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ANALYSIS OF THE SIMILARITY AMONG EUROPEAN UNION COUNTRIES IN TERMS OF SUSTAINABLE ENERGY DEVELOPMENT

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Purpose: The primary purpose of the study was to empirically analyze the similarity among EU countries concerning their energy sustainability.
Methodology: The research methodology developed and applied includes a taxonomic approach based on the k-means method. This method was used to cluster European Union countries into homogeneous groups, based on selected indicators, to identify countries with similar levels of energy sustainability in 2013 and 2022. The indicators represented various aspects of energy sustainability, such as greenhouse gas emissions, the development of renewable energy sources (RES), energy consumption per capita, and energy productivity in terms of euros per kilogram of oil equivalent.
Findings: The study results indicate considerable variation among EU countries in energy sustainability. Scandinavian countries consistently achieve the best results, characterized by a high share of renewable energy in the energy mix and low greenhouse gas emissions, reflecting the successful integration of their energy policies with sustainability goals. In contrast, some Central and Eastern European countries exhibit weaker records of energy sustainability due to economic and political historical contexts and related social challenges. This group is marked by higher GHG emissions, a lower share of renewable energy, and lower energy efficiency.
Practical Implications: The methodology used allows for the grouping of EU countries based on their achievements in energy sustainability and facilitates comparisons between them. It also identifies leaders and outliers from the average, particularly highlighting the need for diagnosing the reasons behind the status of the outlier group and identifying actions to improve the current state. Achieving energy neutrality is now a priority of EU economic policy. The results indicate significant variation in the energy development of EU countries, suggesting the need for more tailored EU financial and technological support.
Originality: The paper presents a holistic approach, utilizing a taxonomic method to analyze the similarity among a group of EU countries in terms of sustainable energy development. This broad and multidimensional approach integrates various aspects of energy sustainability, enabling a comprehensive assessment of energy policy implementation between 2012 and 2022 at the level of EU countries.
Keywords: sustainable energy development, goal 7 - clean and accessible energy, energy policy, European Union, taxonomic method, holistic approach.
Category of the paper: Research paper.

1. Introduction

Sustainable energy development is one of the fundamental challenges of the modern world, particularly in the context of growing environmental awareness and the urgent need to reduce greenhouse gas emissions (Gunnarsdottir et al., 2021; Marti, Puertas, 2022; Tutak et al., 2020). It should be understood as the use of energy sources that meet three basic requirements: they do not deplete as a result of their use, their use does not cause emissions or other environmental risks to humans and/or ecological and climatic systems on a significant scale, and they are not associated with the perpetuation of significant social injustices (Jaiswal et al., 2022).

As part of global sustainable development initiatives, specifically Sustainable Development Goal 7 (SDG 7) adopted by the United Nations, countries are committed to providing universal access to affordable, reliable, and clean energy sources (United Nations, 2021). Within the European Union, which comprises 27 member states with diverse economic and energy profiles, achieving this goal requires coordinated action and effective policies at both the national and EU levels. As one of the world's leading economic and political communities, the European Union plays a key role in achieving these global goals while simultaneously striving to meet its own ambitious domestic targets for environmental protection, energy security, energy efficiency, and greenhouse gas emission reductions. To meet these objectives, numerous directives, regulations, and initiatives have been implemented, such as the European Green Deal, which aims to achieve climate neutrality by 2050. Promoting renewable energy sources (RES), improving energy efficiency, and reducing CO_2 emissions are critical components of this strategy (Council of the European Union, 2021; European Commission, 2019, 2020, 2021).

However, the implementation of these goals is not uniform across the EU. Member states vary significantly in terms of natural resource availability, technological development, economic structure, and energy policy. Social aspects, which are also diverse across the EU, play an important role in these processes. For instance, Scandinavian countries such as Sweden and Denmark are leaders in the field of RES, while Central and Eastern European countries such as Poland and Bulgaria still rely heavily on fossil fuels, resulting in a low share of RES in their energy mix and high GHG emissions.

In this context, studying the EU-27 countries in terms of energy sustainability, both individually and in terms of their similarity, is fully justified. An important tool for analyzing the similarity of EU countries in terms of sustainable energy development is the use of indicators that identify the problem under study and allow for comparisons of individual countries across various aspects of this process.

The purpose of the research presented in this paper is to analyze the similarity among EU countries concerning sustainable energy development, specifically in the context of achieving Goal 7 of Agenda 2030: "Ensure access to affordable, reliable, sustainable, and modern energy for all". This analysis was conducted using a set of nine key indicators to monitor progress toward this goal, with the k-means method (a taxonomic method) employed for the analysis. The first part of the paper presents the research methodology, including the characteristics of the indicators used and a discussion of the k-means method. This was followed by a comparative analysis of EU countries, including key indicators of energy sustainability. The next part of the work included the identification of groups of countries with similar characteristics and achievements in energy transition. Finally, based on the conclusions of the study, recommendations were made for energy policies in the context of further integration and cooperation within the EU.

2. Key indicators of sustainable energy development

Energy sustainability is the foundation of the energy transition, which seeks to meet the growing demand for energy while minimizing environmental impacts. In the context of accelerating climate change and global efforts to decarbonize economies, key indicators of energy sustainability are essential tools for evaluating the progress and effectiveness of energy strategies (Neves et al., 2010; Neves, Leal, 2010; Pan et al., 2023; Vera, Langlois, 2007).

These indicators provide a comprehensive assessment of various aspects of the energy system, such as energy efficiency, reliance on energy imports, diversification of energy sources, and greenhouse gas emissions. They enable the monitoring, analysis, and optimization of energy policies in a way that promotes both economic development and environmental protection. Additionally, these indicators help identify areas requiring intervention and measure the effectiveness of implemented actions.

The existing literature employs various indicators to assess countries' progress in achieving energy sustainability. Table 1 presents and characterizes the most significant of these indicators.

Table 1.
Sustainable energy development indicators

Indicator	Characteristics
Total primary energy supply per capita (TPES per capita), tonnes of oil equivalent (TOE)	This indicator measures the amount of primary energy available per capita. Primary energy refers to energy obtained directly from natural sources, such as coal, oil, natural gas, nuclear power, and renewable energy sources. This indicator serves as a measure of the availability of energy resources within a country.
Primary energy consumption per capita, tonnes of oil equivalent	This indicator measures actual primary energy consumption per capita. It is important because it reflects the amount of energy used for economic, industrial, and domestic needs, making it crucial for assessing a country's energy efficiency.
Energy Import Dependency, %	This indicator measures the percentage of energy consumed in a country that is sourced from imports. A high level of import dependence indicates vulnerability to external energy shocks, such as fluctuations in commodity prices or supply disruptions.

Cont. table 1.

Energy Productivity, Euro per kilogram of oil equivalent (KGOE)	This indicator measures the efficiency of energy use in the economy, expressed as the economic value (e.g., GDP) generated per unit of energy consumed. High energy productivity indicates efficient use of energy in economic processes, benefiting both the economy and the environment.
Share of renewable energy in gross final consumption, %	This indicator measures the percentage of energy derived from renewable sources (such as solar, wind, hydroelectric, biomass, and geothermal) within a country's or region's total final energy consumption.
Share of renewable energy consumption in transport, %	This indicator measures the percentage of energy used in the transportation sector that comes from renewable energy sources. It is important because the transportation sector is a major source of greenhouse gas emissions, and increasing the share of renewable energy sources in this sector can significantly contribute to reducing emissions.
Share of renewable energy consumption in electricity, %	This indicator measures the percentage of electricity generated from renewable energy sources. It is crucial for assessing progress in the energy transition toward more sustainable energy sources, which is important for reducing CO_2 emissions and protecting the environment.
Share of renewable energy consumption in heating and cooling, %	This indicator measures the percentage of energy used for heating and cooling that comes from renewable energy sources. The heating and cooling sector is a significant energy consumer, and its decarbonization is crucial for achieving climate goals.
GHG emissions from energy sector per capita, t CO_2 eq./capita	This indicator measures the amount of greenhouse gases emitted by the energy sector on a per capita basis. It is crucial for assessing the sector's impact on climate change and the effectiveness of emission reduction policies.
Population unable to keep home adequately warm by poverty status, %	This indicator determines the percentage of the population unable to adequately heat their homes due to poverty. It is important for evaluating the social aspects of energy policies.
Energy prices, euro/kilowatt	This indicator refers to the costs associated with purchasing various forms of energy, such as electricity, natural gas, fuel oil, and renewable fuels. These prices are a key factor affecting national economies, households, and the industrial sector.
Energy Intensity, kilograms of oil equivalent (KGOE) per thousand euro	This indicator determines the amount of energy required to produce a unit of economic output or value added in the economy. It is a key parameter for assessing the energy efficiency and economic sustainability of a country. This indicator is typically expressed as the amount of energy (usually in kilograms of oil equivalent, KGOE) per unit of economic value (usually in thousands of euros).

These indicators are used by researchers and international institutions to monitor and evaluate the effectiveness of energy policies, assess the environmental and social impact of energy systems, and plan measures to achieve sustainable development in the energy sector.

3. Materials and methods

The analysis of the similarity of EU countries in terms of their energy sustainability was based on data from the Eurostat database. This database contains comprehensive and reliable statistical data on various aspects of energy sustainability. A total of 9 indicators were used for the study, which characterized the studied EU countries in terms of:

- Total primary energy supply per capita, tons of oil equivalent.
- Primary energy consumption per capita; tons of oil equivalent.
- Energy import dependency, %.
- Energy productivity, Euro per kilogram of oil equivalent.
- Share of renewable energy consumption in transportation, %.
- Share of renewable energy consumption in electricity, %.
- Share of renewable energy consumption in heating and cooling, %.
- GHG emissions from energy sector per capita, t CO_2 eq./capita.
- Population unable to keep home adequately warm by poverty status, %.

The data covered the years 2013 and 2022 and served as the basis for the analysis conducted using the *k*-means method.

The *k*-means method is a clustering technique employed in the analysis of large multidimensional datasets. It divides a dataset into a specified number of clusters (*k*), such that objects (in this case, EU countries) within the same cluster are more similar to each other than to objects in other clusters. The method iteratively minimizes the sum of squared distances between data points and the centroid of their respective clusters (Dol, Jawandhiya, 2023; Ikotun et al., 2023).

The *k*-means algorithm includes the following steps:

1) To create a calculation matrix with dimensions $N \times M$, where N is the number of objects and M is the number of variables:

$$X = \begin{bmatrix} x_{11}\, x_{12} \ldots x_{1M} \\ x_{21}\, x_{22} \ldots x_{2M} \\ \vdots \quad \vdots \quad \ddots \quad \vdots \\ x_{N1} x_{N2} \vdots\, x_{NM} \end{bmatrix} \tag{1}$$

2) To standardize computational data:

$$z_{ji} = \frac{x_{ij} - \mu_i}{\sigma_i} \tag{2}$$

where:
zji - the standardized value of the j-th point for the i-th variable,
μ is the mean value, and σ is the standard deviation.

3) To select initial centroids:

$$\mu_1, \mu_2, \ldots, \mu_k \tag{3}$$

where μ_i are the initial centroids.
A matrix of centroids:

$$\mu^{(t)} = \begin{bmatrix} \mu_{11}^{(t)} \mu_{12}^{(t)} \ldots \mu_{1M}^{(t)} \\ \mu_{21}^{(t)} \mu_{22}^{(t)} \ddots \mu_{2M}^{(t)} \\ \vdots \quad \vdots \quad \vdots \quad \vdots \\ \mu_{k1}^{(t)} \mu_{k2}^{(t)} \quad \mu_{kM}^{(t)} \end{bmatrix} \tag{3}$$

4) To assess points to nearest centroids. For each point xj in the dataset, it is assigned to a cluster Ci with the nearest centroid μ_i:

$$C_i = \left\{x_j: \left\|x_j - \mu_i\right\|^2 \leq \left\|x_j - \mu_l\right\|^2 \forall l = 1, \dots, k\right\} \quad (4)$$

where $\left\|x_j - \mu_i\right\|$ is the Euclidean distance between the point x_j and the centroid μ_i.
The Euclidean distance between the point $x_j = (x_{j1}, x_{j2}, \dots, x_{jn})$ and the centroid of the $\mu_i = (\mu_{i1}, \mu_{i2}, \dots, \mu_{in})$ is determined from this equation:

$$\left\|x_j - \mu_i\right\| = \sqrt{\sum_{m=1}^{n} \left(x_{jm} - \mu_{im}\right)^2} \quad (5)$$

5) Centroid update. To calculate a new centroid for each cluster C_i.

$$\mu_i = \frac{1}{|C_i|} \sum_{x_j \in C_i} x_j \quad (6)$$

where:
$|C_i|$ is the number of points in cluster C_i,
the sum is run over all points x_j assigned to cluster C_i.

6) Steps 2 and 3 are repeated until the centroids no longer change significantly (change less than a preset threshold ϵ) or the maximum number of iterations T is reached.

The *k*-means method requires a priori specification of the number of clusters. The determination of the optimal number of clusters was carried out using the Elbow Method. This method aims to find the optimal number of clusters by analyzing the Within-Cluster Sum of Squares (WCSS) graph (Shi et al., 2021). The formula for calculating WCSS for a given number of clusters *k* is given by:

$$WSCC = \sum_{i=1}^{k} \sum_{x \in C_i} \left\|x_j - \mu_i\right\|^2 \quad (7)$$

where:
k is the number of clusters;
C_i is the i-th cluster;
x is the data point assigned to cluster C_i;
μ_i is the center of *the i-th* cluster (centroid).

4. Results and discussions

In the first stage of the analysis, the optimal number of clusters was determined to which the EU-27 countries were assigned. Calculations using the WCSS method indicated that the optimal number of clusters was 4 (Figure 1).

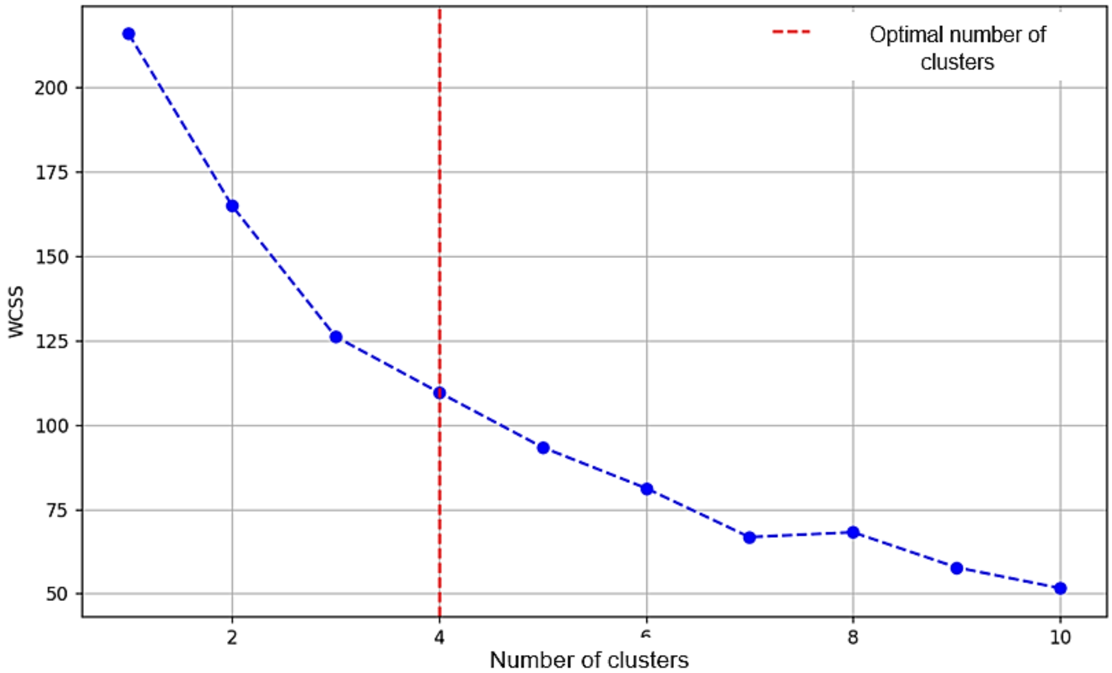

Figure 1. Determination of the optimal cluster count from the WCSS method.

Source: Own elaboration.

Next, the compositions of the clusters of similar countries in terms of energy sustainability for the years 2013 and 2022 were determined. This grouping was based on the 9 indicators of energy sustainability adopted for the study.

The initial analysis focused on clustering EU countries based on data from 2013. In the first step, the cluster compositions for that year were established, as shown in Table 2, along with the distance of each country from the center of its respective cluster.

Table 2.

Cluster compositions of similar countries in energy sustainability in 2013

Cluster 1		Cluster 2		Cluster 3		Cluster 4	
Country	**Distances from Centre of Cluster 1**	**Country**	**Distances from Centre of Cluster 2**	**Country**	**Distances from Centre of Cluster 3**	**Country**	**Distances from Centre of Cluster 4**
Denmark	0.916	Belgium	0.558	Bulgaria	0.869	Luxembourg	0,00
Austria	0.558	Bohemia	0.438	Greece	0.424		
Finland	0.787	Germany	0.424	Spain	0.686		
Sweden	0.730	Estonia	1.159	Croatia	0.582		
		Ireland	1.052	Italy	0.618		
		France	0.455	Cyprus	0.704		
		Netherlands	0.502	Latvia	0.684		
		Poland	0.592	Lithuania	0.453		

Slovenia	0.570	Hungary	0.589
Slovakia	0.497	Malta	0.785
		Portugal	0.601
		Romania	0.747

A *k*-means clustering analysis identified four main clusters of EU countries based on 2013 data. Within each cluster, countries are the most similar in terms of energy sustainability, while being significantly different from countries in other clusters. Countries located closer to the center of a cluster exhibit the greatest similarity to each other. The farther a country is from the center of its cluster, the less similar it is to the countries closer to the center. Assigning such a country to a different cluster would be unwarranted due to insufficient similarity to countries in that cluster.

Cluster 1 includes Denmark, Sweden, Finland, and Austria. These countries are moderately distant from the center of their cluster, indicating similar characteristics in terms of energy sustainability despite some differences. On average, these countries have high per capita energy consumption, ranging from 3.17 to 5.88 tons of oil equivalent (TOE). The total primary energy supply (TPES) per capita ratios also remain at an average level, ranging from 3.11 to 6.08. Dependence on energy imports is relatively low, ranging from 12.31% to 61.26%. High energy productivity, with values ranging from 5.59 to 13.19, is another distinguishing feature of these countries. The share of renewable energy sources in transportation ranges from 6.46% to 10.67%, in electricity from 30.54% to 68.91%, and in heating and cooling from 33.22% to 50.77%. Per capita greenhouse gas emissions are average, ranging from 6.51 to 8.86 tons. The proportion of the population experiencing difficulty maintaining an adequate temperature at home due to energy poverty is low, ranging from 1.2% to 3.8%.

Cluster 2 includes Belgium, Czechia, Germany, Estonia, Ireland, France, Netherlands, Poland, Slovenia, and Slovakia. With the exception of Ireland, these countries are relatively close to the center of the cluster, indicating they share many common characteristics in terms of energy development. They exhibit average to high per capita energy consumption, ranging from 2.27 to 4.36 tons of oil equivalent (TOE). TPES per capita ratios are also average, ranging from 2.35 to 4.96. Dependence on energy imports varies significantly, from 14.52% to 91.55%. Energy productivity ranges from 3.67 to 12.74. The share of renewable energy sources in transportation ranges from 4.90% to 7.30%, in electricity from 9.91% to 25.28%, and in heating and cooling from 4.00% to 43.11%. Per capita greenhouse gas emissions are medium to high, ranging from 5.18 to 14.36 tons. The proportion of the population experiencing difficulty heating their homes due to energy poverty is relatively low, ranging from 2.9% to 10%.

Cluster 3 comprises Bulgaria, Greece, Spain, Croatia, Italy, Cyprus, Latvia, Lithuania, Hungary, Malta, Portugal, and Romania. These countries also share similarities but exhibit greater variability in energy characteristics within the group, with some countries being slightly further from the cluster center. They have low per capita energy consumption, ranging from 1.52 to 2.52 TOE. TPES per capita ratios are low to average, ranging from 1.58 to 2.58. Dependence on energy imports is variable, ranging from 18.32% to 104.14%. Energy productivity ranges from 2.28 to 7.29. The share of renewable energy sources in transportation ranges from 0.95% to 6.67%, in electricity from 1.57% to 49.10%, and in heating and cooling from 13.97% to 37.31%. Per capita greenhouse gas emissions are low to average, ranging from 3.93 to 7.09 tons. The proportion of the population experiencing difficulty heating their homes due to energy poverty is high, ranging from 8% (Spain) to 44.9% (Bulgaria).

Cluster 4 consists solely of Luxembourg. This unique case indicates that Luxembourg's energy characteristics are so distinct that it does not fit into any of the other clusters, showing insufficient similarity to the other EU countries. Luxembourg is characterized by very high per capita energy consumption, at 7.91 TOE, and a very high TPES per capita value of 7.385. Dependence on energy imports is also very high, at 97.1%. Energy productivity is notably high, at 10.35 euros per kilogram of oil equivalent. The share of renewable energy sources in transportation is only 4.07%, in electricity is 5.33%, and in heating and cooling is 5.33%. As a result, per capita greenhouse gas emissions are very high, at 18.5 tons. Conversely, the proportion of the population experiencing difficulty maintaining an adequate temperature at home due to energy poverty is very low, at 1.6%.

Table 3 presents the basic descriptive statistics for each cluster created.

Table 3.
Basic descriptive statistics of the formed clusters for 2013 data

Cluster	Variable	Mean	Min	Max	Variance	Median
Cluster 1 (4 objects)	Primary energy consumption per capita, TOE	4.418	3.17	5.88	1.157	4.31
	TPES per capita, TOE	4.572	3.11	6.08	1.597	4.55
	Energy import dependency, %	38.49	12.31	61.26	355.46	46.46
	Energy productivity, euro per kilogram of oil equivalent	8.48	5.59	13.19	10.52	8.27
	Share of renewable energy consumption in transport, %	8.964	6.456	15.315	15.74	8.081
	Share of renewable energy consumption in electricity, %	51.818	30.543	68.909	212.13	52.411
	Share of renewable energy consumption in heating and cooling, %	45.58	33.222	61.708	139.48	41.199
	Greenhouse gas emissions from energy sector per capita, t CO_2 eq.	6.719	4.15	8.86	3.74	6.93
	Population unable to keep home adequately warm by poverty status, %	2.15	0.9	3.8	1.64	2.35

Cont. table 3.

Cluster 2 (10 objects)	Primary energy consumption per capita, TOE	3.48	2.46	4.34	0.34	3.81
	TPES per capita, TOE	3.65	2.57	4.51	0.45	3.98
	Energy import dependency, %	44.43	14.52	91.55	521.96	47.46
	Energy productivity, euro per kilogram of oil equivalent	6.10	2.63	12.74	8.73	5.16
	Share of renewable energy consumption in transport, %	5.41	0.45	7.60	4.36	6.21
	Share of renewable energy consumption in electricity, %	18.16	9.91	33.08	52.19	16.98
	Share of renewable energy consumption in heating and cooling, %	17.59	4.00	43.11	157.78	14.27
	Greenhouse gas emissions from energy sector per capita, t CO_2 eq.	8.63	5.18	14.36	6.70	8.70
	Population unable to keep home adequately warm by poverty status, %	6.18	2.90	11.40	7.40	5.40
Cluster 3 (12 objects)	Primary energy consumption per capita, TOE,	2.14	1.52	2.53	0.09	2.14
	TPES per capita, TOE	2.16	1.58	2.58	0.08	2.15
	Energy import dependency, %	66.30	18.32	104.14	511.38	70.00
	Energy productivity, euro per kilogram of oil equivalent	5.93	3.64	9.62	3.48	5.22
	Share of renewable energy consumption in transport, %	3.29	0.93	6.34	3.89	3.48
	Share of renewable energy consumption in electricity, %	26.72	1.57	49.10	281.59	31.30
	Share of renewable energy consumption in heating and cooling, %	27.80	13.97	49.65	107.58	26.20
	Greenhouse gas emissions from energy sector per capita, t CO_2 eq.	5.00	3.59	7.09	1.38	4.28
	Population unable to keep home adequately warm by poverty status, %	20.74	8.00	30.50	60.25	21.10
Cluster 4 (1 object)	Primary energy consumption per capita, TOE,	7.91	N/A	N/A	N/A	N/A
	TPES per capita, TOE	7.39	N/A	N/A	N/A	N/A
	Energy import dependency, %	97.10	N/A	N/A	N/A	N/A
	Energy productivity, euro per kilogram of oil equivalent	10.35	N/A	N/A	N/A	N/A
	Share of renewable energy consumption in transport, %	4.07	N/A	N/A	N/A	N/A
	Share of renewable energy consumption in electricity, %	5.329	N/A	N/A	N/A	N/A
	Share of renewable energy consumption in heating and cooling, %	5.33	N/A	N/A	N/A	N/A
	Greenhouse gas emissions from energy sector per capita, t CO_2 eq.	18.46	N/A	N/A	N/A	N/A
	Population unable to keep home adequately warm by poverty status, %	1.6	N/A	N/A	N/A	N/A

Cluster 1 is characterized by a high share of renewable energy sources, high energy productivity, and low dependence on energy imports. Cluster 2 includes countries with medium energy productivity, varying shares of renewable energy sources, and medium greenhouse gas emissions. Cluster 3 consists of countries with low energy productivity, variable shares of renewable energy sources, and a high proportion of the population having difficulty heating their homes. Cluster 4 (Luxembourg) is distinguished by very high energy consumption, high dependence on energy imports, and very high greenhouse gas emissions.

These findings are supported by the analysis of variance (ANOVA) presented in Table 4. The results indicate that many of the variables studied, such as primary energy consumption per capita, TPES per capita, the share of renewable energy in various sectors, and the proportion of the population unable to maintain adequate home temperatures, exhibit statistically significant differences between clusters. This confirms that the groups formed in the cluster analysis are distinct in terms of these indicators. Conversely, variables such as dependence on energy imports and energy productivity do not show significant differences between groups, suggesting relative homogeneity in these aspects among the clusters.

Table 4.
Analysis of variance (ANOVA) for variable

Variable	Between SS	df	Inside SS	df	F	Significance *p*
Primary energy consumption per capita, TOE	21.466	3	4.534	23	36.298	0.000
TPES per capita, TOE	20.210	3	5.790	23	26.762	0.000
Energy import dependency, %	6.291	3	19.709	23	2.447	0.089
Energy productivity, euro per kilogram of oil equivalent	5.916	3	20.084	23	2.258	0.109
Share of renewable energy consumption in transport, %	13.979	3	12.021	23	8.916	0.000
Share of renewable energy consumption in electricity, %	11.536	3	14.464	23	6.115	0.003
Share of renewable energy consumption in heating and cooling, %	12.044	3	13.956	23	6.616	0.002
Greenhouse gas emissions from energy sector per capita, t CO_2 eq.	18.091	3	7.909	23	17.536	0.000
Population unable to keep home adequately warm by poverty status, %	16.513	3	9.487	23	13.344	0.000

The next stage of the analysis involved grouping EU countries by similarity in terms of their energy sustainability in 2022. The determined cluster compositions are shown in Table 5, and in Table 6 the basic descriptive statistics for each cluster formed.

Table 5.
Cluster compositions of similar countries for sustainable energy development in 2022

Cluster 1		Cluster 2		Cluster 3		Cluster 4	
Country	**Distances from Centre of Cluster 1**	**Country**	**Distances from Centre of Cluster 2**	**Country**	**Distances from Centre of Cluster 3**	**Country**	**Distances from Centre of Cluster 4**
Denmark	0.869	Bulgaria	0.877	Bohemia	0.615	Belgium	0.495
Finland	0.647	Greece	0.504	Estonia	0.875	Germany	0.346
Sweden	0.783	Spain	0.534	Poland	1.172	Ireland	1.037
		France	0.500			Luxembourg	1.175
		Croatia	0.587			Netherlands	0.414
		Italy	0.560			Austria	0.775
		Cyprus	0.758				
		Latvia	0.868				
		Lithuania	0.516				
		Hungary	0.593				
		Malta	0.791				
		Portugal	0.635				
		Romania	0.809				
		Slovenia	0.610				
		Slovakia	0.476				

Denmark, Finland, and Sweden are located in Cluster 1. The distances from the center of the cluster for these countries are 0.869, 0.647, and 0.783, respectively, indicating moderate differences between them. These distance values suggest that the countries in this cluster are fairly homogeneous, though some variation exists. Compared to 2013, the composition of Cluster 1 has changed, as Austria is no longer included. The countries in Cluster 1 are characterized by high per capita energy consumption, typical of nations with high living standards and developed economies. TPES per capita is also high, reflecting intensive energy consumption. Dependence on energy imports varies, indicating different strategies for managing energy resources. These countries have high energy productivity, signifying efficient energy use in the economy. A significant share of renewable energy sources, especially in electricity and heating, underscores a strong commitment to sustainable development. Low per capita greenhouse gas emissions reflect effective emission reduction policies (see Table 6).

Cluster 2 includes 15 countries, with distances from the center of the cluster ranging from 0.476 for Slovakia to 0.877 for Bulgaria. This indicates that the countries in this cluster have a moderate level of cohesion, with some differences. Countries in Cluster 2 have lower per capita energy consumption and TPES per capita compared to those in Cluster 1. Dependence on energy imports is medium, reflecting moderate risk from external energy suppliers. Energy productivity is lower than in Cluster 1, suggesting less efficient energy use. The share of renewable energy sources is variable but generally lower than in Cluster 1. Per capita greenhouse gas emissions are higher than in Cluster 1, indicating greater challenges in emission reduction (see Table 6).

Cluster 3 consists of Czechia, Estonia, and Poland. The analysis of distances from the cluster center reveals significant internal variation among these countries, as they are all notably far from the center. This indicates substantial differences in their energy characteristics. These countries exhibit average per capita energy consumption and TPES per capita. Dependence on energy imports is low, suggesting greater energy autonomy. Energy productivity is at an average level, and the share of renewable energy sources varies. Per capita greenhouse gas emissions are relatively high, reflecting a reliance on more carbon-intensive energy sources, such as coal, particularly in Poland (see Table 6).

Cluster 4 includes Belgium, Germany, Netherlands, Ireland, Luxembourg, and Austria. Belgium, the Netherlands, and Germany have the shortest distances from the cluster center, indicating they are very homogeneous and central to this cluster. In contrast, Luxembourg, Ireland, and Austria are farther from the center, highlighting differences compared to the more central countries. The countries in Cluster 4 have high per capita energy consumption and TPES per capita, similar to Cluster 1. They also have high dependence on energy imports, making them vulnerable to external energy suppliers. Energy productivity is high, reflecting efficient energy use. The share of renewable energy sources is moderate, and per capita greenhouse gas emissions are high, due to a significant reliance on emitting fuels in the energy mix, especially in Germany, Ireland, and Luxembourg. This suggests challenges in reducing emissions and transitioning to more sustainable energy sources (see Table 6).

Table 7.
Basic descriptive statistics characterizing the created clusters for 2022 data

Cluster	Variable	Mean	Min	Max	Variance	Median
Cluster 1 (3 objects)	Primary energy consumption per capita, TOE	4.75	3.17	6.09	2.65	4.98
	TPES per capita, TOE	2.69	0.87	4.36	2.60	2.84
	Energy import dependency, %	36.85	26.82	42.87	125.45	40.88
	Energy productivity, euro per kilogram of oil equivalent	11.41	6.36	17.75	22.21	10.11
	Share of renewable energy consumption in transport, %	19.74	10.24	29.16	91.56	18.83
	Share of renewable energy consumption in electricity, %	69.15	47.93	83.34	280.24	69.15
	Share of renewable energy consumption in heating and cooling, %	59.02	50.11	69.39	108.46	58.55
	Greenhouse gas emissions from energy sector per capita, t CO_2 eq.	4.51	2.95	5.92	2.29	4.67
	Population unable to keep home adequately warm by poverty status, %	3.26	1.40	5.10	2.13	3.30

Cont. table 2.

Cluster 2 (15 objects)	Primary energy consumption per capita, TOE	2.68	1.66	3.81	0.33	2.63
	TPES per capita, TOE	9.32	0.09	60.606	659.2	2.188
	Energy import dependency, %	58.08	32.412	99.009	1010.04	58.4
	Energy productivity, euro per kilogram of oil equivalent	7.69	2.53	26.77	58.43	6.76
	Share of renewable energy consumption in transport, %	9.19	2.395	29.158	72.86	8.54
	Share of renewable energy consumption in electricity, %	38.14	15.936	83.34	519.53	37.005
	Share of renewable energy consumption in heating and cooling, %	39.93	15.411	69.393	463.55	37.005
	Greenhouse gas emissions from energy sector per capita, t CO_2 eq.	4.55	3.422	8.837	3.55	4.368
	Population unable to keep home adequately warm by poverty status, %	10.87	2.6	22.5	54.85	7
Cluster 3 (3 objects)	Primary energy consumption per capita, TOE	3.25	2.44	4.98	2.09	3.02
	TPES per capita, TOE	2.7	0.413	160.645	4358.62	2.24
	Energy import dependency, %	48.6	6.159	160.645	4689.36	46.029
	Energy productivity, euro per kilogram of oil equivalent	10.38	4.19	26.77	55.23	5.29
	Share of renewable energy consumption in transport, %	7.5	5.793	10.467	1.25	7.197
	Share of renewable energy consumption in electricity, %	37.58	15.499	65.442	118.94	37.58
	Share of renewable energy consumption in heating and cooling, %	24.53	15.936	60.959	274.25	25.802
	Greenhouse gas emissions from energy sector per capita, t CO_2 eq.	7.02	4.497	8.656	3.65	8.358
	Population unable to keep home adequately warm by poverty status, %	4.73	2.9	8.8	6.73	4.9
Cluster 4 (6 objects)	Primary energy consumption per capita, TOE	3.59	2.44	8.32	5.41	3.74
	TPES per capita, TOE	10.07	0.823	34.108	114.83	6.35
	Energy import dependency, %	60.45	40.884	92.018	169.98	51.917
	Energy productivity, euro per kilogram of oil equivalent	10.16	7.22	26.77	41.67	10.28
	Share of renewable energy consumption in transport, %	8.91	5.512	10.811	7.04	10.241
	Share of renewable energy consumption in electricity, %	41.19	15.936	77.22	257.95	47.637
	Share of renewable energy consumption in heating and cooling, %	35.76	15.411	77.22	272.69	30.579
	Greenhouse gas emissions from energy sector per capita, t CO_2 eq.	6.11	4.066	10.702	6.55	6.575
	Population unable to keep home adequately warm by poverty status, %	4.54	2.1	6.8	5.29	5.3

In the next stage of the study, an analysis of variance was conducted for individual variables to identify whether there are statistically significant differences between groups of countries (clusters) in terms of energy sustainability in 2022 (Table 7).

Table 7.
Analysis of variance (ANOVA) for variable

Variable	Between SS	df	Inside SS	df	F	Significance *p*
Primary energy consumption per capita, TOE	11.988	3	14.012	23	6.560	0.002
TPES per capita, TOE	5.680	3	20.320	23	2.143	0.122
Energy import dependency, %	12.605	3	13.395	23	7.215	0.001
Energy productivity, euro per kilogram of oil equivalent	9.851	3	16.149	23	4.676	0.011
Share of renewable energy consumption in transport, %	14.667	3	11.333	23	9.923	0.000
Share of renewable energy consumption in electricity, %	9.913	3	16.087	23	4.724	0.010
Share of renewable energy consumption in heating and cooling, %	13.479	3	12.521	23	8.253	0.001
Greenhouse gas emissions from energy sector per capita, t CO_2 eq.	15.501	3	10.499	23	11.320	0.000
Population unable to keep home adequately warm by poverty status, %	11.247	3	14.753	23	5.844	0.004

The variable "Primary energy consumption per capita" had an *F-value* of 36.298 and a *p-value* less than 0.000, indicating that the differences between clusters are statistically significant. Similarly, "TPES per capita" had an *F-value* of 26.762 and a *p-value* of 0.000, also showing significant differences between clusters. The variable "Energy import dependency, %" had an *F-value* of 2.447 and a *p-value* of 0.089, suggesting that differences between clusters for this variable are not statistically significant at the 0.05 level. "Energy productivity" had an *F-value* of 2.258 and a *p-value* of 0.109, also indicating no significant differences between clusters.

An *F-value* of 8.916 and a *p-value* of 0.000 were obtained for "Share of renewable energy consumption in transportation," indicating significant differences between clusters. Significant differences were also found for "Share of renewable energy consumption in electricity" and "Share of renewable energy consumption in heating and cooling." The variable "Greenhouse gas emissions from the energy sector per capita, tons" had an *F-value* of 17.536 and a *p-value* less than 0.000, indicating significant differences between clusters. Lastly, "Population unable to keep home adequately warm by poverty status" had an *F-value* of 13.344 and a *p-value* less than 0.000, suggesting significant differences between clusters.

In summary, most variables showed significant differences between clusters, highlighting diversity in energy sustainability among the analyzed countries. Only "Energy import dependency" and "Energy productivity" did not show statistically significant differences between clusters.

A comparison of the 2013 and 2022 analyses reveals changes in the distribution of countries across different clusters. While Cluster 1 remained relatively stable in terms of its main characteristics, other clusters experienced shifts in composition. These changes reflect the evolving implementation of EU energy policies and progress towards SDG Goal 7. The results underscore the importance of continuous monitoring of trends in energy consumption, energy efficiency, the share of renewable energy sources, and greenhouse gas emissions. The dynamic nature of cluster compositions highlights the need for ongoing evaluation of energy strategies at both national and EU levels. Countries should prioritize enhancing energy efficiency, increasing the share of renewables, and reducing greenhouse gas emissions to achieve sustainability and climate change goals. This is particularly crucial for countries that still rely heavily on traditional energy sources, including those in Central and Eastern Europe (CEE). These nations should focus on expanding the use of RES, such as wind, solar, and biomass, and improving energy efficiency. Such measures will facilitate more effective resource use and help reduce dependence on conventional energy sources, which are associated with high greenhouse gas emissions.

5. Conclusions

This paper presents a comparative study of the energy sustainability of EU countries for the years 2013 and 2022, utilizing nine key indicators aligned with the European Union's energy policy and SDG Goal 7 of the 2030 Agenda. The analysis was conducted using the k-means clustering method, which identified four distinct clusters of countries based on their energy sustainability characteristics.

Based on the research conducted for 2013, the following conclusions were made:

- Countries in Cluster 1, i.e., Denmark, Sweden, Austria, and Finland, stood out for their high energy productivity, low dependence on energy imports, and high share of renewable energy sources. These countries have, on average, high energy consumption and greenhouse gas emissions, and the population with heating difficulties is low.
- Countries in Cluster 2, i.e., Belgium, Czechia, Germany, among others, were characterized by average energy consumption and varying shares of renewable energy sources. Energy productivity and greenhouse gas emissions varied.
- Countries in Cluster 3, such as Bulgaria, Greece, and Spain, had low energy consumption, variable import dependence, and low energy productivity. Greenhouse gas emissions are low to average, and heating problems are significant.
- Luxembourg, forming a stand-alone Cluster 4, is unique because of its very high energy consumption, high dependence on imports, and very high greenhouse gas emissions relative to other EU countries.

In turn, the main conclusions of the analysis for 2022 are as follows:

- Cluster 1 is made up of Denmark, Finland, and Sweden, characterized by consistently high energy consumption per capita and TPES per capita, low dependence on energy imports, and high energy productivity. A high share of renewable energy sources results in low greenhouse gas emissions from the energy sector.
- In Cluster 2 (15 countries), moderate consistency is noted with differences in energy consumption and TPES per capita. These countries have lower values for energy consumption and energy productivity than in Cluster 1. The share of renewable energy sources is lower, and GHG emissions are higher, indicating greater challenges in reducing emissions. Dependence on energy imports is medium, indicating a moderate risk to these countries' energy security.
- Cluster 3 included Poland, Czechia, and Estonia, countries of considerable diversity, with marked differences in energy consumption and TPES per capita. These countries have low dependence on energy imports, which means greater energy autonomy. Energy productivity is average, and the share of renewable energy sources varies. High per capita GHG emissions indicate a high share of coal (Poland, Czechia) and other emitting energy sources (Estonia - shale).
- Belgium, Germany, Ireland, Luxembourg, Netherlands, and Austria, which make up Cluster 4, are characterized by high per capita energy consumption and TPES, as are the countries in Cluster 1 (Denmark, Sweden, and Finland). These countries have high dependence on energy imports and high energy productivity. The share of renewables is moderate, but per capita GHG emissions are high, especially in Germany and Ireland, indicating major challenges in transitioning to more sustainable energy sources.

In terms of specific clusters, countries in Cluster 1 should continue their approach to sustainability, investing in renewable energy sources and efficiency-enhancing technologies. Countries in clusters 2 and 3, on the other hand, should focus on increasing energy efficiency and reducing greenhouse gas emissions by developing infrastructure for renewable energy sources. These countries' policies should be tailored to local needs and conditions. Countries in Cluster 4 should consider preparing a new strategy to reduce emissions and transition to more sustainable energy sources, given their high energy consumption and high emissions.

In these activities, cooperation with other EU countries in technological innovation and exchange of best practices is particularly advisable. In general, it can be concluded that European solidarity and cooperation between countries should be the way to achieve the adopted goals. The results also show that the EU-27 countries have different approaches to energy policy and sustainable development. It is therefore advisable to make greater use of the results presented and included in other research works in the process.

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