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A synergistic analysis of solar and wind energy deployment in Europe

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ABSTRACT

Recent energy tensions have added to the pressure that global warming has been exerting for an energy transition towards low-carbon energy sources such as renewable energy sources (RES). This study proposes a novel methodology to inspect the interactions between wind and solar energy development relative to other RES and a wide range of socio-economic and environmental variables in 21 European countries during the period 2007–2021. First, countries are ordered according to their average level during the evaluated period. The ordinal position of each country is used as input for a multivariate analysis that avoids problems of multicollinearity and inefficiency inherent to model estimation with a large number of intertwined covariates. In a second stage, by means of Categorical Principal Component Analysis (CATPCA) all the information from the rankings is synthesized into two factors. This makes it possible to graphically evaluate the interplay between the different variables and the relative positioning of the countries in relation to the average level observed for the different factors during the sample period. Overall, the obtained results suggest a decoupling between the development of wind energy and solar energy sources. High levels of wind penetration in the RES mix seem to be positively associated with energy consumption and economic factors while solar energy seems to have experienced greater development in countries with greater energy dependence. The finding that energy, economic and environmental variables affect the development of wind and solar energy very differently highlights the need to analyze each of the renewable energy sources independently. Likewise, it has important implications in terms of the design of energy policies, highlighting the importance of implementing sector-specific measures.

1. Introduction

The push for the decarbonization of energy resources in recent years has not suffered from lack of motivation. Recent energy tensions observed as a consequence of the ongoing war in Ukraine have highlighted the risk of over-reliance on offshored fossil fuel-based energy and complemented empirical findings on the detrimental effects of energy insecurity and fossil fuel dependence (Doğan et al., 2023a,b). Furthermore, the latest report of the United Nations Environment Programme (UNEP, 2023) shows that along with temperature, global greenhouse gas (GHG) emissions and atmospheric concentrations of carbon dioxide (CO_2) set new records in 2022,

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despite the fact that predicted 2030 greenhouse gas (GHG) emissions still must fall by 28% for the Paris Agreement 2°C pathway. These drivers, among many others, emphasize the need for nations to accelerate economy-wide, low-carbon development transformations, such as those relying on renewable energy (RE). But have these calls been heeded?

According to the European Environment Agency (EEA, 2023), 22.5% of energy consumed in the European Union (EU) in 2022 was generated from renewable energy sources (RES). Given that in October 2023 the EU signed an update of the *Renewable Energy Directive* with the objective of ensuring that the consumption of renewables reaches a weight of 45% in 2030, there is significant work to be done in the coming years in terms of RES development. Despite the growing potential and importance of RES, their penetration in most power grids is still low and varies considerably between different countries. This diversity in the renewables development in European countries was noted by Papież et al. (2018), who found that between 1995 and 2014 all EU countries increased their shares of RES but that the growth was uneven, and that the relative weight of different types of renewables in total RES also differed considerably across countries. Understanding this disparity in RES development will play a key role in reaching the goals posed by the EU and addressing the threats created fossil fuel dependence.

This, of course, is not an easy task. Understanding the 'why' behind RES development first necessitates an understanding of exactly what role RES plays in a nation's society and economy. Previous work on this latter theme has not only shown a special significance in the relationships between energy, economic growth and carbon emissions (Doğan et al., 2020; Grodzicki and Jankiewicz, 2022; Mahmood, 2020, 2022, 2023), but that the emission-reducing nature of RES has a weighty effect on the way these relationships exist and are understood (Doğan et al., 2021; -., 2023; Yao et al., 2019).

However, not all RES are created equal. While the attraction of RE comes from its use of non-finite resources such as the sun or wind, the inconsistent availability of these sources due to weather and climate make integration of some RES complicated. RES suffering from this variability—mainly wind, solar and hydropower—have come to be called variable renewable energy sources (VRES), and are expected to play a key role in increasing the overall share of renewables (Raynaud et al., 2018). Indeed, wind energy represented 13% of the total RE supply in Europe in 2022, and solar was cited as the fastest growing RES (EEA, 2023), making these two energy sources especially of interest.

As such, the development of VRES suffers from a uniquely complex set of circumstances. While VRES depend heavily on weather and climate, they are still subject to many of the same aforementioned socioeconomic conditions that affect their production and consumption. For this reason, VRES studies attempting to model or understand the adoption of these energies should represent an intersection of economic, political, and environmental phenomena to properly account for all the challenges VRES will face (Chen et al., 2019). In the literature as of date, research tends to focus on either the climatological (Castillo et al., 2016; Miglietta et al., 2017) or economic (Dascalu, 2012; Ntanos et al., 2018) interaction with VRES development, but there is a lack of studies utilizing an integrated perspective. Therefore, the goal of this paper is to apply a holistic approach in order to understand the interaction of VRES, namely wind and solar energy, with a wide range of socio-economic and environmental factors.

This study focuses on the interplay between a wide range of socio-economic and environmental factors and the wind and solar energy consumption in a set of 21 European countries over a 15-year period. The consumption of wind and solar energy will be studied relative to the total consumption of RES in a given country in order to understand the preferential development of VRES over other RES. Furthermore, by taking a multidimensional perspective, this analysis makes use of multivariate techniques that eschew some of the potential problems inherent to the estimation of causal models, while providing a comprehensive view of the interdependencies within the variables of interest and their potential determinants.

This novel methodological approach is based on Categorical Principal Component Analysis (CATPCA), which is applied to the rankings of countries obtained after computing the average values of the different variables during the sample period. CATPCA is used to turn this categorical ranking data into two uncorrelated components that allow for nations to be clustered and positioned relative to these components. The use of CATPCA not only allows working with different types of information, be it nominal, ordinal or numerical, but it can also capture non-linearities in the relationships between these variables. Further, the clustering of each economy on a biplot according to its scores in both dimensions allows evaluating the relative relationship between countries with respect to the information captured in the components.

While the analysis cannot derive causal conclusions, this empirical study offers an alternative approach to evaluating the interconnections of various key factors in the development of VRES that includes (a) the use of visualization techniques in understanding VRES development and their connection with a wide array of variables, (b) a quasi-dynamic perspective of the evolution of each country through the rankings of average levels from 2007 to 2021, and (c) an assessment of the relative relationship between different economies with respect to this interplay.

The analysis is divided into three main stages. First, information regarding all variables is collected for the period from 2007 to 2021. This makes it possible to capture the interactions between the different factors included in the study during a time interval sufficiently long to evaluate how they have affected the rate of penetration of solar and wind energy in 21 European countries. The main objective is to cover a wide spectrum of factors, which are divided in four categories: energy, economic, socio-political, and environmental. In this first stage, the countries are ordered according to their average level during the evaluated period. These rankings offer an overview of the relative importance of solar and wind energy, their evolution, and that of their potential determinants from 2007 to the present.

In a second stage, the ordinal position of each country in the ranking is used as input for the multivariate analysis by means of CATPCA. This procedure allows synthesizing the information from all the rankings into two components, which are used to analyze the interplay between the different variables and wind and solar development during the sample period. The output shows a decoupling between the evolution of wind and solar deployment in European countries.

Finally, in the third stage, the scores of each country in each dimension are used to graph the relative positioning of the countries.

Overall, the resulting projection onto a perceptual map shows three clusters that roughly correspond to the major European regions (southern and eastern Europe, northern Europe, and western Europe. The implications of these findings reinforce the role of policy makers in designing sector- and region-specific energy policies in order to accelerate the deployment of these clean technologies.

The present study differs from most previous work in several aspects. First, the interactions between a wide range of factors are analyzed simultaneously, thus avoiding problems of multicollinearity and inefficiency in the estimates of the parameters typical of causal studies (Papież et al., 2018). To do this, a novel approach is proposed that has not previously been used in this context before. Second, the analysis is based on a multivariate technique that allows the use of different types of information. Specifically, CATPCA, also called non-linear PCA, is applied in order to consider the potential non-linearities between the variables. According to Khalfaoui et al. (2023), the existence of a non-linear relationship between variables means that traditional mean-based panel data estimation methods may be providing an incomplete picture of the factors behind environmental problems.

Third, the study focuses on the two main sources of VRES—solar and wind—individually, whereas many previous studies work with RES as a single agglomerated variable, agnostic to the nuances involved with the different sources. Furthermore, these two variables are analyzed as shares of total RES consumption rather than as absolute values, providing a new and fresh perspective on the preferential development of these resources vs other RES. Fourthly, the study incorporates environmental factors as potential determinants of VRES development, which according to Şener et al. (2018) have so far been understudied. Some of the climatic indicators used have been computed *ad-hoc* for the present study.

Fifth, the analysis also considers human development, which incorporates other dimensions like education and health, and which has been shown to be affected by energy consumption (Li et al., 2024). Nguyen and Kakinak (2019) further pointed out the importance of designing RE consumption policies consistent with the level of development of each country.

Finally, the study aims to address the evolution in the interaction between the different variables throughout the evaluated period from an empirical perspective, without making any *a priori* assumption regarding the supposed effect they have on wind and solar deployment, therefore providing researchers with an easy-to-implement framework for the identification of drivers and barriers to RES development.

The remainder of this paper is structured as follows. Section 2 assesses the current state of research surrounding VRES development. Section 3 describes the data. The next section briefly describes the methodology. Section 5 presents the results of the CATPCA analysis and the robustness checks. Section 6 discusses the results and the political implications derived from them. Finally, Section 7 summarizes the main findings, states the limitations of the study, and looks at opportunities for future research.

2. Literature review

Traditionally, research on the development of VRES has primarily looked at natural, economic, or political factors in isolation. To understand the relative weight of these different areas on VRES research, Şener et al. (2018) reviewed 60 qualitative and quantitative studies and identified seven frequently cited categories of drivers and barriers to RE deployment. Environmental, economic, and social factors were identified as drivers of RE, while political, regulatory, technical potential, and technological categories were all found to have undetermined effects on RE development. National income was also identified as a driver. These authors found that economic factors were overrepresented in the selected manuscripts, while there was an underrepresentation of environmental variables. As of the study's date of publication, periods after 2010 were found to be underrepresented in studies relating to RE deployment.

An interdisciplinary study most like the work undergone in this present paper is that of Papież et al. (2018), in which the authors researched the determinants of various types of RE in 26 European countries from 1995 to 2014. Papież et al. (2018) used Principal Component Analysis (PCA) as a part of their research methods to investigate the distribution of energy consumption, first with respect to different RES, and then with respect to fossil fuels and total RE consumption. The principal components from the latter analysis were then used in a cross-sectional regression along with various variables relating to potential determinants of RE growth. While these determinants include a mix of environmental, political, and economic factors, their environmental variables are limited to those representing 'environmental concern', such as CO_2 emissions, but do not include any climate or weather-related factors. That said, their results from the first PCA analysis showed that wind and solar had grown the fastest relative to other RES, and the cross-country patterns of this growth followed the geographical climatic potential of each energy source (i.e. northern countries showed greater wind growth and southern, sunny, countries showed greater solar growth) pointing to a relevant effect of climate on VRES development. Via the regression analyses involving determinants, Papież et al. (2018) also found that one of the most important factors controlling development of renewables in the present was pre-existing levels of RE, implying that early decisions regarding RE implementation have consequences on the future growth of these energy sources.

Another similar study is that of Brodny and Tutak (2020), who analyzed the diversity of EU countries in terms of their use of RES, incorporating economic variables such as development and wealth, population and geographical location. The authors used the k-means algorithm to cluster countries into similar groups by the structure and volume of energy production from RES with the aim of considering additional factors when developing and implementing new climate strategies. Similarly, Tutak and Brodny (2022) analyzed RE use in EU countries at a sectoral level. Using data from 2000 to 2019, the authors implemented a self-organizing maps analysis to generate spatial representations of the data, finding cross-sectoral differences and a positive impact of RES-based consumption on economic growth and the reduction of emissions, especially in the older countries of the EU.

Hernik et al. (2019) took an interdisciplinary approach to analyzing the controls on RE development in Eastern Poland, using a Spearman's rank coefficient correlation test to analyze the relationship of spatial-economic variables with a number of RES in urban vs rural areas. The authors found a significant difference in the nature of RE development between rural and urban districts, where development in urban districts tended to show a correlation with economic factors, while rural districts showed a stronger correlation to 'spatial' factors, i.e., population density and physical characteristics of the land in that area. Additionally, the authors found that of all the RES studied, solar photovoltaic energy sources tended to show higher correlations to more spatial-economic variables than other sources, specifically in urban districts.

As noted by Şener et al. (2018), the relationship of RE development to economic variables, especially relating to Gross Domestic Product (GDP), has been extensively researched. Despite this, the nature of the relationship between GDP and RE development is still not entirely agreed upon. Many studies have pointed to positive relationships between renewables and economic growth (Apergis and Payne, 2010; Doğan et al., 2020; Sadorsky, 2009), especially among higher-income countries (Al-mulali et al., 2013). On the other hand, Menegaki (2011) estimated a random-effects model to assess this relationship in 27 European countries and found no significant relationship between RE and GDP.

Using a different approach, Yao et al. (2019) incorporated GHG emissions into their analysis of RE consumption and GDP using an adapted Environmental Kuznets Curve (EKC). The traditional EKC expresses the relationship between CO_2 emissions and an increasing GDP in three stages: *i)* the scale effect stage, in which emissions are increasing with a relatively low starting GDP; *ii)* the structural effect phase in which emissions stabilize due to a transition from a high-pollution to low pollution environment, and *iii)* the technology effect phase, in which GDP is sufficiently high to allow investing in emissions-reducing technology. This effect creates an inverted U-shaped relationship between CO_2 emissions and GDP, Yao et al. (2019) found that in contrast to emissions, RE has a U-shaped relationship with GDP implying that significant increases in RE consumption will only be seen in high-income nations that have crossed the threshold into the "technology effect" stage. This theory is supported by the work of Magazzino et al. (2022) which showed that, for Scandinavian countries, increasing renewables consumption lowered CO_2 emissions without hindering energy efficiency and economic growth. These findings support the theory that RE can lead to a decrease in CO_2 emissions while still growing GDP.

Bölük and Mert (2014), on the other hand, did not find the EKC hypothesis to hold for 16 European countries over a study period of 1990–2008. Their results showed no evidence that high economic productivity would lead to a decrease in CO_2 emissions, and instead found the opposite—that GHG emissions were continually increasing with GDP. As such, while Bölük and Mert (2014) found that RES produced less emissions than fossil fuels, the authors did not find that RE growth led to a decreasing trend in emissions, given that RE stimulated GDP, and GDP growth was always associated with a CO_2 rise. Similar research has empirically proved (Auci and Trovato, 2011; De Bruyn et al., 1998; Mahmood et al., 2023a, 2023b; Markandya et al., 2006) and disproved (Akbostancı et al., 2009; Grossman and Kreuger, 1995) the EKC hypothesis, making it a contested subject further complicated by the role that RE plays in national economies.

It is worth noting that, save for Şener et al. (2018), all the above literature does not limit its exploration of renewables to VRES, although these energy types are included. While these studies are still useful in contextualizing the state of renewable development, VRES present unique challenges to power systems and the energy grid not present in other types of RES (Babatunde et al., 2020; Huber et al., 2014; Johnson et al., 2020), and it has been posited that addressing these obstacles will require economic and political intervention (Verzijlbergh et al., 2017). Thus, a focus on the interaction of economy and policy with VRES development specifically is relevant in understanding the specificities of this sector apart from other RES.

On the other hand, the weather and climate dependence of VRES has resulted in many climate and weather studies that focus on these types of RES specifically. The existing studies approaching VRES from an earth science perspective have largely focused on potential and hypothetical scenarios, although the relationships identified can still be helpful in understanding the relationship between climate and VRES development. Castillo et al. (2016) used land constraints and resource availability (i.e., solar radiation levels) to create a suitability map for solar power generation across the EU. The authors found that higher suitability tended to correspond to countries with higher solar radiation levels, mainly those of the southern Mediterranean, thus supporting a relationship between solar energy development and climate.

One of the most common concerns regarding VRES from a power systems perspective is the potential for a mismatch between energy demand and energy supply due to the volatility of VRES generation (Johnson et al., 2020; Kroposki et al., 2017). Using weather-to-energy conversion modelling, Raynaud et al. (2018) assessed this supply-demand relationship in VRES across different European climates in the form of insufficient energy production events, or 'energy droughts'. The authors found key characteristics and geospatial differences between wind and solar energy droughts. The authors observed that wind power had more day-to-day variability leading to a higher frequency yet short duration wind energy droughts, regardless of geographic region. Their models also revealed that solar energy droughts are characterized by either short, weather-related events or long, seasonal influences, and that the severity and length of these long droughts are exacerbated in high latitude countries by a decrease in winter-time daylight hours but an increase in winter energy demands.

The models used in Raynaud et al. (2018), as well as those in a similar meteorological study done by Van der Wiel et al. (2019), showed that energy systems with greater mixes of solar and wind energy led to a general decrease in adverse energy production events. This relationship between VRES and the power system itself is also a key factor in VRES development, as higher penetrations of VRES pose greater technical challenges to power systems (Bird et al., 2013; Huber et al., 2014; Sinsel et al., 2020), and thus potentially higher integration costs (Gross et al., 2006; Hirth et al., 2015; Holttinen et al., 2013). Therefore, all these challenges could pose problems to the incentivizing of VRES development at an institutional level (Verzijlbergh et al., 2017). Consequently, understanding VRES development relative to other RE sources may also play a key role in understanding VRES development *per se*.

The above studies cumulatively show that VRES development has clear relationships with a variety of factors relating to economic and political contexts, the nature of the pre-existing energy supply and geographic climates. This implies that the study of VRES development cannot exist in a vacuum with respect to any given sector, and thus a comprehensive representation of the VRES landscape requires a relative understanding of how these different factors relate to each other as well as with VRES, which is the goal of the present study.

3. Data

The study is based on a panel dataset that includes a variety of 17 indicators for 21 European countries. The sample period extends from 2007 to 2021. The selection of countries is done according to the availability of information. Consequently, with the aim of having a sufficiently long period of time and covering the different areas of the continent, a dataset with information for 21 countries was created. These economies are distributed across the four main regions of Europe: Central Europe (Austria, Belgium, France, Germany, Netherlands), Northern Europe (Denmark, Finland, Norway, Sweden, and Ireland), Southern Europe (Croatia, Greece, Italy, Portugal, Slovenia, and Spain) and Eastern Europe (Bulgaria, Czechia, Hungary, Slovakia, and Slovenia). The countries selected not only represent a wide range of geographical locations, but also different stages of development of wind and solar energy (See Figs. 1 below).

The data in this study was chosen to reflect a wide variety of potential determinants on the development of wind or solar energy relative to other RES. Generally, these variables fall into one of four spheres: energy, socio-political factors, economy, and environment. Table 1 shows the explanation of each variable, as well as its units of measurement. Each variable in Table 1 is categorized by one of these dimensions. The data used was sourced from Eurostat, The World Bank, OECD, the United Nations (UN), and the Copernicus Climate Change Service. Note that all weather variables (wind speed at 10m, GHI, temperature range) were taken from climate reanalysis data, provided by the Copernicus Climate Change Service.

The energy category in Table 1 contains the variables of interest, wind and solar shares, which represent the share of RE consumption coming from wind and solar sources (photovoltaic and thermal). The relative shares of wind and solar, as opposed to their absolute values, were chosen for two main reasons. Firstly, it favours an easier comparison across countries. Secondly, it allows the investigation of the preferential use of wind or solar energy vs other RES rather than the general use of wind and solar. Thus, these variables shed light as to why wind or solar might be preferable against other RE options while allowing this comparison to be conducted between countries that, for a variety of reasons, have vastly different absolute amounts of RE generation.

The context of these variables at the beginning and at the end of the sample are represented in Fig. 1, which shows that while both wind and solar shares have increased between 2007 and 2021 in all countries, solar shares have experienced more drastic relative increases given the low values in 2007 for almost all countries. This is especially evident in in Spain, the Netherlands, Hungary, Belgium and Greece, with the latter two countries, along with Ireland and Portugal, boasting notable increases in wind shares as well. A closer inspection at the differentials in growth across countries suggests the existence of some geospatial trends: the countries with the least amount of wind share growth tend to be clustered in southern Europe, while similarly it is the northern countries in Scandinavia that have experienced virtually no significant solar share increase, save for Denmark. These preliminary explorations of the variables of interest not only provide important context for their study, but also motivate the analysis of the different trends in VRES deployment observed across European countries.

With respect to the selection criterion for the other variables in the energy category, the representation of 'energy consumption' was divided into three distinct sectors (industry, transportation and household) to investigate any sector-specific relationship to energy consumption. See Toma et al. (2023) for the role of transportation in order to ensure environmentally sustainable growth. 'Energy import' was chosen to introduce the very relevant question of energy dependency in Europe, especially given the war in Ukraine and the empirical findings of Chu et al. (2023a,b), who showed that geopolitical risk can actually be a driver of RES deployment in high income countries. The 'energy intensity' variable was chosen in tandem with 'GHG emissions' and 'per capita income' as a nod to the previous research discussed in Sections 1 and 2, which placed so much emphasis on the interplay between carbon emissions, economic growth and energy. In the context of the debates as to whether RE is capable of decoupling increased economic output with increased emissions, decreasing energy intensity has been specifically named as a possible mechanism for achieving this (Aydin and Turan 2020), hence its introduction here.

In the socio-political category, 'population density' and the percentage of 'urban population' are meant to capture the effect population distribution, given the significance of this factor on VRES development, as found in studies like Hernik et al. (2019).

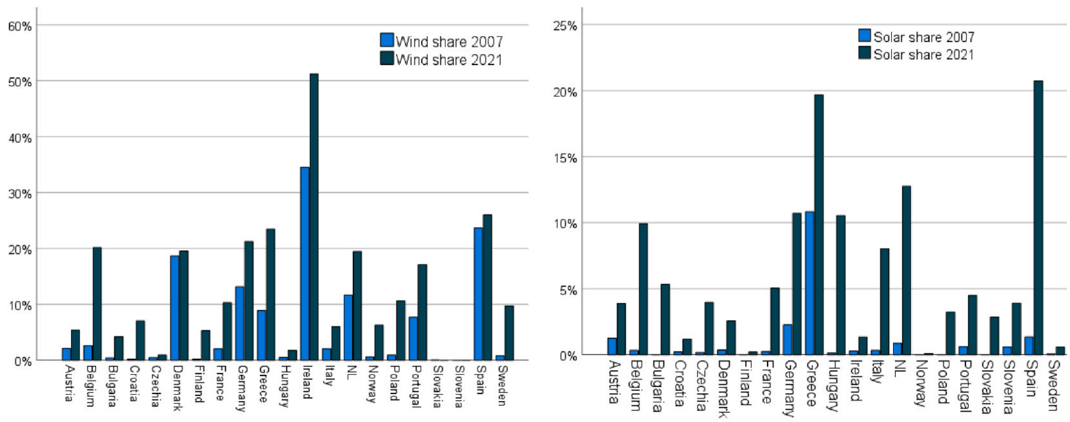

Fig. 1. Shares of wind and solar energy consumption (relative to all RES) – 2007 vs. 2021.

Table 1
List of variables.

Dimension	Variable	Explanation	Units
Energy			
1	Wind share	Share of gross renewable energy consumption attributable to wind	%
2	Solar share	Share of gross renewable energy consumption attributable to solar (photovoltaic + geothermal)	%
3	Industry consumption	Final energy consumption by the industry sector	GWh
4	Transportation consumption	Final energy consumption by the transportation sector	GWh
5	Household consumption	Final energy consumption by households	GWh
6	Energy import	Percent of total energy imported	%
7	Energy intensity	Final energy consumption over GDP	MJ/$2011 PPP GDP
Socio-political			
8	Urban population	Percent of population living in urban areas	%
9	Population density	Total population over land area	People per square km. of land area
10	HDI	Human Development Index - Composite statistical indicator of life expectancy, access to education and standard of living	Index
11	GHG emissions	Total greenhouse gas emissions excluding land use, land use change and forestry	kt of CO_2 equivalent
Economy			
12	Per capita income	Average income per capita	current $USD
13	Taxes on pollution	Sum of tax revenue from pollution and resource taxes	Millions of euros
Environment			
14	GHI	Global Horizon Irradiance - average solar radiation that reaches a horizontal plane at the surface of the earth	W m-2
15	Wind speed	Average horizontal air velocity at 10 m	m s-1
16	Precipitation days	Number of days with total precipitation greater than 4 mm	days
17	Temperature Range	Difference between the warmest and coldest month in a year, based on average hourly maximum and minimum temperatures	Kelvins

Notes: GWh stands for Gigawatts per hour, MJ for Megajoule, PPP for purchasing power parity, GDP for Gross Domestic Product, USD for US Dollars, W m-2 for watts per meters squared, m s-1 for meters per second.

Development is proxied by the Human Development Index (HDI), which is a composite indicator of life expectancy, education, and income-per-capita, whose introduction allows us to incorporate the interactions between natural dependence and development beyond a strictly economic sense. Studies like the meta-analysis of Doğan et al. (2023a,b) have additionally found HDI to be implicated in various conversations surrounding economy and energy. The justification of 'GHG emissions' was already discussed with respect to energy intensity, but is also relevant as it is the principal metric for many national and international level climate-change mitigation policies like the Paris Agreement and the Kyoto Protocol.

'Taxes on pollution' joins 'per capita income' in the economy section as an indicator of a nation's economic attitude towards pollution, and its inclusion stems from the metrics' inconclusive effect on RE development. Some studies show environmental taxes stimulate RE development (Fang et al., 2022), while others show the opposite effect (Dogan et al., 2023). In the present work, the variable's inclusion allows the investigation of whether the hindering or stimulating effect of pollution taxes is specific to wind or solar energy generation.

Amongst the climactic variables, 'solar irradiance' and 'wind speed' were chosen as direct proxies for solar and wind energy resource availability, while 'temperature range' and 'precipitation days' were computed as auxiliary factors affecting the resource availability of each energy source. Both of these auxiliary factors have been investigated as affecting wind and solar energy generation not only in terms of resource availability but also infrastructure performance (Sareen et al., 2014; Jo et al., 2023). The threshold of 4 mm for precipitation days was chosen to ensure the rainfall being considered was significant enough to have effects on VRES infrastructure. The choice of temperature range over other temperature related values was intended to capture the (in)stability of a given climate. A major concern with VRES is their ability to consistently serve as an energy source regardless of season or time of year. The temperature range variable aims to categorize nations where large differences in temperature within a given year might exacerbate these challenges for wind and solar.

The climatic variables were aggregated at the country level, and thus, represent spatial averages of each value. Average weather data across a countrywide spatial area is not ideal, as weather data tends to be incredibly granular and can vary greatly across the geographical landscape of a single nation. Therefore, the goal of this analysis is to capture broad climate trends of countries relative to other countries (i.e., which nations tend to be sunnier/windier and thus, on average, have more of that resource available).

To avoid the issues derived from working with non-stationary data and to circumvent some of the problems that may arise when dealing with time series, such as the presence of outliers, average levels for the sample period were computed. Table 2 presents the summary statistics of all the variables included in the analysis.

Regarding the level of deployment of the VRES analyzed, an enormous difference is observed between countries. While in Ireland there is an average wind share of 44%, in Slovakia or Slovenia it does not even reach 1%. The same differences can be seen in terms of the level of development of solar energy. Greece shows the greatest development with an average penetration of 17%, while Norway does not reach 1%. A similar disparity is observed in the other variables. For example, while in France the average revenue from taxes

Table 2
a. Summary statistics – Average level (2007–2021).

	Wind share	Solar share	Industry consumption	Transport consumption	Household consumption	Energy imports	Energy intensity	Urban population	Population density
	1	2	3	4	5	6	7	8	9
Austria	3.59	2.40	86951.10	96094.05	78260.59	63.89	3.11	57.91	104.17
Belgium	10.79	5.83	121241.15	101744.51	97487.07	77.85	4.28	97.82	368.93
Bulgaria	4.54	4.38	32358.16	35320.04	26055.72	39.92	5.42	73.65	66.45
Croatia	3.15	0.65	14264.36	23749.62	28649.82	50.52	3.42	56.06	74.86
Czechia	0.98	3.62	80070.50	72952.06	81338.26	31.70	4.80	73.55	136.29
Denmark	20.75	1.51	27352.33	49408.97	52166.01	7.42	2.55	87.35	141.53
Finland	2.07	0.05	123164.77	48630.13	62525.34	47.98	5.67	84.73	17.90
France	6.63	2.64	329004.59	515218.38	483888.49	47.80	3.77	79.41	120.72
Germany	16.46	7.86	652386.70	631021.81	676099.30	62.34	3.26	77.12	234.87
Greece	15.00	17.67	36756.10	73574.94	52949.65	70.18	3.22	77.67	84.57
Hungary	1.74	2.06	42646.49	49982.27	71374.25	57.25	4.01	70.10	108.84
Ireland	44.80	0.99	23597.81	46322.26	36246.76	80.92	2.01	62.37	68.25
Italy	4.51	5.76	315089.82	427032.72	379287.31	78.31	2.72	69.41	202.03
NL	15.50	4.21	159310.55	124513.14	118684.49	42.99	3.65	89.25	501.98
Norway	1.92	0.01	72247.87	58881.89	51477.51	−590.03	3.87	80.71	13.98
Poland	6.95	0.68	171494.35	214482.57	238244.11	34.16	4.13	60.49	124.13
Portugal	16.31	2.34	56190.51	68051.81	33780.77	75.39	2.97	62.88	113.81
Slovakia	0.04	2.42	38955.68	28999.34	25972.81	63.07	4.72	54.22	112.67
Slovenia	0.04	2.24	15056.29	21340.38	14034.22	49.47	4.03	53.61	102.37
Spain	25.40	13.63	241781.60	370483.11	176673.70	74.19	3.03	79.38	93.27
Sweden	5.13	0.17	130032.42	84219.33	87501.85	32.35	4.23	86.29	23.95

Table 2 **b.** Summary statistics – Average level (2007–2021)

	Development (HDI)	Greenhouse emissions	Per capita income	Taxes on pollution	Irradiance	Wind speed	Extreme precipitation days	Temperature range
	10	11	12	13	14	15	16	17
Austria	0.91	73538.20	53235.89	79.00	140.77	2.02	110.07	21.02
Belgium	0.92	120804.01	49267.45	532.83	124.53	3.89	81.40	16.79
Bulgaria	0.80	48517.57	20099.26	30.57	166.80	2.28	63.27	23.04
Croatia	0.85	20393.65	26254.87	10.59	154.86	2.29	85.67	21.92
Czechia	0.88	128761.43	36190.97	32.40	130.41	3.01	66.33	21.36
Denmark	0.93	58771.64	53495.76	570.01	119.31	4.92	72.27	16.65
Finland	0.92	43609.31	46844.56	90.93	92.45	3.31	57.13	27.03
France	0.89	438478.71	43421.07	2874.73	148.22	3.14	87.60	17.39
Germany	0.94	874236.10	50376.92	13.13	125.96	3.25	78.53	19.20
Greece	0.87	100367.93	30640.02	36.25	186.22	2.06	68.20	20.15
Hungary	0.84	59421.29	27696.95	234.08	146.66	2.79	57.67	23.44
Ireland	0.92	68920.58	68651.45	46.23	109.80	4.19	99.13	10.73
Italy	0.89	435807.32	41858.58	531.93	171.03	2.04	90.67	19.43
Netherlands	0.93	197700.30	53621.87	3200.87	121.20	4.21	75.27	16.21
Norway	0.95	33954.01	63468.95	299.16	95.90	2.75	136.67	20.94
Poland	0.86	364307.43	27400.84	640.80	122.88	3.60	61.73	22.19
Portugal	0.85	64991.49	32017.72	33.54	192.26	2.95	58.60	14.80
Slovakia	0.85	36710.32	28094.02	34.16	135.67	2.50	71.07	22.68
Slovenia	0.91	14787.46	35214.66	58.19	145.11	1.94	95.80	21.40
Spain	0.88	297008.22	37863.17	646.53	191.34	2.72	53.33	18.20
Sweden	0.93	10085.69	49952.60	182.68	99.62	3.22	62.27	23.31

on pollution is greater than 2.8 billion euros, Germany is at the opposite extreme, with an average tax collection of 13 million. Thus, the methodology employed in the present study was specifically chosen for its ability to handle such vast numerical disparities between countries and variables.

It also bears noting that the UN defines an HDI score greater than 0.80 as "very high human development" and not a single country in the present study falls below this threshold. Because this nuance will not be visible when these values get converted to rankings, it is important to keep in mind that any findings related to "higher" or "lower" development should be interpreted within the context of Europe, where this metric is already extremely high across the board.

4. Methodology

This study applies different multivariate techniques for dimensionality reduction. The objective is to synthesize the information from a panel dataset that includes a variety of 17 VRES-related indicators for 21 European countries in the time period 2007–2021, as thoroughly discussed in the previous section. The utility of multivariate, dimensionality reduction techniques with respect to this type of study is that it allows for an empirical clustering of variables that are already 'conceptually' grouped (i.e., 'environmental' variables

Table 3
a. Ranking of countries according to their average level during the sample period (2007–2021).

Wind share	Solar share	Industry consumption	Transport consumption	Household consumption	Energy imports	Energy intensity	Urban population	Population density
Ireland	Greece	Germany	Germany	Germany	Ireland	Finland	Belgium	NL
Spain	Spain	France	France	France	Italy	Bulgaria	NL	Belgium
Denmark	Germany	Italy	Italy	Italy	Belgium	Czechia	Denmark	Germany
Germany	Belgium	Spain	Spain	Poland	Portugal	Slovakia	Sweden	Italy
Portugal	Italy	Poland	Poland	Spain	Spain	Belgium	Finland	Denmark
NL	Bulgaria	NL	NL	NL	Greece	Sweden	Norway	Czechia
Greece	NL	Sweden	Belgium	Belgium	Austria	Poland	France	Poland
Belgium	Czechia	Finland	Austria	Sweden	Slovakia	Slovenia	Spain	France
Poland	France	Belgium	Sweden	Czechia	Germany	Hungary	Greece	Portugal
France	Slovakia	Austria	Greece	Austria	Hungary	Norway	Germany	Slovakia
Sweden	Austria	Czechia	Czechia	Hungary	Croatia	France	Bulgaria	Hungary
Bulgaria	Portugal	Norway	Portugal	Finland	Slovenia	NL	Czechia	Austria
Italy	Slovenia	Portugal	Norway	Greece	Finland	Croatia	Hungary	Slovenia
Austria	Hungary	Hungary	Hungary	Denmark	France	Germany	Italy	Spain
Croatia	Denmark	Slovakia	Denmark	Norway	NL	Greece	Portugal	Greece
Finland	Ireland	Greece	Finland	Ireland	Bulgaria	Austria	Ireland	Croatia
Norway	Poland	Bulgaria	Ireland	Portugal	Poland	Spain	Poland	Ireland
Hungary	Croatia	Denmark	Bulgaria	Croatia	Sweden	Portugal	Austria	Bulgaria
Czechia	Sweden	Ireland	Slovakia	Bulgaria	Czechia	Italy	Croatia	Sweden
Slovenia	Finland	Slovenia	Croatia	Slovakia	Denmark	Denmark	Slovakia	Finland
Slovakia	Norway	Croatia	Slovenia	Slovenia	Norway	Ireland	Slovenia	Norway

Table 3 **b.** Ranking of countries according to their average level during the sample period (2007–2021)

Development (HDI)	Greenhouse emissions	Per capita income	Taxes on pollution	Irradiance	Wind speed	Extreme precipitation days	Temperature range
Norway	Germany	Ireland	NL	Portugal	Denmark	Norway	Finland
Germany	France	Norway	France	Spain	NL	Austria	Hungary
Denmark	Italy	NL	Spain	Greece	Ireland	Ireland	Sweden
NL	Poland	Denmark	Poland	Italy	Belgium	Slovenia	Bulgaria
Sweden	Spain	Austria	Denmark	Bulgaria	Poland	Italy	Slovakia
Finland	NL	Germany	Belgium	Croatia	Finland	France	Poland
Belgium	Czechia	Sweden	Italy	France	Germany	Croatia	Croatia
Ireland	Belgium	Belgium	Norway	Hungary	Sweden	Belgium	Slovenia
Slovenia	Greece	Finland	Hungary	Slovenia	France	Germany	Czechia
Austria	Austria	France	Sweden	Austria	Czechia	NL	Austria
France	Ireland	Italy	Finland	Slovakia	Portugal	Denmark	Norway
Italy	Portugal	Spain	Austria	Czechia	Hungary	Slovakia	Greece
Spain	Hungary	Czechia	Slovenia	Germany	Norway	Greece	Italy
Czechia	Denmark	Slovenia	Ireland	Belgium	Spain	Czechia	Germany
Greece	Bulgaria	Portugal	Greece	Poland	Slovakia	Bulgaria	Spain
Poland	Finland	Greece	Slovakia	NL	Croatia	Sweden	France
Croatia	Slovakia	Slovakia	Portugal	Denmark	Bulgaria	Poland	Belgium
Slovakia	Norway	Hungary	Czechia	Ireland	Greece	Portugal	Denmark
Portugal	Croatia	Poland	Bulgaria	Sweden	Italy	Hungary	NL
Hungary	Slovenia	Croatia	Germany	Norway	Austria	Finland	Portugal
Bulgaria	Sweden	Bulgaria	Croatia	Finland	Slovenia	Spain	Ireland

Notes: Countries are ranked in decreasing order according to their average growth rates during the sample period (2007–2021). NL refers to the Netherlands.
Notes: Countries are ranked in decreasing order according to their average growth rates during the sample period (2007–2021). NL refers to the Netherlands.

vs 'economic' variables, etc.). This, coupled with the fact that these techniques are able to preserve a high level of information from the original data set, make these approaches an ideal way to work with and draw conclusions from a large number of variables while avoiding potential issues caused by multicollinearity.

While PCA is a widely used method of multivariate dimensionality reduction, it has not been practically used in this area. Some exceptions are the studies of Brodny and Tutak (2020) and Papież et al. (2018). However, PCA is limited by its requirement of numerical variables and its assumption of linear relationships between data, which could pose problems for a study of this nature. For example, data representing natural processes, such as the weather and climate variables used in this study, are prone to be non-linear given the complex spatial-temporal relationships of the processes governing these types of variables (Bueso et al., 2020). Additionally, given that one of the goals of this study is to cluster countries with respect to each other, the exclusive use of numerical variables may not be the most efficient way to uncover and visualize these relationships.

For these reasons, the study implements CATPCA—also known as non-linear PCA—to cluster and position the 21 European countries with respect to their VRES development and the various potential determinants thereof. While CATPCA can more or less be considered an extension of traditional PCA (Meulman et al., 2002), this technique is able to deal with non-linear relationships between

Table 4
CATPCA analysis – Summary.

Dimension	Cronbach's alpha	Variance	
		Total (eigenvalue)	% of variance
1	0.91	7.09	41.69
2	0.89	6.30	37.04
Total	0.98*	13.84	78.73

Notes: *Cronbach's alpha mean is based on the mean of the eigenvalue.

data, including nominal and ordinal data. An additional advantage of CATPCA is that, due to the non-linear transformations of the variables achieved by optimal quantification, it tends to concentrate more variation in the first few principal components (De Leeuw and Meulman, 1986). This study additionally aims to highlight the utility of CATPCA for visualizing relationships. The propensity of CATPCA to concentrate variability in fewer components, allows visualizing the interplay between variables as well as the relative positioning of the countries in two-dimensional maps, thus creating a graphical representation easy to interpret.

As a robustness check two additional multivariate techniques are applied. First, Hierarchical Clustering Analysis (HCA) is implemented to generate a dendrogram in order to illustrate the arrangement of the clusters in the dataset. Second, Multidimensional Scaling (MDS) is applied to synthesize all the information into two components and to project the countries onto a two-dimensional map according to their level of similarity.

MDS is a multivariate analytical procedure also known as Principal Coordinates Analysis, and can be regarded as a form of non-linear dimensionality reduction. MDS is used for visualizing the level of similarity of individual cases of a dataset. The proximity of individuals to each other in the generated perceptual map indicate how similar they are. See Borg et al. (2013) and Borg and Groenen (2005) for a comprehensive overview of MDS.

The methodology used in this study is based on the following stages. First, the average levels for the sample period presented in Table 2 are used to rank the countries in decreasing order (see Table 3). Second, each country is assigned a numerical value according to their position in the rankings. These ordinal variables are then used as the input for CATPCA. This procedure allows synthesizing the information from all the rankings into two dimensions, which are used to analyze the interplay between the different variables and wind and solar development during the sample period. The results of this stage are presented in in Tables 4 and 5 and in Fig. 2. Then, using the scores of all countries in each dimension, a plot is generated to evaluate the relative positioning of the countries (Fig. 3). See Pérez and Claveria (2020) for an implementation of the methodology to test the resource curse hypothesis.

Finally, as a robustness check, HCA and MDS are implemented to compare the resulting groupings of countries with those obtained by means of CATPCA. This is the first study to compare the performance of these techniques in positioning countries based on the evolution of wind and solar energy and its potential determinants.

Table 5
Rotated component loadings – CATPCA.

Category	Position	Dimension	
		1	2
Energy			
	Wind share	0.807	0.338
	Solar share	0.001	0.989
	Industry consumption	0.870	−0.030
	Transport consumption	0.965	0.013
	Household consumption	0.954	0.020
	Energy imports	−0.077	0.938
	Energy intensity	−0.425	−0.481
Society and politics			
	Urban population	0.871	−0.248
	Population density	−0.025	0.982
	Human development	0.212	−0.929
	GHG emissions	0.780	0.505
Economy			
	Per capita income	0.725	−0.355
	Taxes on pollution	0.746	−0.232
Environment			
	Irradiance	0.024	0.899
	Wind speed	0.776	−0.172
	Precipitation days	0.017	−0.904
	Temperature range	−0.745	−0.338

Notes: Rotation method – Varimax with Kaiser Normalisation. Component loadings indicate Pearson correlations between the quantified variables and the principal components.

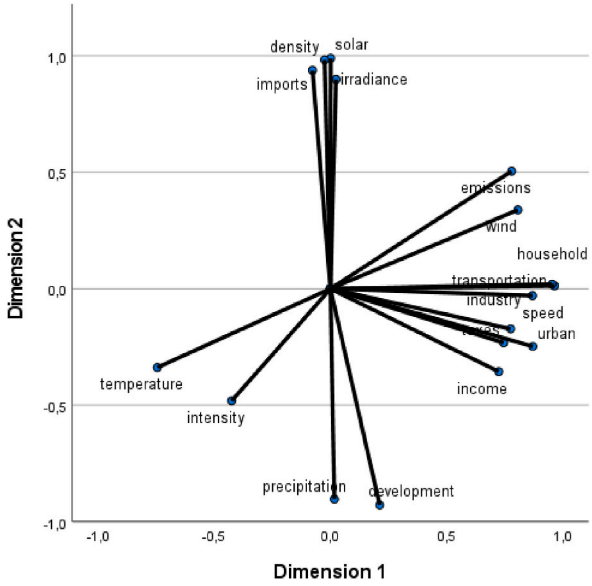

Fig. 2. Rotated component loadings – Average levels 2007–2021.

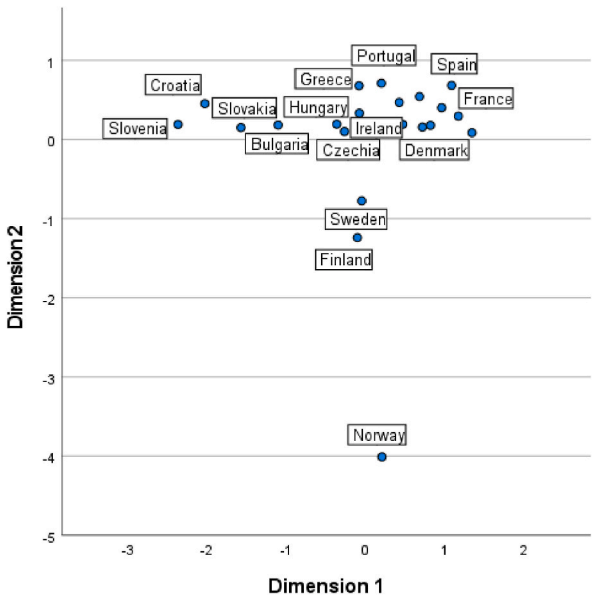

Fig. 3. Object points labelled by country – Average levels 2007–2021.

5. Results

In this section, CATPCA is applied to the ranks of all variables in order (i) to reduce the dimensionality of data, (ii) to explore the relationship among all the factors according to their average level during the sample period, and (iii) to position the countries according the interplay between the different variables synthesized into two components. As a robustness check, two additional multivariate procedures—HCA and MDS—are implemented and compared with the previous results.

5.1. Ranking of countries

Following the three-stage methodology previously explained, countries are ranked for each variable in decreasing order according to the average level experienced over the period extending from 2007 to 2021. Rankings are presented in Table 3.

With respect to the environmental variables, despite being country-level averages the rankings of these variables accurately capture the expected distribution of the nations under study, i.e., southern European nations dominated irradiance, windy climates have the highest wind speed rankings, etc. This is a positive indicator that despite being low granularity, the averaged climate data reflects the appropriate conditions for each nation and can be used to represent country-level natural resource availability in our analysis. For all this, it is not surprising that the Scandinavian countries are located in the lowest positions when it comes to the deployment of solar energy. On the other hand, the development of wind energy seems to be distributed evenly among the different regions of the continent, without a clear predominance of a specific area being observed. Spain, Germany, and, to a lesser extent, the Netherlands dominate in both the wind and solar share categories. Of extreme interest is that these three countries also claim high rankings in energy consumption and GHG emissions, a fact that already generates curiosity about the circumstances surrounding wind and solar energy preference.

5.2. Dimensionality reduction

To implement CATPCA, the ranks for each variable according to their average level over the period 2007 to 2021 are used as input. Each country is assigned a numerical value corresponding to its position, obtaining a set of categorical data that are used as input for CATPCA. All the analysis has been done with IBM SPSS Statistics 27.

Given that the first two factors account for more than 78% of the variance of the variables under analysis, the analysis is implemented for those two dimensions. Table 4 shows a summary of the model. As mentioned before, CATPCA transforms the original set of correlated variables into a smaller set of uncorrelated variables (Linting et al., 2007), applying a non-linear optimal procedure that relates the category quantifications versus the original categories.

Table 5 shows the obtained component loadings of each variable in both dimensions. Varimax rotation was applied to facilitate the interpretation of the components thereby derived. Loadings greater than 0.70 in absolute value in a given dimension can are the most relevant with respect to interpreting the dimensions.

It is worth noting that the share of *wind* energy is mostly captured in the first dimension, while the second dimension entirely captures *solar* deployment. Dimension 1 shows the highest loading components belonging to energy consumption factors (*transportation*, *industry* and *household*) and GHG *emissions*, as well as *urbanization*, *taxes* on pollution, and per capita *income*, which proxies economic growth. On the other hand, dimension 2 is dominated by energy *imports*, population *density*, and *irradiance*. The number of days of *precipitation* and *development* (as measured by the HDI) also show high loading components, although with a negative sign.

The positive association of energy consumption, *emissions*, and economic growth in dimension 1 is not surprising given the known relationship of these variables as explored in the various studies surrounding the EKC (see Section 2). However, what is of considerable interest is the potential implication of *wind* energy in this dynamic.

Similarly, dimension 2 could be capturing some kind of socio-economic phenomena inversely relating *development* and energy *imports*, a finding which on its own could be intuitively justified (e.g., countries with lower quality of life are less likely to achieve energy independence), but it is the nexus of this interplay with *solar* that is less intuitive and merits investigating.

Fig. 2 displays the rotated component loadings (indicators). The coordinates of the endpoint of each vector are given by the loadings of each variable on the two components. Long vectors are indicative of a good fit. The variables that are close together in the plot are positively related, while the variables with vectors that make approximately a 180° angle with each other are closely and negatively related. Finally, variables that are not related correspond with vectors making a 90° angle.

Given this framework for interpretation, the most interesting finding reflected in Fig. 2 is the stark lack of correlation between the *wind* and *solar* share variables and their respective associated factors. This implies a very clear decoupling between the socio-economic and climactic conditions surrounding preferentially wind or solar heavy RES mixes in a nation.

This trend is not absolute, however, as few variables do show association with both *wind* and *solar*. Namely *temperature* and energy *intensity*. Despite the strong belief that RES will play a fundamental role in decreasing carbon emissions, Fig. 2 shows that high dependence of wind is actually associated with higher *emissions* for the given countries across the given sample period. On the other hand, energy *intensity* is negatively associated with *wind* and *solar*, implying that countries with high levels of wind or solar energy are achieving a more energy efficient economy.

Fig. 2 also highlights an interesting dynamic between *urban* population and population *density*, two variables representing similar phenomena but highly uncorrelated with each other, and strongly linked to their respective dimension (*urban* in dimension 1 with *wind*, and *density* in dimension 2 with *solar*).

Finally, with regards to the ‘environmental’ factors, the results show that all climactic variables included in the study are of high importance in at least one of the dimensions. As expected, the *wind* share is positively associated with increased wind *speed*, and the *solar* share is positively linked with increased solar *irradiance*. The other climactic variables, however, have negative relationships with our variables of interest in their respective dimensions. In the second dimension, *solar* energy shows a negative relationship with the variable *precipitation* which captures the number of days of the year with precipitation greater than 4 mm. This finding is generally not surprising, as rainier climates are often associated with lower levels of global irradiance—supported by the inverse relationship between *irradiance* and *precipitation* in this study—, which in turn makes rainy climates ill-suited for high amounts of solar energy development (Ibrahim et al., 2022; Shorabeh et al., 2019). Meanwhile, the negative association of *temperature* range and *wind* share could perhaps imply the suitability of more stable climates for wind energy development.

5.3. Clustering of countries

Fig. 3 displays the positioning of countries according to their scores in the two retained dimensions. Countries can roughly be divided in three groups: (i) those with low scores in dimension 2 which roughly correspond to all four Scandinavian countries (Norway, Finland, Sweden, and to a lesser extent, Denmark), (ii) those in the upper quadrant with negative scores in dimension 1 and moderately low yet positive scores in dimension 2 (Slovakia, Croatia, Slovakia, and Bulgaria), where there is a predominance of south-eastern countries, and finally iii) all the countries with high scores in both dimensions, clustered in the upper right quadrant. This last subset of economies includes the Mediterranean countries and the countries of central and western Europe.

Given these clusters, the resulting positioning seems to be linked to the geographical location of the countries. These results are in line with Śmiech and Papież (2014) who identified four groups of European countries which meet energy policy targets at similar levels. In a recent study, Tutak and Brodny (2022) analyzed similarities between the EU countries in terms of the use of energy from RES at a sectoral level. The authors found a significant increase in the consumption of energy from RES but significant differences in the use of this energy among the studied countries. Also, it was found that RES-based energy consumption had a positive impact on economic growth and the reduction of gas emissions, but that this impact was greater in the "old" than in the "new" EU countries. These findings would be in line with the clear divergence observed in Fig. 3 between the countries with higher scores in dimension 1 (which would encompass what could be called "old Europe") and those that obtain the lowest scores in that dimension (Slovenia, Croatia and Slovenia, and to a lesser extent Hungary and Czechia, which would belong to the newer-countries category).

5.4. Robustness check

As a robustness check, the CATPCA analysis is complemented by means of other multivariate techniques. First, by means of hierarchical clustering, a dendrogram is generated to better illustrate the arrangement of the clusters (Fig. 4). Second, MDS is implemented to synthesize all the information into two dimensions and compare the resulting groupings of countries with those obtained by means of CATPCA. This is the first study to compare the performance of these techniques to position countries based on the evolution experienced in terms of the development of wind and solar energy and its determinants.

Fig. 4 contains the obtained dendrogram, which shows the arrangement of the clusters in the dataset, pointing at two main groups of countries. The graph corroborates the similarity between Mediterranean countries, as well as among Scandinavian countries which also appear to be clustered together, with the exception of Denmark, which is closer to Ireland.

Next, MDS is applied to synthesize all the information in two components. The obtained squared correlation (RSQ) in distances was 0.80, indicating a good fit. This statistic indicates the proportion of variance of the scaled data (disparities) in the partition which is accounted for by their corresponding distances. This result is corroborated by the stress statistic, which shows how well the distances in the lower-dimensional space match the dissimilarities in the original space. Stress varies between 0 and 1, with values near 0 indicating better fit. In this case, the stress value generated by the model was 0.18.

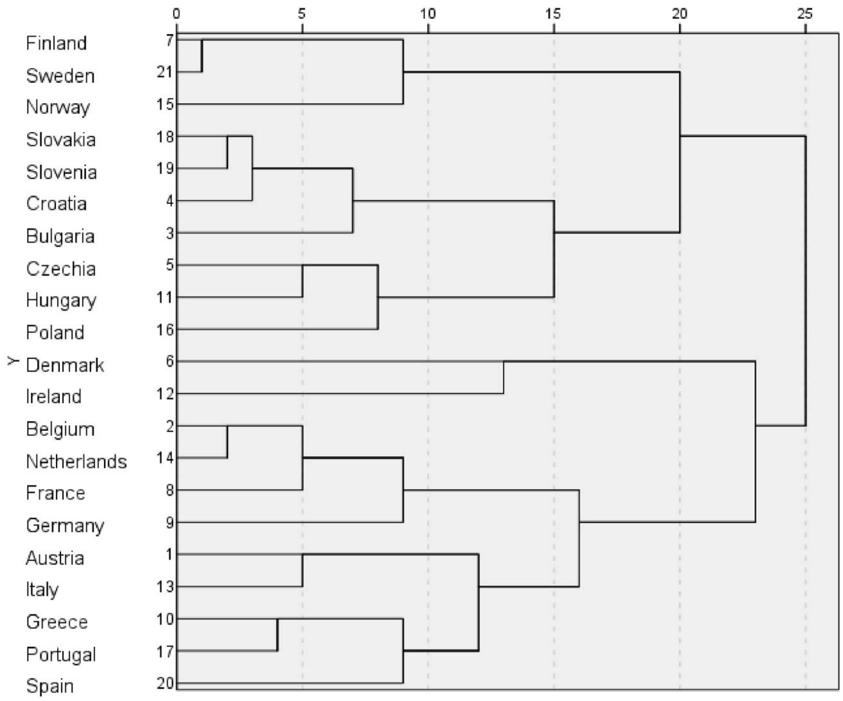

Fig. 4. Dendrogram.

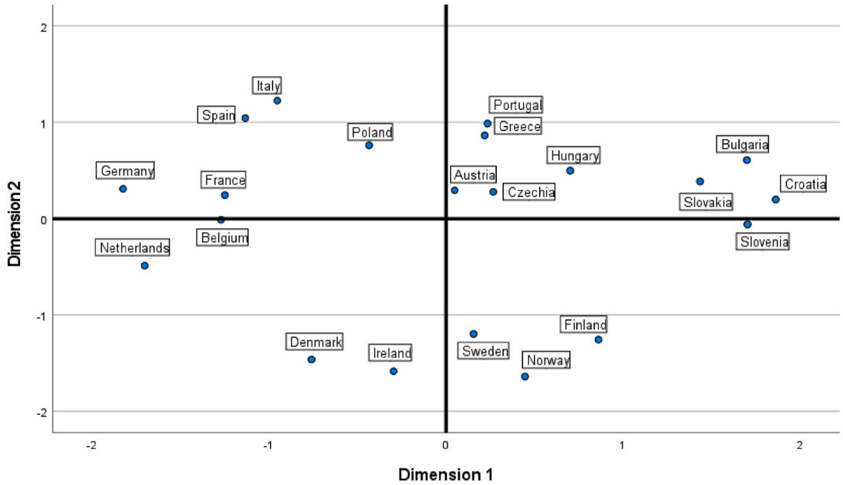

Fig. 5. Perceptual map – Average levels 2007–2021.

Fig. 5 shows a perceptual map in which countries are projected according to their level of similarity. MDS translates all the information about the pairwise distances among countries into abstract Cartesian space. The proximity of individuals to each other in the generated perceptual map indicate how similar they are. Compared to CATPCA, MDS generates a more uniformly distributed projection in the two-dimensional space. However, it can be seen that in general terms the distribution of countries on the map is very similar to that achieved through CATPCA. Furthermore, the similarity between the different groupings of countries also coincides with that reflected in the dendrogram.

6. Discussion and policy implications

The present study highlights how the preferences towards wind energy and solar energy in a country's RES mix are distinctly characterized from each other given that they are affected differently by the factors analyzed. This is reflected in the fact that the average shares of each type of energy are collected almost completely in one of the two dimensions in which all the information has been synthesized. That said, many of the results were not immediately intuitive and merit further discussion.

For example, solar share was found to be positively associated with energy imports and negatively assosciated with HDI. To understand this result it should be noted that to a large extent this result is conditioned by the fact that the Scandinavian countries—with the lowest levels of irradiation and the highest in terms of development—have a very low development of solar energy and rely on other renewables instead. To this it should be added that Norway is the only country in the sample that is a net energy exporter, which means that the inverse association observed between development and penetration of solar energy is highly conditioned by this circumstance. As such, this result should not be taken to mean that solar energy is not suitable for supporting energy dependency or that solar energy is associated with lower quality of life, but rather that countries with the highest quality of life and the highest levels of energy independence have achieved these feats without any sort of dependence on solar energy.

Additionally, although a positive association between income, emissions and energy consumption was indeed captured in the analysis, the finding is complicated by the fact that these relationships were specifically associated with high levels of wind penetration. On the other hand, only GHG emissions maintained a relevant and positive correlation with solar in the second component.

As mentioned in Section 2 of this paper, the relationship between GDP and GHG emissions is contested, with some finding evidence in favour of the EKC hypothesis—i.e. there is a threshold after which increases in GDP lead to decreases in GHG emissions— (e.g. Chu et al., 2023a,b; Mahmood, 2022; Mahmood et al., 2023c, 2023d, 2023e; Yao et al., 2019), while others that find no evidence of such relationship (e.g. Bölük and Mert, 2014). There is no consensus on this question, and indeed the results here do not point in any clear direction. For example, the results in Fig. 2 did not show an overtly strong association between GDP and GHG emissions. Based on the time period and the sample of countries, the most that can be gleaned from the obtained results is that the relationship between *wind/solar* development and *emissions* does not seem to be necessarily informed by their relationship to economic growth, as it is emphasized by the renewables-informed EKC theory.

Despite this, energy intensity, which can be interpreted as a proxy for the efficiency with which an economy turns energy into GDP, is negatively correlated with both wind and solar, implying that nations with a high reliance on these resources compared to other RES tend to have more energy efficient economies. This finding is empirically supported by Díaz et al. (2019), which confirms that it is RES like wind and solar specifically, over those like bioenergy and hydropower, that are associated with a decreased energy intensity.

Wind and solar both showed some kind of relationship to the distribution of population, with wind being strongly assosciated to highly urban nations and solar showing correlation with densely populated nations. As a reminder, *density* refers to inhabitants per square kilometer, while *urban* refers to the percentage of a nation's population living in urban areas. It is possible that a positive association between population density and solar energy could come from the unique advantage of solar over wind energy in that small-scale installations are possible, such as rooftop panels. As such, the land use constraints caused by a densely populated nation create a society that can much more easily benefit from the deployment of solar over wind. The Netherlands, for example, which has the highest rank of population density in this study, is known to be nation with a large market for rooftop photovoltaic installations (International Energy Agency, 2022). On the other hand, nations with more of their population centered in urban areas will not only have more space to install wind turbines, but may also benefit from less social pushback to the windfarms due to less inhabitants affected by their erection. This is not because urban populations are more likely to accept wind farms than rural populations, a claim that has been debunked by several studies (Umit and Schaffer, 2022; Liebe et al., 2017), but because wind farm acceptance has been very strongly linked to visual distance and participation in decision making about the infrastructure.

All of these findings are particularly highlighted in the positioning maps, where three large groups of countries are observed that, to a certain extent, coincide with different geographical areas of the continent. The first group corresponds to the Scandinavian countries in northern Europe which, in this study, are characterized by extremely high levels of development, low population density, and very low dependence both solar energy and, to a lesser extent, wind energy in RES implementation. The second group is made up of eastern European countries, among which Bulgaria, Croatia, Slovenia, and to a lesser extent, Hungary, are characterized by low levels of wind energy, energy consumption, income, and pollution. The rest of the countries representing western and southern Europe make up the final and most varied cluster, with the Mediterranean nations (Greece, Italy Portugal) showing a slightly stronger dominance in the *solar* dimension, and the countries of Central Europe (Germany, the Netherlands, France) having a slightly firmer hold in the *wind* dimension. (Spain is the exception with the highest values in both dimensions within its geographical cluster). The geographical clustering of these nations is further displayed in Fig. 6.

While the results of this study emphasize the need for further research that is centered on individual RES rather than renewables as a whole, there are some policy implications that can be extrapolated from the findings presented. First, the role of physical climate should not be underestimated in describing not only a nation's historical RE mix, but also the barriers to introduction of lesser used RES, as is the goal with RE portfolio diversification (Aihua et al., 2022). As RE becomes more popular, its implementation becomes increasingly muddled with policy, social attitudes and economic factors. The findings here encourage policy makers to ensure that climate and environment continue to have their fair share of emphasis amidst those conversations. Emphasis on technological advances such as storage techniques or more weather-resistant infrastructure will pave the way for countries that have not historically been able to enjoy the benefits of certain type of VRES due to their environmental conditions. The sensitivity of VRES to climate also emphasizes the potential impact of climate change on these infrastructures and the need for preventative measures with regard to preserving the integrity of pre-existing infrastructure, as well as pro-active planning to ensure future installations are resilient to these changes.

Secondly, and perhaps in tandem with the previous paragraph, the results here show that the geo-spatial clustering of countries with respect to their wind and solar energy shares extends far beyond simply their geographically informed similarities in climate, as shown in Fig. 6. Understanding the geo-spatial trends of other correlations with wind and solar energy generation such as development, and energy consumption and dependence can not only contribute to a more holistic understanding of the RE landscape in Europe, but also allow for pro-active and informed decision making when it comes to supporting the RE transition in different regions of the EU.

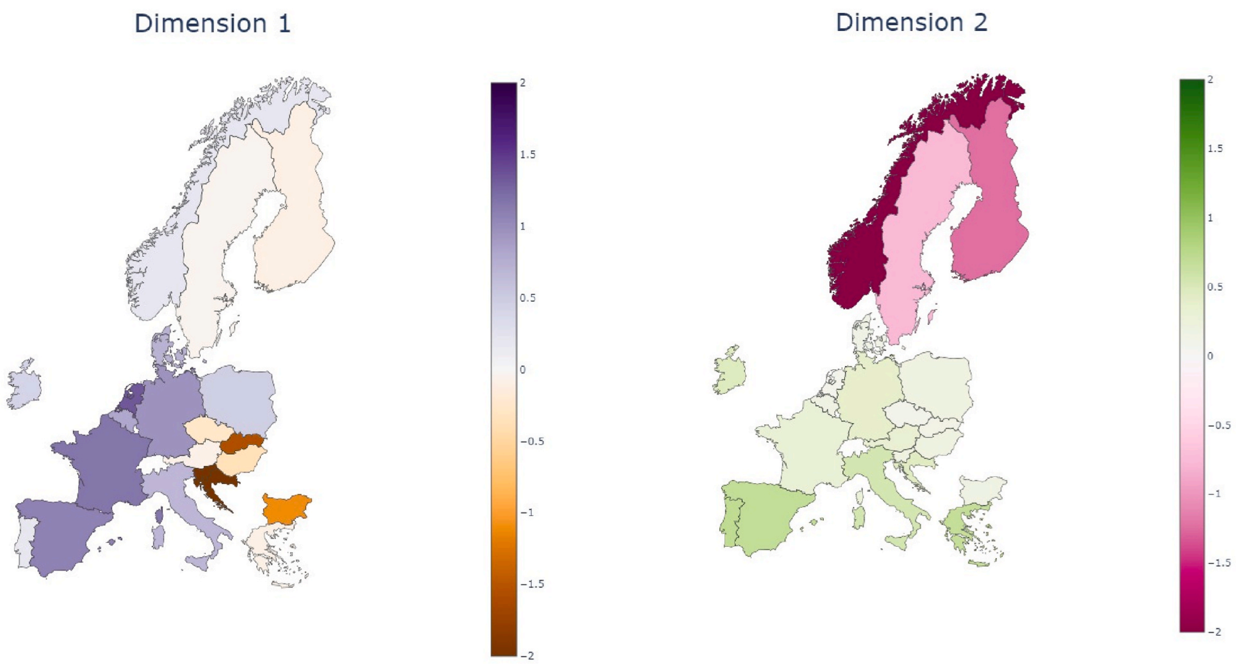

Fig. 6. Visualization of countries according to their scores in each dimension.

Thirdly, working with the distribution of population will play a key yet very different role in successfully increasing shares of wind and solar energy. The success of solar energy implementation in densely populated nations may support the efficacy of small-scale solar photovoltaic installations as a way to promote RE consumption when land use for large-scale structures are limited. Conversely, and especially given the trend of increasing urbanization in Europe, highly urbanized nations can expect wind energy to be a favorable option in more sparsely populated areas with greater land use availability. That said, it is strongly emphasized that decreased populations in rural areas where wind farms are likely to be erected should be an incentive for working more closely with the individuals who will be affected by these installations, rather than exploiting them and dismissing their concerns with the justification that they are few.

Fourthly, policies centering around European energy independence should consider the tendency for countries with high levels of solar energy within their renewables mix to experience much greater reliance on energy imports. Further studies should be conducted to discover whether this is a consequence of solar energy or not, as the results could have serious implications on where RE development is focused in the goal of creating an energy independent Europe.

Finally, while wind and solar energy play an important role in the road to decarbonization it is emphasized that these energy sources cannot serve as a one-size-fits-all band-aid to emission reduction goals. To really achieve the goals set out by the EU concerning climate-change mitigation and carbon footprint reduction, countries must take a more robust approach to tackling the root causes of these issues rather than just blindly joining the trend of using wind and solar energy development as the holy grail of climate change solutions.

7. Conclusion

This study shows the potential of multivariate and data-visualization techniques to capture the complex set of linkages amongst wind and solar energy development and various socio-economic, political and environmental factors, as well as for the positioning of economies according to the dynamic interplay among them with respect to these factors. The proposed approach is based on a dimensionality reduction technique that can handle ordinal and numerical variables simultaneously and can deal with nonlinearities in the relationship between them. Through this methodology, this study also aims to provide researchers with an alternative approach to identify key attributes in the positioning of economies.

With this objective, a descriptive analysis was conducted on the evolution of a set of variables related to environmental, economic, and social factors over the period extending from 2007 to 2021, along with variables representing the share of wind or solar energy in a nation’s renewable energy mix. Then, countries were ranked according to the average level experienced over the sample period. By assigning a numerical value to each country corresponding to its ranking, we generated a set of categorical data that was summarised into two components. Wind and solar energy variables were completely captured in the first and second component, respectively, along with their most common climactic determinants (wind speed and global irradiance, respectively). In addition to wind, the first component had strong relationships to urban population as well as income, energy consumption and greenhouse gas emissions.

One of the primary findings of this study is that there seems to be a decoupling between the development of wind and solar energy sources, given that the economic, socio-political and environmental factors considered in the study show a very different association with each of the energy variables. Additionally, the strong association found between carbon emissions, income and energy consumption agrees with previous studies that emphasize a significant relationship between these factors. That said, high levels of wind were found to be associated with GHG emissions, challenging the assumption that these resources are a one-size-fits-all solution to reducing a nations carbon footprint.

Finally, we also found that the positioning of the countries with respect to the natural and economic dimensions derived from the analysis roughly correlates with cultural and geographic clusters. Three large groups of countries seem to emerge from the perceptual maps generated. Eastern European countries presented the lowest values in wind development and energy consumption, while the Scandinavian countries had exceedingly low positions regarding solar energy, but low dependence on energy imports and high levels of human development. The rest of the countries, representing western and southern Europe were categorized by varied values in both dimensions, with the Mediterranean countries displaying a slight dominance in the solar dimension and western European countries like Germany, France and the Netherlands displaying higher wind deployment. Spain here is a notable outlier, displaying strong values in both dimensions. This clustering suggests some sort of regional trend in the preferential development of wind and solar energy that extends beyond simply climactic and environmental differences.

Notwithstanding, this research is not without limitations. First, it is emphasized that this is a descriptive study, thus generalizable inferences cannot be drawn from the results. Additionally, the introduction of climatic variables was done on a very coarse resolution both temporally and spatially. Even within a single country, there can exist greatly varying climates, and this in-nation variability is not reflected in our work. Relatedly, in taking the average level of all the variables across the sample period, the results cannot account for the growth patterns of these factors. Given the rapidly expanding and changing landscape of renewables, these patterns could be desirable in complementing the present results. Finally, given the vast complexity of determinants on renewable energy development, as well as the difficulties involved in data collection, it is noted that there very well could be additional key indicators relating to wind and solar energy development that were not included here.

An issue left for future research is the application of techniques that take advantage of the panel structure of the database and the exploratory analysis carried out in the present study, in order to model the development of wind and solar energy. Within that framework, the formal testing of the EKC hypothesis has also been left as a next step, especially with regard to specific forms of renewable energy. Another question left for future research is the extension of the analysis to other countries and a comparison of the results with those obtained using other dimensionality-reduction techniques such as self-organizing maps.

CRediT authorship contribution statement

Christina Carty: Conceptualization, Data curation, Investigation, Resources, Software, Visualization, Writing – original draft, Writing – review & editing, Supervision. **Oscar Claveria:** Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Software, Supervision, Visualization, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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