Wilks' Lambda	0.7440	2.75	0.0646
Variable	R-Square	F-Value	Pr > F
GDP	0.2560	2.75	0.0646
GDPGR	0.1012	0.90	0.4553
UN	0.1079	0.97	0.4242
Misclassification rate: 28.57%			

Significance level α ; ** $\alpha \leq 1\%$; * $\alpha \in]1\%; 5\%]$

Trade performance 2014-2019			
Complete model: 4 explanatory variables Multivariate Statistics and Approximations F			
Statistic	Value	F Value	Pr > F
Wilks' Lambda	0.7356	2.88	0.0571
Variable	R-Square	F-Value	Pr > F
EDEP	0.2644	2.88	0.0571
TRADE	0.0796	0.69	0.5661
ETRADE	0.2199	2.25	0.1078
HTEX	0.0359	0.30	0.8265
Misclassification rate: 53.57%			

Innovation system 2014-2019			
Complete model: 4 explanatory variables Multivariate Statistics and Approximations F			
Statistic	Value	F Value	Pr > F
Wilks' Lambda	0.667779	3.81	0.0236*
Variable	R-Square	F-Value	Pr > F
PAT	0.2839	3.04	0.0494*
SPAT	0.3322	3.81	0.0236*
EPBI	0.3277	3.74	0.0253*
R&D	0.2624	2.73	0.0674
Misclassification rate: 33.33%.			

Policy mix design 2014-2019			
Complete model: 5 explanatory variables Multivariate Statistics and Approximations F			
Statistic	Value	F Value	Pr > F
Wilks' Lambda	0.7558	2.59	0.0767
Variable	R-Square	F-Value	Pr > F
GEPE	0.2442	2.59	0.0767
ENTV	0.1141	1.03	0.3967
ENT	0.1364	1.26	0.3092
GEER&R	0.0723	0.62	0.6069
GR&D	0.2109	2.14	0.1218
Misclassification rate: 32.14%			

4.3.2 Discriminant Effect on the Spatial Typology over the Period 2014–2019

As we showed in Sect. 4.1, the energy transition is on track for the period 2014–2019, so we focus our research on the drivers of the EU energy transition over this sub-period. We use DA¹⁴ models to see how each of the four themes distinguishes different classes of EU countries grouped according to their energy transition performance. Table 5 shows the overall results of the DA models for each theme. It can be seen that only one model, that of the *innovation system*, is significant and therefore discriminating—the Wilks' lambda of this model is below the 5% significance level. The *innovation system* is a key factor in the energy transition and explains the differences observed between the classes in terms of performances in the ET over the 2014–2019 period.

The *innovation system* model over the 2014–2019 sub-period as a whole is significant: three explanatory variables are discriminant with a significance level less than 5%, and consequently they perfectly differentiate the four classes of EU countries. The only significant discriminating factor (84.87%) opposes the fourth class consisting of Bulgaria and Estonia (characterized by a high share of environment-related technologies patents (SPAT) and a high level of environmental patent Balassa index (EPBI)), to the first class (characterized by a high level of patents in environment-related technologies (PAT) per million inhabitants and a high research and development expenditure (R&D) in % GDP).

The DA models highlight that the temporal and spatial determinants of the ET differ with respect to the three targets defined by the 2020 European Climate Energy Package. Indeed, while the four themes selected make it possible to discriminate the trajectory of the energy transition of the European Union over the period 2000–2019, only the *innovation system* theme explains the contrasted environmental performance of the countries over the period 2014–2019. Our findings provide strong evidence that, on the one hand, all the themes considered have been particularly effective in promoting ET over the period 2000–2019, and on the other hand that the national specificities of the *innovation system* also help to explain the contrasting results observed at country level over the last period.

5 Conclusion and Policy Implications

This paper aims to assess the progress made by the 28 EU members towards the ET over the period 2000–2019 by simultaneously considering the three energy and climate

targets, the reduction of GHG emissions, the development of renewable energies and the improvement of energy efficiency, using a multidimensional approach. It proposes a framework for evaluating the ET of the EU, and contributes to the existing literature in several ways. First, it offers a dynamic approach to the study of the EU's ET over a long period. Second, it identifies several trajectories, and highlights the similarities and dissimilarities between countries. Third, we use numerous variables relating to the national specificities of energy systems—*economic performance*, *trade performance*, *policy mix design* and *innovation system*—to explain the contrasting performance of countries in the ET process.

We note 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 identify four distinct types of energy transition profiles over the three sub-periods, and point out a stability in EU-28 member countries trajectories for the two first sub-periods. Over the last period, namely 2014–2019, we observe an opposition between two classes (1 and 2) that are rather virtuous in terms of ET, and two classes (3 and 4) showing degraded performances relative to the three ET targets. In particular, some economically more advanced developed countries, namely Germany, Ireland, Belgium, the Netherlands and Luxembourg, as well as Cyprus and two Eastern countries, the Czech Republic and Poland, are lagging significantly behind in achieving their three targets. This class failed to meet its energy efficiency target, and indeed a deterioration in the rate of effort has appeared since 2017. On average over the last 3 years, the rate of effort is insufficient regarding the target (the gap is 5.6%). Furthermore, in this class fossil fuels strongly contribute to the energy and electricity mix.

Finally, discriminating analyses show that the four explanatory themes considered (*economic performance*, *trade performance*, *innovation system* and *policy mix design*) differentiate the temporal classes and significantly explain the trajectory of EU's ET over the period 2000–2019. Note that energy taxes, public expenditure in R&D (including RE promotion schemes), environmental technology patents and R&D expenditure in % of GDP have strongly contributed to improving environmental performance over this period. On the other hand, only the *innovation system* theme makes it possible to differentiate the spatial classes and to explain the contrasting results observed at the country level over the 2014–2019 period. The most virtuous class is characterized by a high level of patents in environment-related technologies per million inhabitants and a high research and development expenditure in % GDP.

While there is no doubt that European environmental policy has led countries to make efforts in the right

¹⁴ DA is based on the 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.

direction, we note that in some countries the results are clearly insufficient compared to the targets set. According to the EEA report [82], the EU has achieved its three climate and energy targets for 2020. However, these targets have been achieved against the backdrop of the COVID-19 crisis, which weighed heavily on activity, sharply reducing energy consumption and GHG emissions. The progress already achieved will need to be strengthened during the recovery from the COVID-19 pandemic, so that Europe can meet its commitments of carbon neutrality by 2050, including the intermediate 2030 target of an at least 55% reduction in GHG emissions.

From our results, two policy recommendations can be made to promote the energy transition and strengthen Europe's leading position. There is a need to better target public policies and spending to ensure a sustainable and efficient allocation of energy resources.

First, the EU as well as national governments have a leading role to play in fostering innovation for the ET, and thus investing in research and innovation must be their priority to fight against global warming. The levers are numerous. Investments in improving energy efficiency and developing a circular economy need to be boosted with the aim of reducing energy demand, as they represent the most cost-effective way to achieve the EU's climate goals. At the same time, the EU needs to launch an ambitious R&D program promoting the development of large-scale deployment of low-carbon technologies and fuel substitutions (hydrogen, natural gas, sustainable bio-based feedstocks) through combinations of new and existing technologies and practices, including electricity storage to overcome intermittency, and carbon capture, utilization and storage. Furthermore, the Intergovernmental Panel on Climate Change [84] and the OECD have stressed the urgency for action, and consider that nuclear energy is the keystone for achieving carbon neutrality by 2050, in addition to renewable energies. Recent experience has shown that countries that have withdrawn from nuclear power have had to resort to restarting fossil fuel power plants, including coal, greatly increasing their GHG emissions. So governments should also invest to accelerate nuclear energy deployment. Small Modular Reactors are opening new applications for nuclear energy and offer many advantages: they represent savings in cost and construction time, as well as flexibility, and can be deployed incrementally to meet growing energy demand. Recently, for the first time in decades, France has decided to relaunch the construction of nuclear reactors. According to a group of ten EU countries, led by France and Poland, nuclear power is a crucial and reliable asset for a low-carbon future, and these countries are trying to convince the European Union that nuclear power should be classified as clean energy.

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 taxes have been the drivers of the energy transition. In order that the European commitment to becoming the first climate-neutral continent by 2050 does not remain without follow-up, an appropriate legal framework must be defined. This is why the European Commission has adopted a series of legislative proposals aimed at revising existing legislation, notably concerning the EU ETS, the Effort-Sharing Regulation, transport and land use legislation.

The EU must continue its efforts to ensure its leadership in the battle against global warming, but will have to overcome various obstacles. In a context of massive indebtedness of states and the high degree of uncertainty on energy prices induced by the COVID-19 pandemic, the development of the energy transition and renewable energies may be threatened in the short term. Despite economic recovery and low interest rates, private investment remains low and budgetary margins are narrow. Mobilizing both public and private investment will be essential to meeting climate change goals. 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 addition, the EU must prevent negative impacts of its environmental policy, both on firm's competitiveness and on the energy vulnerability of low-income households. In a global context dominated by the proliferation of trade disputes between the USA and China, Europe must sound its voice by imposing a simple rule: given the climate emergency, it is now necessary to subordinate the freedom of 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.

Given the immense financial demands of sustainable development,¹⁵ public funds are clearly insufficient. There is an urgent need to mobilize private funding; according to the European green deal investment plan [85], an additional €350 billion per year is required in the decade 2021–2030 compared to the previous decade, in order to achieve the 2030 climate and energy targets.¹⁶ The definition of criteria

¹⁵ "Sustainable finance refers to the process of taking environmental, social and governance (ESG) considerations into account when making investment decisions in the financial sector, leading to more long-term investments in sustainable economic activities and projects." https://ec.europa.eu/info/business-economy-euro/banking-and-finance/sustainable-finance/overview-sustainable-finance_fr

¹⁶ An increased emissions reduction target of 55% by 2030 as compared to 1990.

to identify economic activities that contribute substantially to climate and environmental objectives; the provision of information to companies (including SMEs) that must publish relevant, reliable and comparable sustainability information; the obligation for financial actors to disclose the environmental effects of their activities; the creation of a European green label for retail financial products; a legislative proposal on a standard for European green bonds; etc.—all these are only some of the means that are being, or will be, implemented as part of this effort.

Author Contribution Patricia Renou-Maissant: conceptualization, data preparation, validation, the writing, review and editing, and project administration. Rafik Abdesselam: data preparation, methodology, data analysis methods and statistical modeling, the writing. Jean Bonnet: conceptualization, data preparation, the writing, review and editing. All authors have read and agreed to the published version of the manuscript.

Availability of Data and Materials Available.

Code Availability Not applicable.

Declarations

Ethics Approval We have conducted ourselves with integrity, fidelity and honesty. The submitted work is original and has not been published elsewhere in any form or language.

Consent to Participate We are willing to participate to the process of evaluation of our work by the Journal *Environmental and Modeling Assessment*.

Consent for Publication We are willing to participate to the process of publication of our work by the Journal *Environmental and Modeling Assessment*.

Conflict of Interest The authors declare no competing interests.

Appendix

Table 6 Active variables

Components of energy transition EU-28	Source
GHGC: greenhouse gas emissions per capita (tonnes of CO ₂ equivalent per capita)	Eurostat
PEI: primary energy intensity (tonnes of oil equivalent (toe) per thousand euros at 2010 market prices)	Eurostat
SREC: share of renewable energy consumption (% of total final energy consumption)	Eurostat

Table 7 Illustrative and Explanatory variables

A Descriptive variables related to energy system	Source
PECON - Primary energy consumption (per capita), tons per capita	Eurostat
FECON - Final energy consumption tons per capita	Eurostat
EU - Energy use (kg of oil equivalent per capita)	Eurostat
FFEC - Fossil fuel energy consumption (% of total)	Eurostat
EAFC - Electricity available for final consumption (kWh per capita)—	Eurostat
SB - Share of biofuels in gross inland renewable energy consumption (%)	Eurostat
SSFF - Share of solid fossil fuels in gross available energy (%)	Eurostat
SHP - Share of hydro power in gross inland renewable energy consumption (%)	Eurostat
SSP - Share of solar photovoltaic in gross inland renewable energy consumption (%)	Eurostat
SNG - Share of natural gas in gross available energy (%)	Eurostat
SOPP - Share of oil and petroleum products (excluding biofuel portion) in gross available energy (%)	Eurostat
SRB - Share of renewables and biofuels in gross available energy (%)	Eurostat
SNRW - Share of non-renewable waste in gross available energy (%)	Eurostat
SNH - Share of nuclear heat in gross available energy (%)	Eurostat
SFF - Share of fossil fuels in gross available energy (%)	Eurostat
SST - Share of solar thermal in gross inland renewable energy consumption (%)	Eurostat
SWP - Share of wind power in gross inland renewable energy consumption (%)	Eurostat
EPSFFS - Electricity production from solid fossil fuels sources (% of total)	Eurostat
EPNGS - Electricity production from natural gas sources (% of total)	Eurostat
EPOPP - Electricity production from oil and petroleum products (excluding biofuel portion) sources (% of total)	Eurostat
EPRBS - Electricity production from renewables and biofuels sources (% of total)	Eurostat
EPHS - Electricity production from hydroelectric sources (% of total)	Eurostat

Table 7 (continued)

A Descriptive variables related to energy system	Source
EPNH - Electricity production from nuclear heat (% of total)	Eurostat
EPOGC - Electricity production from oil, gas and coal sources (% of total)	Eurostat
EPROD - Energy productivity (Euro per kilogram of oil equivalent (KGOE))	Eurostat
PERBS - Electricity production from renewables and biofuels sources, excluding hydroelectric (% of total)	Eurostat
PERBK - Electricity production from renewables and biofuels sources, excluding hydroelectric (kWh) per capita	Eurostat
B Effort ratios to national target	Source
EF_GHG: Greenhouse gas emissions	Eurostat
EF_PEC: Primary energy consumption	Eurostat
EF_SREC: Share of renewable energy in final energy consumption	Eurostat
C Explanatory thematic variables of the discrimination models	Source
Economic performance	
GDP - GDP per capita (constant price 2010)	World Bank
GDPGR - GDP growth rate	World Bank
UN - Unemployment rate (all 15–64)	Eurostat
Innovation system	
PAT - Patents in environment-related technologies per million inhabitants 2017	OECD
SPAT - Share of environment-related technologies patents in total patents (%) 2017	OECD
EPBI - Environmental patent Balassa index 2017	OECD
R&D - Research and development expenditure (% of GDP)	World Bank
Trade performance	
EDEP - Energy dependence measured as energy imports in % of energy uses	Eurostat
TRADE - Terms of trade measured as the ratio of export prices to import prices	Eurostat
ETRADE - Energy terms of trade measured as the ratio of energy exports (Mtoe) to energy import (Mtoe)	Eurostat
HTEX - High-technology exports (% of manufactured exports)	Word Bank
Policy mix design	
ENT - Energy taxes (% of GDP)	Eurostat
ENVT - Total environmental taxes (% of GDP)	Eurostat
GR&D - Total government budget allocations for R&D (% of GDP)	Eurostat
GEPE - Governments' environmental protection expenditures (% of GDP)	Eurostat
GEER&R - Governments' environmental and energy R&D expenditures (% of GDP)	Eurostat

In the temporal DA on the sub-periods, we do not have the GEER&R data from 2000 to 2003, thus the variable is dropped and there are only 4 variables in the model

Table 8 Class weights in terms of GDP and population in the EU-28 (%)

	2000–2008		2009–2013		2014–2019	
	GDP	POP	GDP	POP	GDP	POP
Class 1	8.87	8.38	11.21	14.59	10.51	9.10
Class 2	8.10	18.36	5.17	11.08	53.79	56.77
Class 3	82.67	73.14	83.25	74.20	35.23	32.51
Class 4	0.36	0.12	0.36	0.12	0.45	1.62

Table 9 Synthesis of the partition into 4 classes of the EU-28 countries over the sub-period 2014–2019

Sub-period 2014-2019		Class 1	Class 2	Class 3	Class 4
Frequency (%)		7 (25%)	11 (39.29%)	8 (28.57%)	2 (7.14%)
Countries		Austria Croatia Finland Latvia Portugal Sweden Denmark	Malta Italy Spain France Greece U-Kingdom Romania Slovakia Hungary Lithuania Slovenia	Netherlands Belgium Czechia Germany Ireland Poland Cyprus Luxembourg	Bulgaria Estonia
Active Variables	Profile (+)	+ SREC 14 to 19		+ GHGC 14 to 19 + PEI 18,19	+ PEI 14 to 17
	Anti-Profile (-)	- PEI 18,19	- GHGC 14 to 19	- SREC 14 to 19	
Supplementary variables Thematic variables & Effort ratios & Energy system		+ EPRBS 14 to 19 +SRB 14 to 19 +EPHS 14 to 19 +PERBK 14 to 19 +SHP 17 14 to 19 +PERBS 14 to 16 +SNRW 15,16,19 +EAFC 14 to 19 +EF_SREC 14 to 19 +PAT 14 to 17 +GR&D 14 to 18 +R&D 14 to 19	+EPNH 15 +GEPE 14 to 16 +UN 19	+FFEC 14 to 19 +SFF 14 to 19 +EPOGC 14 to 19 +FECON 14 to 19 +PECON 14 to 19 +SWP 15 to 19 +EU 14 to 19 +EF_PEC 15 to 19 +EF_GHG 14 to 19 +GDP 14 to 19	+SRB 17 to 19 +SB 18,19 +SNRW 14 +EF_SREC 17 to 19 +SPAT 14 to 17 +ETRADE 17 to 19 +EPBI 14 to 17 +ENT 19
		-FFEC 14 to 19 -SFF 14 to 19 -EPOGC 14 to 17,19 -SSP 14, 17 to 19 -GEPE 14 to 19 -GDPGR 14	-PERBK 14 to 19 -FECON 14 to 19 -PECON 14 to 19 -EU 14 to 19 -EAFC 14 to 19 -SRB 18, 19 -SNRW 14 to 19 -EF_GHG 14 to 19 -GR&D 14 to 19 -GDP 18 to 19 -PAT 14 to 16 -R&D 19	-SHP 14 to 19 -SRB 14 to 19 -EPHS 14 -EPRBS 14 -EF_SREC 14 to 19 -ETRADE 18 to 19 -SPAT 15 -EPBI 15	-EPROD-14 to 19 -FFEC 14 -SFF 19 -SOPP 19 -EDEP 14 to 19

This table summarizes the main results of the HAC characterization of the chosen partition into four classes of countries, obtained from the cut of the hierarchical tree of Fig. 5. Division is carried out according to the positions of the countries, on the factorial axes of the PCA. All the variables presented in this table are significant with a risk of error less than or equal to 5%. The sign ‘-’ (respectively ‘+’) indicates a level significantly lower (respectively higher) of the average of the variable in the class considered compared to the average of the variable over all 28 countries. The years for which the variables are significant are specified after the names of the variables

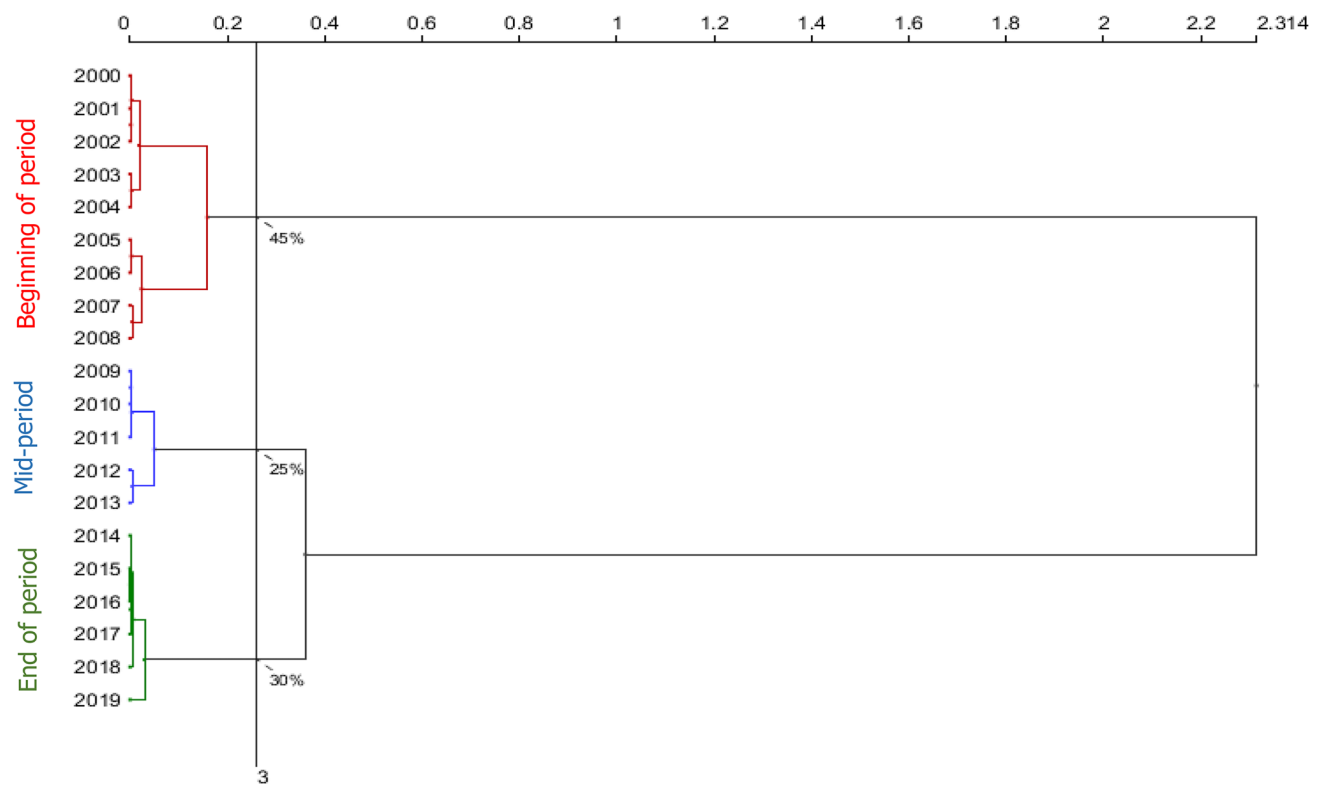


Fig. 4 Hierarchical tree of the temporal evolution according to the EU energy transition

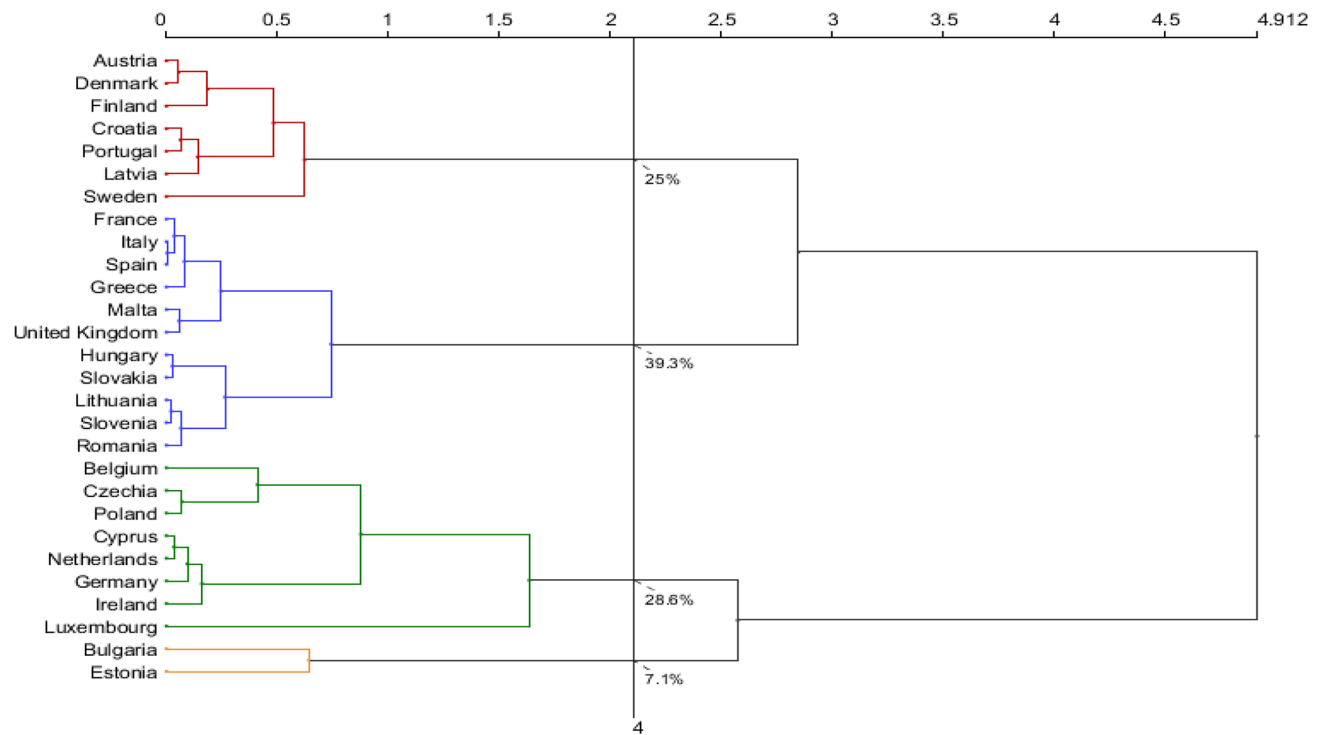


Fig. 5 Hierarchical tree of the EU countries according to the energy transition over the sub-period 2014–2019

Fig. 6 Average effort to the target according to spatial typology classes over the 2014–2019 sub-period

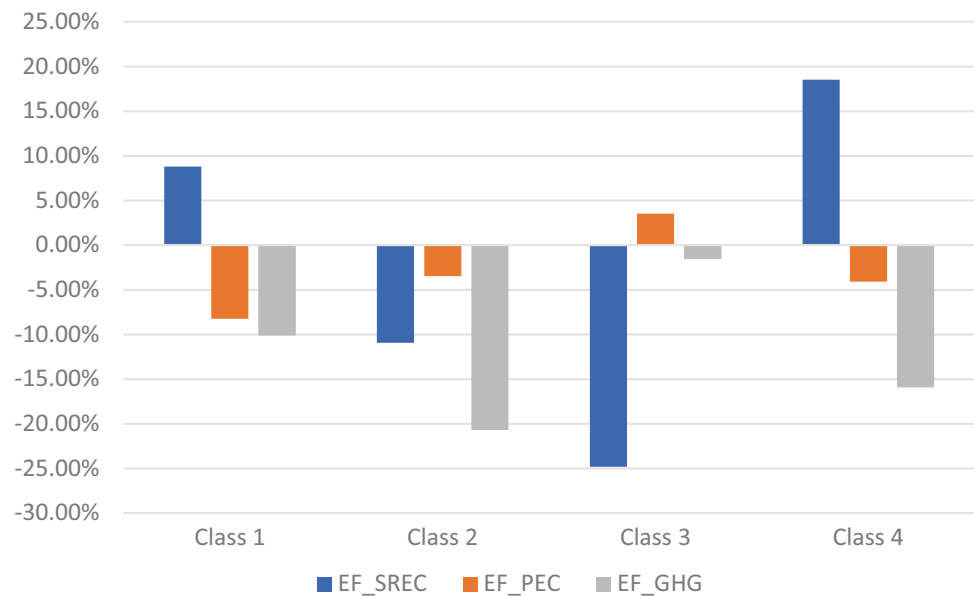
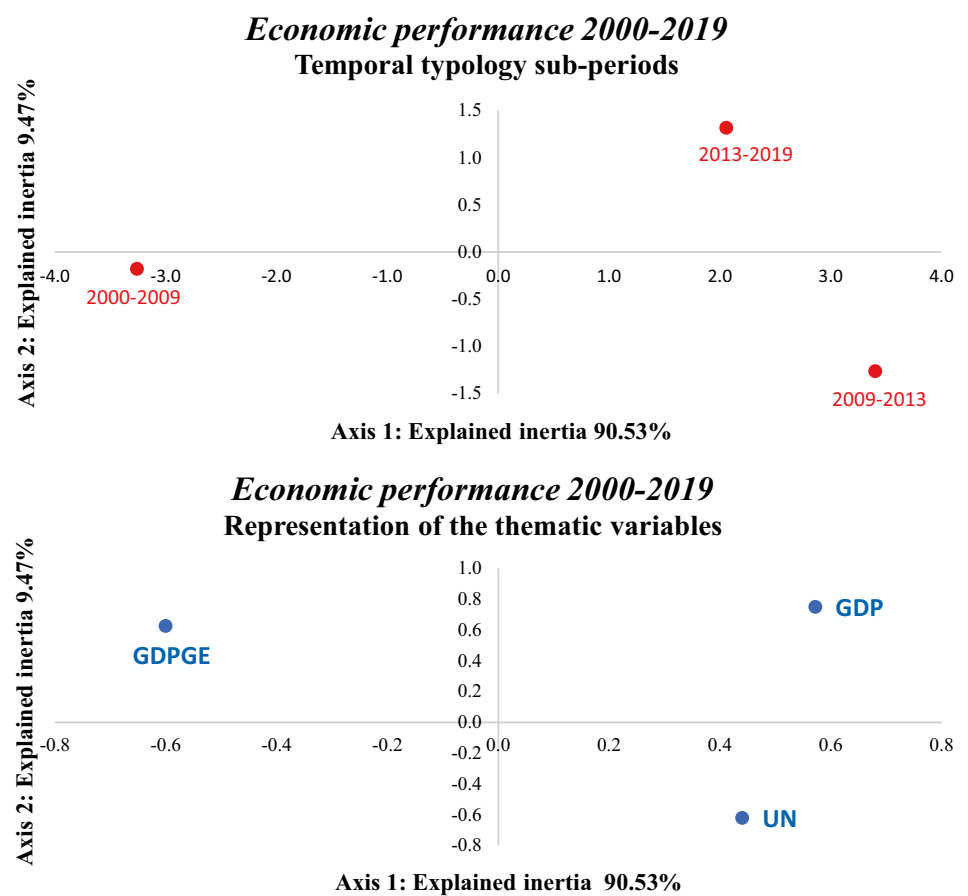


Fig. 7 DA — economic performance and temporal typology



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