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"The nexus between variable renewable energy, economy and climate: Evidence from European countries by means of exploratory graphical analysis"

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Abstract

We propose a new approach for the visual inspection of interactions between several variables related to the wind and solar energy sector, and a set of socioeconomic variables and natural factors that may be affecting the sector. Focusing on fifteen European countries in the period from 2007 to 2019, we use Categorical Principal Component Analysis to reduce our data into two factors, the first relating to energy consumption, greenhouse gas emissions, per capita income, and solar energy, and the second capturing climactic and sociopolitical factors. The dimensionality reduction also displays a decoupling between natural factors and variable renewable energy sources (VRES) development, particularly in the case of solar energy, and instead shows a more influential relationship with economic factors. We additionally project all countries into a perceptual map and observe three clusters that roughly correspond to the main European regions (Southern and Eastern Europe, Northern Europe and Western Europe). Finally, we plot the average level and growth level of both the wind and solar energy share for each nation and observe a negative relationship in wind share and a slightly positive relationship in solar share. Our results show that, especially for wind energy, countries with higher levels of overall renewable energy development are more likely to show more intense VRES development than countries who already have high existing levels of the technology in their renewable energy mix. Solar energy investment on the other hand is more likely to be dominated by countries with pre-existing high levels of solar in the renewables mix. Our results emphasize the importance of individual nations attitude towards renewables as a whole as playing a key role in VRES development, as much as the natural resource availability of these energies.

JEL Classification: C38, C55, O44, Q20, Q50.

Keywords: Renewable energies, Wind share growth, Solar share growth, Economic growth, Human development, Multivariate analysis, Europe.

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1. Introduction

In the face of global warming, more nations are aiming for the decarbonisation of energy resources in order to mitigate greenhouse gas emissions and the effects of climate change. By 2050, Europe aims to become the first climate-neutral continent by primarily relying on renewable energies (European Commission, 2018). Despite this lofty goal, individual European countries show a wide range in share of renewable energy consumption and the lack of consistent success across individual nations will likely pose a problem to Europe's climate-neutrality goal. The variation of success in renewable energy adoption in Europe not only highlights the great challenge in moving away from fossil fuels but the fact that this challenge is disproportionately felt by different nations.

These many challenges presented by a transition to a renewable energy scheme are exacerbated for variable renewable energy sources (VRES) such as wind and solar, whose dependency on meteorological climate can create complications in their integration to a power system (Huber et al., 2014). Despite the high volatility of these energy sources, wind energy made up 35% of energy in Europe in 2019 and solar was cited as the fastest growing renewable energy (Eurostat, 2022).

Given the prominent role of VRES in Europe’s energy landscape, it is important to be able to understand what makes these energy sources more or less likely to be used by European countries in the general implementation of renewable energy. While VRES depend heavily on weather and climate, they are still subject to many of the same socioeconomic conditions that affect the production and consumption in the energy sector. The complex interaction between climate and economy on wind and solar energy is not so feasibly modelled as it is not yet well understood.

For this reason, VRES studies attempting to model or understand the adoption of these energies must represent an intersection of economic, political, and physical 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 utilising the aforementioned integrated approach. Therefore, the goal of this paper is to apply a holistic approach in order to understand the interaction of VRES growth with a wide range of indicators.

With this aim, we use Categorical Principal Component Analysis (CATPCA) to carry out exploratory research on the growth of wind and solar energy relative to other forms of renewable energy, specifically with respect to meteorological, economic, and sociopolitical indicators for a range of European nations. The categorical component of this analysis is generated by the procedure proposed by Claveria (2016), in which time series data of a wide range of indicators are converted to ordinal series by ranking the countries according to the growth experienced during the sample period. CATPCA is then used to turn this categorical ranking data into uncorrelated components which allows for nations to be clustered and positioned relative to these components.

The use of CATPCA not only allows us to work with variables that are nominal (i.e., the regions of the countries chosen for this study), ordinal (i.e., the rankings of said nations) and numerical (i.e., the original indicator data) simultaneously, but it can also capture nonlinearity in the relationships between these variables. Further, the clustering of each country on a biplot of the generated components allows us to analyse the relative relationship between countries with respect to the information captured in the components.

While our analysis cannot derive causal conclusions, this empirical study offers an alternative approach to evaluating the interplay of various key factors in the development of VRES that includes (a) quasi-dynamic analysis of each nation via the rate-of-growth rankings over the study period of 2007-2019, (b) the use of visualization in understanding VRES development, and (c) an assessment of the relative relationship between different economies with respect to this development.

In this study, the results from these analytical elements highlight a decoupling between the development of VRES and the initial factors that helped establish these industries, such as resource availability. The implications of these findings reinforce the role of the individual nation in championing the development of these clean energy technologies relative to the environmental obstacles that exist with VRES development.

The remainder of this paper is structured as follows. In Section 2, we assess the current state of research surrounding VRES development. The following section describes the data used and gives greater detail on the methodology behind our analysis. Section 4 presents and discusses the results of the CATPCA analysis as well as a comparison of country growth rates and average levels of wind and solar energy share in the renewables mix. Finally, Section 5 summarises our main findings 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 renewable energy deployment. Environmental, economic, and social factors were identified as drivers of renewable energy while political, regulatory, technical potential and technological categories were all found to have undetermined effects on renewable energy deployment. 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 renewable energy deployment.

An interdisciplinary study most like the work undergone in this present paper is that of Papież et al. (2018), in which the authors research the determinants of various types of renewable energy in 26 European countries from 1995 to 2014. Similar to our study, Papież et al. (2018) used principal component analysis as a part of their research methods to investigate the distribution of energy consumption, first with respect to different renewable energy sources, and then with respect to fossil fuels and total renewable energy consumption. The principal components from the latter analysis were then used in a cross-sectional regression analysis along with various variables relating to potential determinants of renewable energy 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, and 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 over the study period relative to other renewable energy sources, 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 renewable energy development in the present was pre-existing levels of renewable energy, implying that early decisions regarding renewable energy implementation have consequences on the future growth of these energy sources.

Hernik et al. (2019) took an interdisciplinary approach to analysing the controls on renewable energy development in Eastern Poland using a Spearman's rank coefficient correlation test to analyse the relationship of spatial-economic variables with a number of renewable energy sources in urban vs rural areas. Hernik et al. (2919) found a significant difference in the nature of renewable energy development between rural and urban districts, where development in urban districts tends to show correlation with economic factors, while rural districts show 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 renewable energies 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 renewable energy 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 renewable energy development is still not entirely agreed upon. Many studies have pointed to positive relationships between renewables and GDP (Apergis & Payne, 2010; 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 renewable energy and GDP.

Using a different approach, Yao et al. (2019) incorporated greenhouse gas emissions into their analysis of renewable energy 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 CO_2 emissions are increasing with a relatively low starting GDP; *ii)* the structural effect phase in which CO_2 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 inverse U-shaped relationship between CO_2 emissions and GDP, Yao et al. (2019) found that in contrast to emissions, renewable energy has a U-shaped relationship with GDP implying that significant increases in renewable energy consumption will only be seen in high-income nations that have crossed the threshold into the "technology effect" stage. These findings support the theory that renewable energy 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 to 2008. Their results showed no evidence that high economic productivity would lead to decrease in CO_2 emissions, and instead found the opposite—that greenhouse gas (GHG) emissions were continually increasing with GDP. As such, while Bölük and Mert (2014) found that renewable energy produced less CO_2 emissions than fossil fuels. The authors did not find that renewable energy growth lead to a decreasing trend in CO_2 emissions, given that renewable energy stimulated GDP, and GDP growth was always associated with a CO_2 rise. Similar research has empirically proved (Auci & Trovato, 2011; Bruyn et al., 1998; Markandya et al. 2006) and disproved (Akbostanci et al., 2009; Friedl & Getzner, 2002; Grossman & Kreuger, 1995) the EKC hypothesis, making it a contested subject further complicated by the role that renewable energy 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 contextualising the state of renewable development, VRES present unique challenges to power systems and the energy grid not present in other types of renewable energy sources (Babatunde et al., 2018; 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 renewable energy sources.

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 renewable energy sources 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 European Union (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 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 characteristic and geospatial differences between wind and solar energy droughts. Firstly, they 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. On the other hand, 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., 2017; Huber et al., 2014; Johnson et al., 2020; 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, 2017). Consequently, understanding VRES development relative to other renewable energy 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 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 VRES, which is is the goal of the present study.

3. Data and methods

This study proposes a multivariate dimensionality reduction procedure for a panel dataset that includes a variety of VRES related indicators for 15 European countries in the time period of 2007-2019. 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. ‘climatological’ variables 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 remaining compatible with panel data structure of data used in this study. See Pérez and Claveria (2020) for further examples.

Principal Component Analysis (PCA) is a widely used method of multivariate dimensionality reduction and has even been successfully applied in a study like this one (e.g., 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 nonlinear given the complex spatio-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, we use CATPCA—also known as nonlinear PCA—to cluster and position 15 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 nonlinear relationships between data, including nominal and ordinal data. An additional advantage of CATPCA is that, due to the nonlinear transformations of the variables achieved by optimal quantification, it tends to concentrate more variation in the first few principal components (De Leeuw & Meulman, 1986). This study additionally aims to highlight the utility of CATPCA for visualising relationships. Given the ability of CATPCA to concentrate variability in fewer components, we are able to project the top two components in a two-dimensional map together with the relative positioning of the countries, thus creating a graphical representation of the relative positioning of countries with respect to the variables summarised in the two components.

We use the methodology proposed by Claveria (2016), in which the data are first converted into ordinal rankings of each country based on their average growth (or average level in the case of climate variables) with respect to a given variable. Table 1 shows the explanation of each variable, its units of measurement, as well as whether they have been incorporated into the analysis in growth rates or levels.

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
Sociopolitical				
	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
Climate				
	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 meters	m s-1
	16	Precipitation days*	Number of days with total precipitation greater than 4mm	days
	17	Temperature Range*	Difference between the warmest and coldest month in a year, based on average hourly maximum and minimum temperatures	Kelvins

Notes: *Ranking based on average level instead of average rate of growth. 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.

The data was chosen to reflect factors relating to energy, economy, sociopolitical measures, and natural climate. Each variable in Table 1 is categorised by one of these dimensions. The data used was sourced from Eurostat, The World Bank, OECD, the United Nations, 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 data were aggregated at the country level, and thus, represent spatial averages of each value. Average weather data across a country wide 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). Note also that indicators representing wind and solar energy consumption are represented as a share of renewable energy sources, not all energy sources. This was done to ensure that potential relationships were specific to wind and solar, and not to the general increase of renewable energy across Europe.

The Human Development Index (HDI) is a composite indicator of life expectancy, education, and income per capita (Alzate, 2006), whose introduction allows us to incorporate the interactions between natural dependence and development beyond a strictly economic sense. All data can be freely downloaded. The sample period extends from 2007 to 2019.

Our analysis focuses on a set of European countries. We have selected a sample of fifteen countries which are distributed across the four main regions of Europe: Western Europe (Austria, Belgium, France, Germany, Netherlands), Northern Europe (Denmark, Finland, Sweden, Ireland, the United Kingdom –from now referred to as the UK), Southern Europe (Greece, Italy, Portugal, Spain) and Central Europe (Bulgaria). The countries were selected to not only represent a wide range of geographical locations, but also a range of renewable energy goals and consumption levels (see Table 2).

Table 2. Average % share of wind and solar gross energy inland consumption (GEIC) with respect to total renewable GEIC consumption (2007-2019)

	Wind share	Solar share
Austria	3.3	2.2
Belgium	9.2	5.3
Bulgaria	4.5	4.2
Denmark	20.5	1.3
Finland	1.5	0.0
France	5.9	2.3
Germany	15.5	1.7
Greece	13.7	17.3
Ireland	44.1	1.0
Italy	4.3	5.4
Netherlands	14.9	3.0
Portugal	16.2	2.1
Spain	25.1	12.6
Sweden	4.4	0.1
UK	18.4	2.9

GDP per capita is included as a measure of economic growth while population density and the percentage of urban population aim to capture the population distribution of each country. Taxes on pollution serve as a measure of the level of disincentive of non-renewable resources. Energy imports represent a country's dependency non-domestic sources to meet its energy needs—note that since the technology to import renewable energy is still in its infancy, imported energy is often non-renewable.

To avoid the issues derived from working with non-stationary time series (Clements & Hendry, 1998) and to circumvent some of the problems that may arise when dealing with time series from developing countries, such as the presence of outliers, hereafter we use the percentage growth rates of the variables or the average levels during the sample period. Growth rates are dimensionless measures of the amount of increase (or decrease) of a specific variable from one year to another in percentage terms. This allows us to undertake a comparative analysis of the evolution of the different indicators.

In Table 3 and Table 4, we present the summary statistics of all the variables included in the analysis. Table 3 contains the average growth rates during the sample period, while Table 4 the average levels of natural factors during the sample period. We can observe that some of the variables (energy intensity and greenhouse gas emissions) have experienced a decrease in all countries. Other variables related to energy consumption and energy imports also tend to show negative values, as opposed to the share of wind and solar energy, which have increased in all countries. This is representative of the general trend towards renewable energy and climate neutrality in Europe. Variables representing a positive climactic impact (such as wind and solar energy use) increase, while variables representing negative climate impacts (such as green- house gas emissions, total energy consumption, energy intensity) tend to show negative growth.

Following Claveria's (2016) two-step procedure, in Table 5 and Table 6 we have ranked the countries in decreasing order according to the average growth (variables 1 to 12) or to their average level (variables 13 to 16) experienced over the period extending from 2007 to 2019 for each variable.

Table 3. Summary statistics – Average growth rates (2007-2019)

	Wind share	Solar share	Industry consumption	Transport consumption	Household consumption	Energy imports
	1	**2**	**3**	**4**	**5**	**6**
Austria	1.95	1.50	0.00	0.06	0.07	0.05
Belgium	6.20	26.83	-0.03	-0.02	-0.05	0.00
Bulgaria	10.19	0.18	-0.30	0.23	0.05	-0.26
Denmark	0.23	6.16	-0.20	-0.09	-0.03	-2.60
Finland	21.65	10.07	-0.08	-0.05	0.10	-0.21
France	4.15	17.05	-0.15	0.01	-0.01	-0.06
Germany	0.81	0.40	-0.04	0.04	0.04	0.16
Greece	1.21	0.94	-0.44	-0.23	-0.24	0.05
Ireland	0.54	2.36	0.02	-0.14	-0.10	-0.22
Italy	1.88	22.41	-0.31	-0.15	-0.04	-0.07
NL	0.56	9.21	-0.13	-0.08	-0.07	0.73
Portugal	1.50	4.66	-0.21	-0.08	-0.10	-0.09
Spain	0.07	11.99	-0.25	-0.16	-0.06	-0.06
Sweden	8.78	4.47	-0.10	-0.09	0.04	-0.18
UK	1.51	4.21	-0.27	-0.06	-0.08	0.71

Note: NL refers to the Netherlands and UK to the United Kingdom.

Table 4. Summary statistics – Average level (2007-2019)

	Energy intensity	Urban population	Population density	Per capita income	Taxes on pollution	Greenhouse emissions	HDI	Irradiance	Wind speed	Precipitation days	Temperature range
	7	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**
Austria	-0.11	0.58	103.51	48777.04	78.78	81032.37	0.91	142.58	2.03	109.77	28.51
Belgium	-0.14	0.98	366.93	45276.65	525.48	123486.58	0.92	126.82	3.88	80.23	23.23
Bulgaria	-0.28	0.73	66.89	7683.35	31.15	60217.69	0.8	169.49	2.28	62.62	32.04
Denmark	-0.27	0.87	137.79	59223.98	575.63	56662.23	0.93	122.36	4.94	72.85	21.74
Finland	-0.12	0.85	17.85	48166.41	97.15	63373.33	0.93	94.86	3.29	56.15	33.33
France	-0.17	0.79	120.25	41064.45	2863	485590.01	0.89	150.75	3.13	87.08	24.85
Germany	-0.21	0.77	234.38	44404.82	13.92	911640.57	0.93	128.49	3.26	77.69	25.76
Greece	-0.01	0.77	84.84	23181.33	2.08	107749.14	0.87	189.06	2.06	68.85	28.61
Ireland	-0.43	0.62	67.57	60423.30	51.57	61658.95	0.92	112.09	4.19	98.15	15.72
Italy	-0.14	0.69	202.98	35236.49	533.85	475190.08	0.88	173.42	2.04	92.69	26.62
Netherlands	-0.19	0.89	499.31	51332.43	3122.08	195002.27	0.93	123.77	4.21	74.31	22.39
Portugal	-0.14	0.62	114.01	22165.77	33.35	68534.65	0.84	195.52	2.95	59.15	24.82
Spain	-0.20	0.79	93.02	29937.42	591.92	353436.79	0.88	194.61	2.73	52.92	27.64
Sweden	-0.18	0.86	23.64	54880.01	164.57	57066.5	0.93	102.29	3.20	61.15	29.13
UK	-0.29	0.82	265.16	43313.49	1632.45	549894.36	0.92	113.10	4.31	97.77	17.17

Note: UK refers to the United Kingdom.

Table 5. Ranking of countries according to their growth (variables 1 through 6) or average level (variables 7 through 9) during the sample period (2007-2019)

Wind share	Solar share	Industry consumption	Transport consumption	Household consumption	Energy imports	Energy intensity	Urban population	Population density
Finland	Belgium	Ireland	Bulgaria	Finland	NL	Greece	Portugal	Sweden
Bulgaria	Italy	Austria	Austria	Austria	UK	Austria	NL	Denmark
Sweden	France	Belgium	Germany	Bulgaria	Germany	Finland	Bulgaria	Ireland
Belgium	Spain	Germany	France	Sweden	Austria	Portugal	Greece	UK
France	Finland	Finland	Belgium	Germany	Greece	Italy	Italy	Belgium
Austria	NL	Sweden	Finland	France	Belgium	Belgium	Ireland	Austria
Italy	Denmark	NL	UK	Denmark	France	France	France	NL
UK	Portugal	France	NL	Italy	Spain	Sweden	UK	France
Portugal	Sweden	Denmark	Portugal	Belgium	Italy	NL	Sweden	Finland
Greece	Bulgaria	Portugal	Sweden	Spain	Portugal	Spain	Spain	Spain
Germany	UK	Spain	Denmark	NL	Sweden	Germany	Finland	Italy
NL	Ireland	UK	Ireland	UK	Finland	Denmark	Denmark	Germany
Ireland	Austria	Bulgaria	Italy	Portugal	Ireland	Bulgaria	Germany	Portugal
Denmark	Greece	Italy	Spain	Ireland	Bulgaria	UK	Belgium	Greece
Spain	Germany	Greece	Greece	Greece	Denmark	Ireland	Austria	Bulgaria

Notes: Countries are ranked in decreasing order according to their average growth rates during the sample period (2007-2019). UK refers to the United Kingdom and NL to the Netherlands.

Table 6. Ranking of countries according to their average level during the sample period (2007-2019)

Per capita income	Taxes on pollution	Greenhouse emissions	HDI	Irradiance	Wind speed	Precipitation days	Temperature range
Ireland	NL	UK	Germany	Portugal	Denmark	Austria	Finland
Denmark	France	Sweden	Denmark	Spain	UK	Ireland	Bulgaria
Sweden	UK	Spain	NL	Greece	NL	UK	Sweden
NL	Spain	Portugal	Sweden	Italy	Ireland	Italy	Greece
Austria	Denmark	NL	Finland	Bulgaria	Belgium	France	Austria
Finland	Italy	Italy	Ireland	France	Finland	Belgium	Spain
Belgium	Belgium	Ireland	Belgium	Austria	Germany	Germany	Italy
Germany	Sweden	Greece	UK	Germany	Sweden	NL	Germany
UK	Finland	Germany	Austria	Belgium	France	Denmark	France
France	Austria	France	France	NL	Portugal	Greece	Portugal
Italy	Ireland	Finland	Spain	Denmark	Spain	Bulgaria	Belgium
Spain	Portugal	Denmark	Italy	UK	Bulgaria	Sweden	NL
Greece	Bulgaria	Bulgaria	Greece	Ireland	Greece	Portugal	Denmark
Portugal	Germany	Belgium	Portugal	Sweden	Italy	Finland	UK
Bulgaria	Greece	Austria	Bulgaria	Finland	Austria	Spain	Ireland

Notes: Countries are ranked in decreasing order according to their average growth rates (variables 10 to 12) or their average level (variables 13 to 17) during the sample period (2007-2019). UK refers to the United Kingdom and NL to the Netherlands.

The rankings captured in Tables 5 and 6 varied, with no single country consistently dominating in any given variable. This is not surprising given the wide range of variables used in the study. An exception may be Greece, which has the lowest ranking for energy consumption across all sectors represented, pointing to an overall decrease in energy consumption where other countries experience an increase across the study period.

Despite being country-level averages, the rankings of the climatic 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.

4. Results and discussion

In this section we implement CATPCA to (i) reduce the dimensionality of data and (ii) generate a plots with the relative positioning of the economies and the variables. Finally, we compare the average levels and growth rates of the wind and solar share variables to supplement and contextualise the CATPCA findings.

4.1. Dimensionality Reduction

To carry out the CATPCA analysis we first rank the economies in decreasing order for each variable according to either their average level or the growth experienced over the period under study (2007 to 2019). We then assign a numerical value to each country corresponding to its position, obtaining a set of categorical data that we use to cluster the different states. The grouping of all countries is done by means of CATPCA using IBM SPSS Statistics 24.

Since the first two factors account for more than 77% of the variance of the variables under analysis, we have retained these two factors. In Table 7, we present 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 nonlinear optimal procedure that relates the category quantifications versus the original categories.

Table 7. CATPCA analysis – Summary

Dimension	Cronbach's alpha	Variance	
		Total (eigenvalue)	% of variance
1	0.92	7.14	42.01
2	0.90	6.11	35.92
Total	0.98*	13.25	77.93

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

Table 8 on the next page shows the obtained component loadings of each variable in both dimensions. We also applied Varimax rotation to facilitate 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.

First, dimension 1 shows the highest loading components belonging to energy factors as well as per capita income, GHG emissions, and solar share. On the other hand, the second dimension is dominated by all of the climate category factors, as well as HDI, population density, taxes on pollution and, to a lesser extent, urban population. Although wind share does not have a high loading in either dimension, the magnitude is consistent in both dimensions with the caveat that it has a positive effect on dimension 1 and a negative effect on dimension 2. Third, while strongly represented in dimension 1, solar share has a much weaker effect on dimension 2. Based on these results, dimension 1 could be interpreted as relating to the same interplay between energy, emissions, and GDP explored in the various studies surrounding the EKC mentioned in Section 2 of this paper. Dimension 2 seems more closely related to climatic variables, as well as variables that could jointly be described as "socio-environmental", i.e. the physical distribution of population (urban population) and policy on carbon emissions (taxes on pollution). HDI is also included in this second dimension.

Table 8. Rotated component loadings – CATPCA

Category	Position	Dimension	
		1	2
Energy			
	Wind share	0.436	-0.424
	Solar share	0.791	-0.154
	Industry consumption	0.952	0.270
	Transport consumption	0.963	0.221
	Household consumption	0.971	0.195
	Energy imports	-0.519	0.457
	Energy intensity*	-0.964	-0.215
Society & Politics			
	Urban population*	-0.184	-0.722
	Population density*	0.411	0.829
	Human development*	0.299	0.913
	GHG Emissions*	0.964	0.214
Economy			
	Per capita income*	0.964	0.216
	Taxes on pollution*	0.340	-0.829
Climate			
	GHI*	-0.197	-0.897
	Wind speed*	0.166	0.847
	Precipitation days*	0.124	0.781
	Temperature range	0.002	-0.731

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

Figure 1 displays the rotated component loadings (indicators). The coordinates of the end point 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 180º angle with each other are closely and negatively related. Finally, variables that are not related correspond with vectors making a 90º angle.

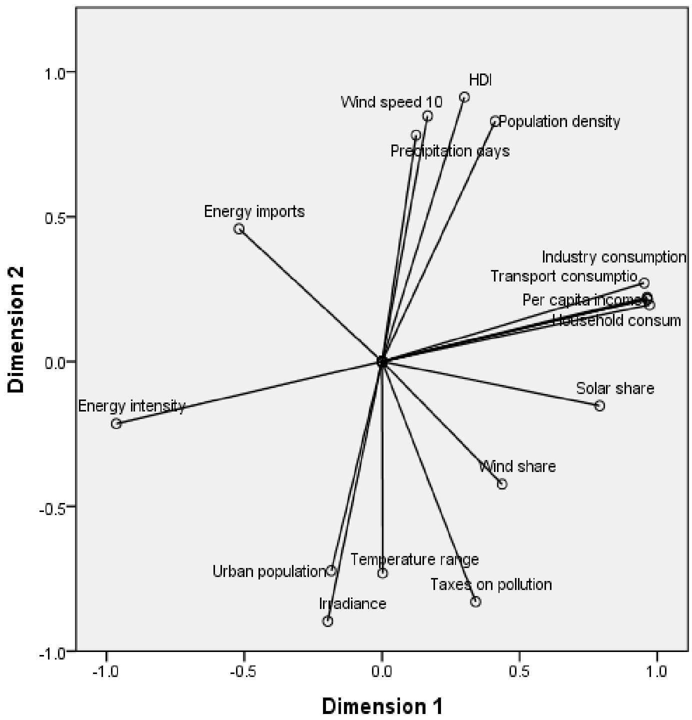

Figure 1. Rotated component loadings

An interesting dynamic captured by Figure 1 is that of the energy intensity variable. Energy intensity is expressly calculated using the ratio of energy consumption over GDP, thus the inverse relationship between energy intensity and per capita income in this study is to be expected. What is less intuitive, however, are the mechanisms behind the nature of this relationship. The drivers behind changes in energy intensity have been theorised to result from either decreasing energy consumption relative to GDP (i.e. "structural") or increasing GDP relative to energy consumption (i.e. "technological", referring to technological advances that allow energy production to be more efficient) (Voigt et al., 2014). The close relation between consumption and GDP in Figure 1 may indicate that a decrease in energy consumption as proposed by a structural change scenario is not captured in the present results. On the other hand, the negative dynamic between solar share and energy intensity, could be a reflection of a technological mechanism, implying that solar energy could be regarded as one of these technologies that allow for greater energy efficiency. Wind share also shows a negative, albeit much weaker relationship to energy intensity, implying that, at the very least, wind energy development is not associated with the energetically inefficient regimes represented by high energy intensity values.

Figure 1 shows that in the 2nd dimension, GHG emissions are positively related to per capita income. GHG also has a positive relationship with solar share and, to a lesser extent, with wind share. 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. Yao et al., 2019), while others that find no evidence of such relationship (e.g. Bölük & Mert, 2014). Our results suggest that if there is such a threshold at which a nation's GDP becomes decoupled from GHG emissions, either it is not captured here or the countries in this study have not crossed it during the sample period.

Another interesting finding reflected in Figure 1 is the disconnect between climatic factors and wind and solar energy development. Irradiance shows no relationship with solar share growth, and wind speed seems to have a very weak and surprisingly inverse relationship with wind share growth. Given that most of the climate variables used here are annual averages, this result could emphasise the importance of finer resolution temporal and spatial climate effects, such as weather unpredictability or diurnal and seasonal cycles of VRES resources. This could however also signal something about the growth vs the current state of VRES, and that the development of these technologies goes, at this point and for these nations, beyond mere resource availability. This theory would seem to hold more true for solar energy, given its strong relationships with the energy and economy variables, than wind share which has a more neutral presence in both dimensions. Despite these differences, wind and solar development appear to have some relationship given the proximity of the wind share and solar share variables. Finally, Figure 1 also shows an inverse relationship between energy imports and both wind and solar share. This finding is likely pointing to the role VRES plays in allowing nations to develop energy autonomy and transition away from fossil fuels.

4.2. Clustering of Countries

Figure 2 displays three clusters of countries that roughly correspond to the main European regions. To a certain extent, the top quadrant is dominated by Southern Europe economies (Greece, Italy, Portugal, Spain) and Bulgaria, from Eastern Europe, while in the lower quadrant there is a predominance of Western European states (Belgium, Germany, Netherlands, Ireland, and the UK), all very close to each other, with low scores in both dimensions. Finally, Finland and Sweden, with lower scores on the first dimension but higher on the second one, would make up a final cluster corresponding to the countries of Northern Europe.

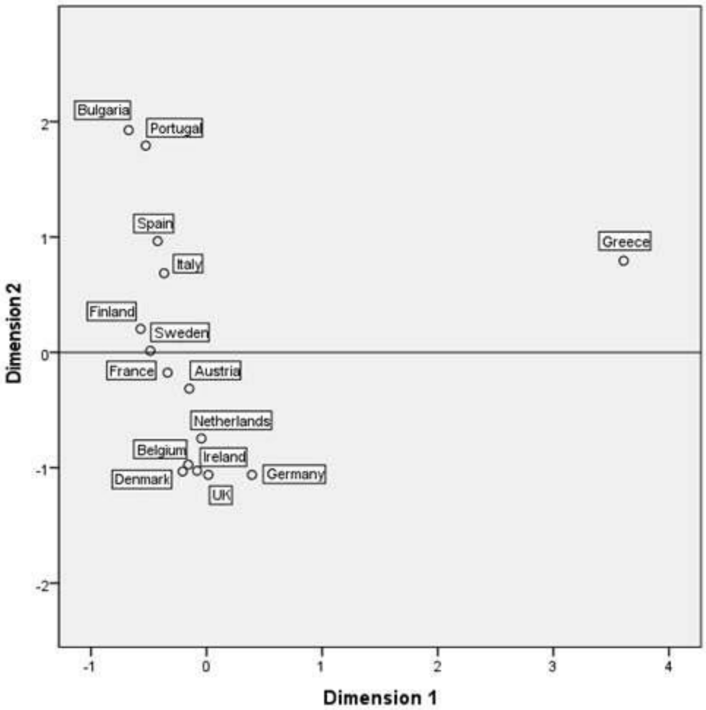

Figure 2. Object points labelled by country

The two-dimensional plot in Figure 2 represents the coordinates of the first two retained dimensions for each country. In the graph, one can observe a slightly negative slope in the positioning of the economies along both dimensions, which is indicative of a certain inverse relationship between the energy/economy factors and the climate/environment factors.

When interpreting Figure 2 it is important to recall that countries have been ranked in decreasing order. As such, countries with lower scores in the 1st dimension represent countries with high per capita income, high consumption, high GHG emission rates, strong growth in the Solar energy sector and low energy intensity. In dimension 2, countries with lower scores are likely to have more climatic variation as they represent high rankings across many different climatic features like wind speed, GHI, precipitation days and temperature range. Of the non-climatic variables captured by dimension 2, countries in the strongly positive direction of the vertical axis in Figure 2 will contain nations with lower HDI rankings and lower population density, while countries towards the bottom of the axis will represent nations with less urban population and less taxes on pollution.

There seems to be also a positioning linked to the geographical location of the countries. The top quadrant is completely dominated by the countries of Southern Europe (Spain, Italy, Portugal), all of which rank high in natural variables such as irradiance and temperature range. In the lower quadrant there is a predominance of Western Europe states (Belgium, Germany, Netherlands, Ireland, and the UK), all very close to each other, with low scores in both dimensions. Finally, Finland and Sweden, with lower scores on the first dimension but higher on the second one, would make up a final cluster corresponding to the countries of Northern Europe. These results are therefore in keeping with Śmiech and Papież (2014), who identified four groups of European countries which meet energy policy targets at similar levels. Notwithstanding, two outliers appear in the form of Greece, a southern country with an incredibly high score in the 1st dimension, and Bulgaria, the sole Eastern European country with the highest dimension 2 score and the lowest score in dimension 1.

The outlier of Greece is likely explained by its low rankings across all consumption categories as well as its relatively low average per capita income (see Table 5). These values mean that Greece saw a decrease in its energy consumption across the study period. This is to be expected as GDP is known to be positively correlated with consumption (Soytas & Sari, 2003). And while our study only captures static, average per capita income levels, Greece's economy saw a sharp decline across the study period (Pegkas, 2019).

Bulgaria's score in dimension 1 can be explained by similar mechanisms. Again, although not captured in the data used for this study, Bulgaria's per capita income has seen a steady increase over the study period (Can & Korkmaz, 2020) despite the fact that its level is on average relatively low compared to the other nations under study. That said, it is the highest ranking nation for energy intensity, indicating that despite the increase in consumption, Bulgaria's economy is not energetically efficient. Given the fact that Bulgaria holds the bottom ranking for solar power development, this could support the theory that technological advancements in energy production is at least one of the driving factors in improving a nation's energy intensity. Bulgaria's low ranking in the 2nd dimension is most likely explained by the fact that it holds the bottom ranking in in both HDI and population density

4.3. Average vs growth levels of wind and solar share

Finally, in order to shed some light regarding the complex interplay between the average share of wind and solar energy inland consumption in European countries during the sample period, and their growth rate in both shares, we present the scatterplot for both the wind share and the solar share in Figures 3 and 4 on the following page.

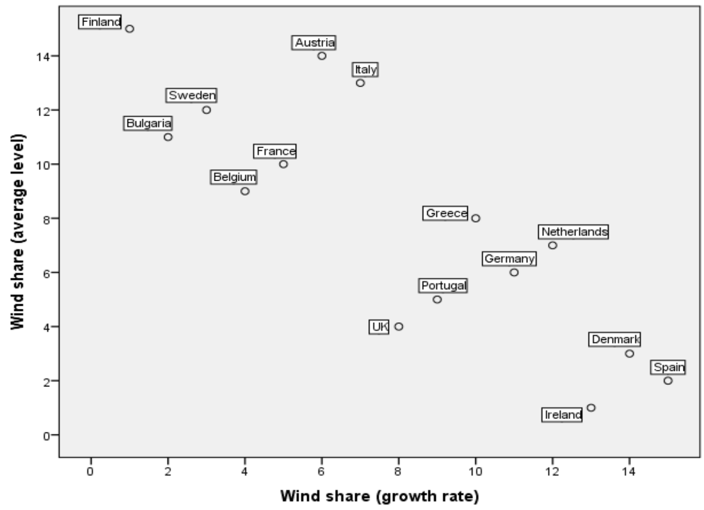

Figure 3. Scatterplot – Average wind share and average growth rate of wind share ranking

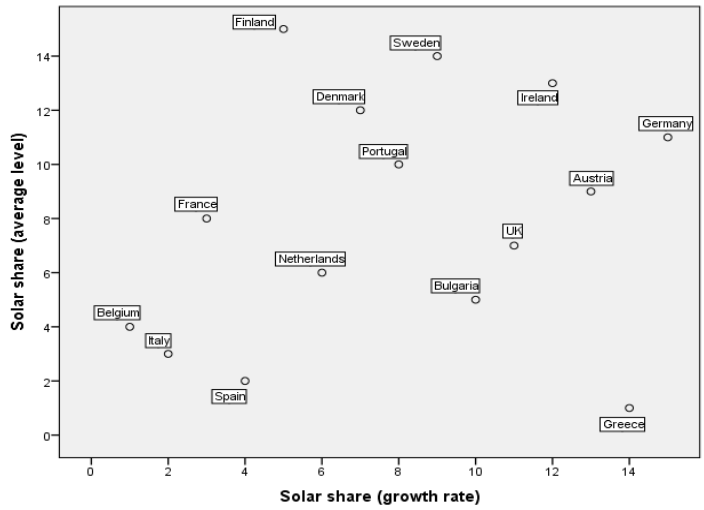

Figure 4 . Scatterplot – Average solar share and average growth rate of solar share ranking

Figure 4 shows that there is a positive relationship between the rankings related to the average relative weight of solar energy consumption and that of the average growth rate experienced during the sample period, with the exception of Greece, while the opposite is found for wind energy consumption (Figure 3). While the obtained results are not directly indicative of a negative relationship between natural factors and economic growth, neither are they indicative of the reverse situation. These results somehow indicate a very unequal growth between countries in the wind energy sector, which does not correspond to the average relative position observed since 2007, which highlights the growing investment that is being made from countries that started from a much more modest relative position.

While the stark differences in Figures 3 and 4 may point to a vastly different landscape between wind and solar markets, it is important to restate that these variables represent the share of renewable energy consumption in the given nation. That is, the total consumption of renewable energies is given equal weight for all countries, despite the actual share of energy from renewable sources varying wildly across the countries under study. This understanding aids in contextualizing the results found.

For example, Figure 3 shows an inverse relationship between wind share level and wind share growth, but some of the countries with the lowest wind share level are Sweden, Finland, and Austria—countries with the 1st, 2nd and 5th highest share of total energy consumption from renewables, respectively (Eurostat Renewable Energy Statistics, 2021). Thus, the low level/high-growth relationship in these nations could point to a preference for other renewable sources over wind, but a highly progressive attitude towards renewables that drives growth in renewable sources in general. Likewise, de Llano-Paz et al. (2015) found that while wind energy investment is one of the promising avenues to the EU's reaching its emission targets, investment in solar photovoltaic power systems is not at all needed to reach efficiency targets. This, in conjunction with the findings that Northern European countries show a very high suitability for wind energies (Raynaud et al., 2018) could explain why countries with high total consumption of renewables dominate growth in wind share more than solar share.

In addition, the high level/high growth relationship in solar according to Figure 4 does not apply to certain Northern European countries like Finland and Sweden which still show moderate relative growth in these energies despite low levels. Koivisto et al. (2018) showed that Northern European countries, despite having generally high levels of renewable consumption already, could benefit from a mixing in the renewable energy balance, i.e., by incorporating wind and solar.

This behaviour in the Northern European countries could also play a role in explaining the surprising result that the solar irradiance variable is not related to growth in the solar share variable. In some respects, this result could also be influenced by the heavy outlier of Greece who, despite being a country very well suited for solar, lies in one of the lowest positions for growth. However this is most likely a reflection of the fact that the main climatic challenges relating to VRES exist on time scales shorter than annual. This is supported by the fact that although wind share shows a stronger relationship to climatic variables, these relationships are also relatively weak. Challenges with VRES are the result of uncertainty and variability in the diurnal cycles of the sun and wind, the non-synchronicity of decreased hours of sunlight but increased demand during the winter, inclement weather events, etc. This short to medium scale variability in VRES supply is not reflected in our study, and in fact, the natural impacts are less represented in our results. While annual levels may be helpful in understanding the effect of climate change on VRES, the response and adaptation of the power systems play a greater role in understanding the effect on these energy sources than the climate change induced fluctuations in the natural factors controlling VRES energy supply (Bloomfield et al., 2021).

5. Conclusion

This study aims to provide researchers with an analytical framework to visualise the interplay between natural renewables, human development, and other socioeconomic factors, and to position economies with respect to those interactions. 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.

With this objective, we first undertook a descriptive analysis of the evolution of a set of variables related to natural, economic, and social factors over the period extending from 2007 to 2019. Then, countries were ranked according to the average growth experienced over the sample period for most variables, with the exception of variables that measure natural phenomena, which are ranked according to their average level during the sample period. By assigning a descending numerical value to each country corresponding to its ranking, we generated a set of categorical data that was summarised into two components. The first component pertained to the relationship between energy, greenhouse gas emissions and economic growth, thus emphasising the importance of these factors especially with respect to solar power development. The second component pertained more to "socio-environmental" factors such as climate, physical environment, and environmental policy.

One of the primary findings of this study is that there seems to be a decoupling between climatic conditions and growth of wind and solar energy relative to other renewable energy sources. This could indicate that, at this point in the development of the renewable energy market other factors other than resource availability/quality are controlling wind and solar development.

Relatedly, we found that in wind energy there is a strong inverse relationship between a country's average relative share of wind energy and the growth in the relative share of wind energy. The opposite is true for solar. This could be because Northern European countries are being increasingly identified as highly suitable, and these countries already have very high penetration of renewable energy consumption from sources other than wind and solar, thus their low average level. 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, save for Bulgaria and Greece.

This study shows the potential of dimensionality-reduction and data-visualization techniques to capture the complex set of linkages among renewable energy, human development, and other natural factors, as well as for the positioning of economies according to the dynamic interplay among them. Our goal is to provide researchers with an alternative approach to identify key attributes in the positioning of economies. Notwithstanding, this research is not without limitations. First, we want to note 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. The yearly periodicity of the data also provides limitations in understanding the interplay between climate and variable renewable energy sources because, as mentioned, much of these challenges exist on a daily or seasonal scale. Due to the lack of available information, we have not included additional indicators that could give further insight into other factors operating in the renewables industry. Another question left for future research is an extension of the analysis to other countries and comparison of the results with those obtained using other dimensionality-reduction techniques such as self-organizing maps.

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