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Primary Energy Consumption Patterns in Selected European Countries from 1990 to 2021: A Cluster Analysis Approach

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Abstract: This study delves into the structure of primary energy consumption in European countries, utilizing data from the Eurostat database, and focuses on the years 1990 and 2021. Through cluster analysis, countries were categorized based on their consumption patterns, revealing significant insights into energy security. The findings indicate a discernible shift away from solid fossil fuels, with renewable energy sources witnessing the most substantial growth. Natural gas, serving as a transitional fuel, has seen a rise in consumption, while nuclear energy's development remained relatively stagnant. Oil, despite its declining share, remains a crucial component in the European energy mix. The study also highlights the challenges and implications of over-reliance on a single energy source, emphasizing the need for a diversified energy strategy. The analysis underscores the importance of diversifying primary energy sources to ensure energy security. While renewable sources are environmentally favorable, their inherent instability necessitates backup from other energy sources. Solid fossil fuels, despite their availability, face challenges due to environmental concerns. Natural gas, while flexible, requires extensive infrastructure and is highly politicized. Nuclear energy, despite its potential as an ideal complement to renewables, faces barriers in terms of investment and public perception. Oil, though convenient, is a fossil source with associated CO_2 emissions and largely needs to be imported. In conclusion, the study advocates for a well-diversified set of energy sources tailored to individual country-specific situations, emphasizing the importance of strategic planning in energy consumption to ensure long-term energy security.

Keywords: Europe; energy security; primary energy; energy policy; energy; cluster analysis; renewables; natural gas; nuclear energy

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1. Introduction

This Introduction section is designed to provide the reader with a background on energy security, followed by a description of primary energy sources, and finally, the specific focus and contributions of this paper.

1.1. Historical Development of Energy Security

Energy is a key factor that determines many areas of socio-economic life [1]. Its role in the functioning of the economy, economic development [2], social welfare, and consumption processes is undeniable [3]. The availability of sufficient energy resources underpins the economic and political strength of a state [4], making energy a pivotal element in both national and international security [5]. The modern world is profoundly influenced by energy dynamics [6].

The concept of energy security has evolved over time, with several distinct periods identifiable:

1. The non-politicized stage;

2. The politicized stage;
3. The securitized stage [4].

The 1970s "oil shocks" and subsequent energy crises marked the onset of energy politicization [7]. This era saw a burgeoning awareness of the strategic importance of energy resources, transcending mere economic considerations.

Initially, in the 1970s, energy security was narrowly defined, typically emphasizing the aspiration for high energy self-sufficiency [8]. This nationalist approach prioritized efficient energy project management [9] and the utilization of advanced energy technologies [10]. However, as the turn of the century approached, the definition expanded. Influences included enhanced international cooperation between energy importers and exporters, a focus on equitable energy access across societal strata, and the rising prominence of environmental considerations in energy production [11].

Given its multifaceted nature, defining energy security is intricate, necessitating a holistic approach encompassing economics, geology, ecology, and geopolitics. Its essence and significance are context-dependent [12]. As Skinner posits, the understanding of energy security is contingent upon temporal and spatial contexts, with the prevailing energy market conditions being paramount [13].

1.2. Modern Definitions and Components

Today, energy security is commonly defined as ensuring sufficient supplies at affordable prices [14]. Klare, for instance, views it as a guarantee of energy resource availability to meet a state's fundamental needs, even amidst crises or international conflicts [15]. The Asia Pacific Energy Research Centre offers a similar perspective, emphasizing timely and sustainable energy supply at prices that will not hamper economic performance [16].

Contemporary definitions often encompass four key elements, known as the four As approach:

- Availability: Ensuring physical access to energy.
- Accessibility: Overcoming geographical, political, demographic, and technological barriers to obtain energy resources.
- Affordability: Ensuring cost-effective energy sources.
- Acceptability: Prioritizing environmentally and societally acceptable energy sources [11].

Of these, accessibility and affordability are deemed paramount due to their overarching influence on other facets of energy security [17].

1.3. Threats and Challenges

The literature identifies three primary threats to energy security:

- Technical challenges, such as infrastructure failures.
- Social behaviors, including volatile energy demand or politically motivated supply suspensions.
- Natural threats, like the depletion of fossil fuel reserves [18].

While energy security is often equated with supply security, organizations like the International Energy Agency (IEA) define it as the "uninterrupted availability of energy sources at an affordable price" [19]. The European Commission shares a similar sentiment, emphasizing the importance of diversifying energy sources to mitigate dependency risks [20]. For many global governments, ensuring stable energy supplies is a top-tier priority [21,22].

The multifaceted nature of energy security, coupled with its evolving definitions and the myriad threats it faces, underscores its significance in contemporary geopolitics and economics. As the world grapples with the challenges of sustainable energy, understanding and ensuring energy security becomes paramount.

1.4. Primary Energy Consumption and Energy Security

Primary energy sources refer to natural energy sources that have not yet been transformed into other forms of energy. Among the most important primary energy sources are coal, crude oil, natural gas, nuclear energy, and renewable energy sources such as wind, solar, and geothermal energy [23].

The structure of primary energy consumption can influence energy security in various ways. Notably

- The diversification of sources: A country primarily reliant on a single energy source is more susceptible to supply disruptions than a country utilizing a diverse range of energy sources [24].
- Dependency on imports: A high level of energy imports, especially from a single country or region, can increase the risk of supply disruptions due to political or economic factors. Dependence on hydrocarbon imports, such as crude oil and natural gas, can pose a significant risk to a country's energy security. High levels of import of these resources lead to several key issues, including the following [25–28]:
  - Sensitivity to price fluctuations: Hydrocarbon prices are often unstable and can undergo rapid changes in response to geopolitical factors, natural disasters, or decisions by the OPEC cartel. Countries heavily dependent on imports are more exposed to these fluctuations, which can lead to rising energy prices for consumers.
  - Risk of supply disruptions: Political conflicts, economic sanctions, or even trade decisions can lead to disruptions in hydrocarbon supplies, which, in turn, can affect the stability of energy supplies.
  - Geopolitical dependency: Dependence on hydrocarbon imports can lead to geopolitical dependency on exporting countries, which can influence the political and diplomatic decisions of the importing country.
- Investments in renewable energy sources: Long-term investments in renewable energy sources can enhance energy security by diversifying sources and reducing dependency on unstable commodity markets. This trend is driven by both environmental and economic considerations [29,30]:
  - Reduction in CO_2 emissions: Fossil fuels are the primary source of carbon dioxide emissions, which contribute to global warming. Transitioning to renewable energy sources can aid in reducing these emissions.
  - Production costs: The costs of producing energy from renewable sources, such as solar or wind energy, are continually decreasing, making them increasingly competitive compared to traditional fossil fuels.
- The challenges of renewable energy sources: However, renewable energy sources, such as solar or wind energy, also present certain challenges, such as the following [31–33]:
  - Stability and predictability of supplies: Renewable energy sources, like solar or wind energy, are inherently unstable. Their production depends on weather conditions, which can lead to irregular energy supplies.
  - Need for energy storage: To compensate for the instability of renewable energy sources, there is a need to develop energy storage technologies, which come with additional costs and pose a technological challenge.
- The trend of moving away from fossil fuels: The modern world observes a global trend of moving away from fossil fuels, such as coal, in favor of more sustainable and ecological energy sources. This trend is driven both by environmental and economic considerations. Fossil fuels are the main source of carbon dioxide emissions, which contribute to global warming. Transitioning to renewable energy sources can help in reducing these emissions.

- The diverse approaches and attitudes towards nuclear energy: Nuclear energy, as a primary energy source, has always been a subject of intense debate and varying perceptions across countries. Its utilization and integration into the energy mix are influenced by myriad factors [34,35]:
  - Safety concerns: Historical events, such as the Chernobyl and Fukushima disasters, have heightened safety concerns surrounding nuclear energy. These incidents have led to rigorous safety standards and protocols, but they have also fostered skepticism and apprehension in certain regions.
  - Economic implications: The initial investment required for nuclear power plants is substantial. However, once operational, they can offer a stable and often cost-effective source of energy. The economic viability of nuclear energy is often weighed against its long-term benefits and the costs associated with waste management and plant decommissioning.
  - Environmental impact: While nuclear energy produces minimal greenhouse gas emissions, the challenge of radioactive waste management remains. Solutions such as deep geological repositories are being explored, but the long-term environmental implications are a significant consideration.
  - Geopolitical considerations: The need for uranium as a fuel, and the potential for nuclear weapon proliferation, make nuclear energy a geopolitical concern. Countries with abundant uranium reserves wield a certain level of influence, and international treaties, such as the Nuclear Non-Proliferation Treaty, aim to ensure peaceful nuclear energy use.
  - Public perception and acceptance: The public's perception of nuclear energy varies widely. While some view it as a clean alternative to fossil fuels, others are wary of its potential risks. Public opinion can significantly influence governmental policies and decisions related to nuclear energy development.
  - Small Modular Reactors (SMRs): A recent innovation in the realm of nuclear energy is the development and promotion of Small Modular Reactors (SMRs). These reactors offer a different approach compared to traditional large-scale nuclear reactors. SMRs represent a promising avenue for the future of nuclear energy, offering a blend of flexibility, safety, and economic viability. As countries grapple with the challenges of energy security, carbon reduction, and economic growth, SMRs may play a pivotal role in shaping the nuclear landscape [36–38].

  Incorporating nuclear energy into a country's energy strategy requires a holistic assessment of its benefits and challenges. While it offers a solution to reduce carbon emissions and provides a stable energy supply, the complexities associated with safety, waste management, and geopolitics cannot be overlooked. As the global community strives for a sustainable energy future, the role of nuclear energy remains a nuanced and evolving discussion.

The structure of primary energy source consumption plays a pivotal role in shaping a country's energy security. To ensure stable energy supplies, it is essential to diversify sources, invest in renewable technologies, and strategically plan energy imports. Contemporary research indicates the need for a thoughtful energy policy that considers economic, ecological, and social aspects. To meet these challenges, countries must develop a balanced and diversified energy strategy that encompasses both traditional and renewable energy sources.

1.5. Objectives and Contributions of This Study

The primary objective of this study is to conduct a cluster analysis of primary energy consumption patterns in selected European countries, utilizing data from the Eurostat database for the years 1990 and 2021 (specifically table "nrg_bal_s") [39]. This research aims to categorize these countries into distinct groups based on their energy consumption characteristics, thereby providing valuable insights into their energy security landscape. The contributions of this paper are twofold: first, it offers a nuanced understanding of the evolving energy consumption patterns in Europe, highlighting the shift from fossil fuels to more sustainable energy sources. Second, it identifies the implications of these consumption patterns for energy security, considering economic, ecological, and geopolitical factors. The novelty of this study lies in its application of cluster analysis to Eurostat data, allowing for a comprehensive and up-to-date assessment of energy consumption trends and their implications for energy security.

The analysis was conducted using the R programming language [40] and RStudio IDE [41], supplemented with the tidyverse libraries [42].

The structure of the article is as follows: the introduction delineates the concept of energy security and its relationship with primary energy consumption. The subsequent section provides the theoretical foundations of cluster analysis. Following this, the authors describe the primary energy consumption in selected European countries from 1990 to 2021. The results of the cluster analysis for the structure of primary energy consumption in individual countries in 1990 and 2021 are then presented. The paper concludes with a summary and implications.

2. Cluster Analysis

Cluster analysis is a powerful statistical technique that enjoys enduring popularity in many fields. This technique is used to group similar objects based on their characteristics and to identify patterns or structures in data that may not be obvious at first glance. Cluster analysis finds applications in many real-world problems.

The following are examples of cluster analysis applications:

- In marketing, cluster analysis is often used to identify groups of customers based on their purchasing or demographic behaviors. By clustering customers based on their similarities in purchase history, preferences, and other factors, firms can create more targeted marketing campaigns and tailor products and services to specific customer groups.
- In biology, cluster analysis can be used to group genes with similar expression patterns. This can help researchers identify genes that are involved in a specific biological process or disease and develop new methods of treatment or therapy.
- In computer science, cluster analysis can be used to identify groups of similar documents or web pages. This can be useful in information retrieval when the fast and accurate retrieval of relevant information is important.
- In the energy sector, for example, it can be used to cluster households with similar energy consumption patterns, which can help energy companies develop more targeted energy efficiency programs and demand response initiatives. It can also be used to cluster wind turbines with similar wind speeds and other environmental conditions, which can help optimize energy production and reduce costs. This method can also find its application in solving many other business problems in the energy sector.

The literature provides a lot of information on different types of clustering algorithms and their applications, as well as their strengths and weaknesses. MacQueen (1967) introduced the k-means clustering algorithm, which is still widely used. This algorithm assigns data points to clusters by minimizing the sum of squared distances between data points and the assigned cluster centroid [43]. Jain and Dubes (1988) wrote a comprehensive book on clustering algorithms that covers the most commonly used methods of cluster analysis, their strengths and weaknesses, and how to apply them to real-world problems [44]. Kaufman and Rousseeuw (1990) also wrote a book on the subject, which provides a thorough introduction to cluster analysis and its applications [45].

Xu and Wunsch (2005) conducted a survey of clustering algorithms, which provides an overview of different types of clustering algorithms and their applications [46]. Mirkin (2005) wrote a book on clustering for data mining, which presents an approach to data recovery for clustering and provides a comprehensive analysis of different types of clustering algorithms [47]. Everitt et al. (2001) wrote a book on cluster analysis, which covers different types of clustering algorithms and their applications, as well as the interpretation of results [48].

Hennig (2015) proposed a new criterion for evaluating the quality of clustering results, which is based on the concept of true clusters. This criterion provides a more accurate assessment of the quality of clustering results and helps identify true clusters in the data [49].

There are several different types of cluster analysis, each with its own strengths and weaknesses:

- Hierarchical clustering is a popular method of grouping similar data points into clusters based on a similarity measure. It can be performed using either a "bottom-up" or "top-down" approach. In the "bottom-up" approach, each data point is initially treated as a separate cluster, and then clusters are successively merged based on their similarity. In the "top-down" approach, all data points initially belong to one cluster, which is then successively divided into smaller clusters based on their differences.
- K-means clustering is another popular method of assigning data points to clusters by minimizing the sum of squared distances between data points and the assigned cluster centroid. The number of clusters is usually predetermined by the user, and the algorithm iteratively assigns data points to the nearest cluster centroid until convergence is achieved. K-means clustering is a fast and efficient method that can be used for large datasets.
- Density-based clustering is another type of clustering that identifies clusters based on areas of high density in the data. The most well-known density-based clustering algorithm is DBSCAN (Density-Based Spatial Clustering of Applications with Noise), which clusters data points that are within a certain distance of each other and have a minimum number of neighboring points. DBSCAN is particularly useful for datasets with a lot of noise or when clusters have irregular shapes.

The choice of method in cluster analysis depends on the specific needs of the analysis and the characteristics of the data. It is important to carefully consider the data and analysis goals in order to choose the most appropriate clustering method. Researchers and practitioners in different fields can benefit from applying cluster analysis to real-world problems, but it is important to note that cluster analysis is not a panacea and requires the careful consideration of data and appropriate use of statistical methods.

2.1. K-Means

In this paper the k-means approach was used. K-means clustering is a popular unsupervised machine learning algorithm used for partitioning data points into distinct groups or clusters. It is an iterative algorithm that aims to minimize the variance within clusters by finding the optimal centroids for each cluster [50–52].

2.1.1. Steps of the K-Means Clustering Algorithm

- Initialization: First, the number of clusters, k, needs to be specified. Randomly initialize k centroids, either by selecting k data points from the dataset or by using a different initialization strategy such as k-means.
- Assignment: Assign each data point to the nearest centroid based on a distance metric, commonly Euclidean distance. This step forms k clusters.
- Update: Recalculate the centroids of the clusters by computing the mean of all the data points assigned to each cluster.
- Convergence: Repeat steps 2 and 3 until convergence is achieved, i.e., when the centroids no longer change significantly or a maximum number of iterations is reached.
- Final result: After convergence, the algorithm assigns each data point to the cluster represented by the nearest centroid. The result is a partitioning of the dataset into k clusters.

2.1.2. Advantages

- Simplicity: K-means is a straightforward and easy-to-understand algorithm with a clear objective.
- Scalability: It can handle large datasets with a linear time complexity, making it suitable for clustering big data.
- Efficiency: The algorithm converges relatively fast due to its simplicity.
- Interpretability: The resulting clusters can often be interpreted meaningfully, especially in low-dimensional spaces.
- Versatility: K-means can be applied to various types of data, such as numerical, categorical, or binary.

2.1.3. Limitations

- Dependency on Initial Centroids: The algorithm's performance heavily depends on the initial placement of centroids, which can lead to different results for different initializations.
- Sensitivity to Outliers: K-means is sensitive to outliers, as they can significantly affect the position and size of clusters.
- Cluster Shape Assumptions: The algorithm assumes that the clusters are convex and have similar sizes, which can be limiting in some scenarios.
- Determining the Optimal Number of Clusters: Deciding the appropriate value of k is often subjective and can impact the clustering quality.
- Influence of Feature Scaling: If features have different scales, the algorithm may be biased towards features with larger values.

2.1.4. Optimal Number Od Clusters

One of the biggest problems in the k-means method is determining the optimal number of clusters. Two approaches were used in the article:

- Total within-cluster sum of square (WSS) minimization;
- Average silhouette method.

Total within-cluster sum of square minimization (the "elbow method") is a popular technique for estimating the optimal number of clusters in a dataset when using clustering algorithms like k-means. The method involves plotting the within-cluster sum of squares (WSS) against the number of clusters, and identifying the "elbow" point where the rate of decrease in WSS slows down significantly. This point represents the number of clusters where adding more clusters is unlikely to significantly improve the clustering quality ([53], text).

To use the elbow method, follow these steps:

1. Apply the clustering algorithm, such as k-means, for different values of k (the number of clusters), typically ranging from a minimum to a maximum value.
2. For each value of k, calculate the WSS, which is the sum of squared distances between each data point and its assigned centroid within the cluster.
3. Plot the values of k on the x-axis and the corresponding WSS on the y-axis.
4. Examine the resulting plot and look for a distinctive "elbow" point, which appears as a bend or curve in the plot.
5. The elbow point represents the value of k where adding more clusters provides diminishing returns in terms of reducing the WSS.
6. Based on the elbow point, select the corresponding value of k as the estimated optimal number of clusters.

It is important to note that the elbow method provides a rule-of-thumb rather than a definitive solution for determining the optimal number of clusters. The elbow point is subjective and may not always be clearly defined, especially in complex datasets. Additionally, the elbow method does not account for other factors such as domain knowledge or the specific objectives of the clustering task. Therefore, it is recommended to combine the results of the elbow method with other techniques and domain expertise to make an informed decision on the number of clusters [52,54].

The silhouette approach is a method used to determine the optimal number of clusters in a dataset when applying clustering algorithms such as k-means. It provides a quantitative measure of how well each data point fits its assigned cluster and helps assess the overall quality of clustering [45,55].

The silhouette coefficient for an individual data point measures its cohesion within its assigned cluster and separation from other clusters. The silhouette coefficient, denoted as s_i, is calculated as follows:

$$s(i) = \frac{b(i) - a(i)}{\max(a(i), b(i))}$$

where:

- $a(i)$ represents the average dissimilarity (distance) between data point i and all other points within the same cluster.
- $b(i)$ represents the average dissimilarity between data point i and all points in the nearest neighboring cluster (i.e., the cluster with the smallest average dissimilarity to data point i).

The silhouette coefficient ranges from -1 to 1, with higher values indicating better clustering. A value close to 1 suggests that the data point is well-matched to its assigned cluster, while a value close to -1 indicates it would fit better in a different cluster. A value around 0 indicates overlapping or ambiguous clusters.

To determine the optimal number of clusters using the silhouette approach, the following steps can be followed:

1. Apply the clustering algorithm for different values of k (the number of clusters) ranging from a minimum to a maximum value.
2. For each value of k, compute the average silhouette coefficient across all data points.
3. Identify the value of k that maximizes the average silhouette coefficient. This value represents the optimal number of clusters.

By using the silhouette approach, one can select the number of clusters that maximizes the cohesion within clusters and the separation between clusters, leading to more meaningful and well-separated clusters. It is important to note that the silhouette approach is not limited to k-means clustering and can be applied to other clustering algorithms as well.

3. Consumption of Primary Energy in Selected European Countries between 1990 and 2021

The consumption of primary energy in the European Union countries changed to a relatively small extent between 1990 and 2021, increasing by just under 1.5 EJ (Figure 1). However, substantial changes did occur in the structure of consumption (Figure 2). Throughout the period in question, oil remained the largest source, but there were quite significant changes in the subsequent rankings. In the early 1990s, the second most popular source of primary energy in the EU27 countries were solid fossil fuels, but within a few years, they fell to third place, to find themselves in fourth place in 2018, and in fifth place a year later. Natural gas took the place of solid fossil fuels, ranking second in 1998 and maintaining that position until the end of the period under review. This is a result of the selection of natural gas as a transition fuel in the energy transformation process, and its substitution for nuclear energy, as occurred, for example, in Germany. Nuclear energy held the fourth position for most of the described period, only dropping to fifth from 2015 to 2018, first ceding to renewable energy sources, and then to solid fossil fuels, before returning to the fourth position in 2019. The growth in the importance of renewable energy sources is noteworthy; they occupied the fifth position in 1990 but moved to the third position by the end of 2021.

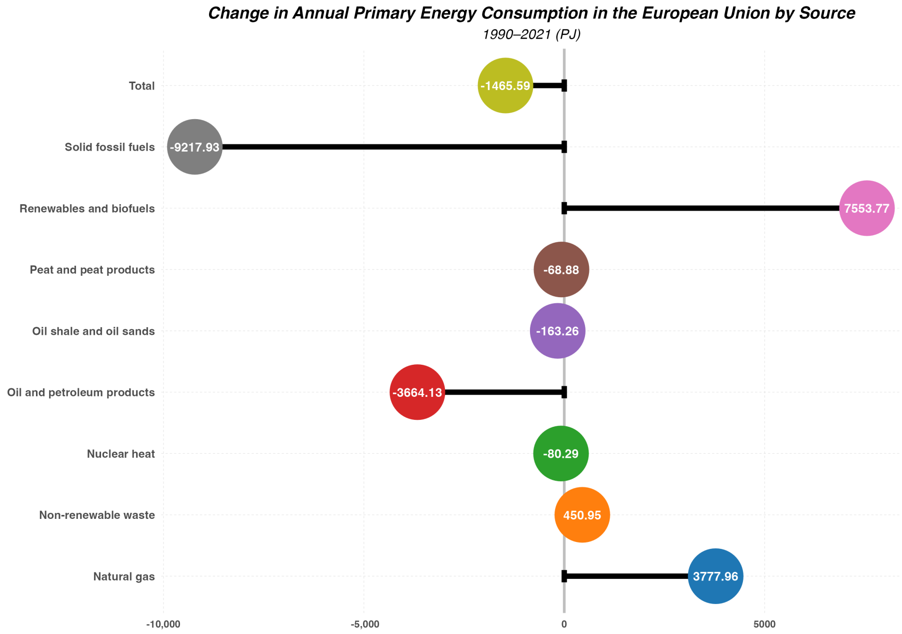

Figure 1. Change in primary energy consumption. Source: Developed based on data from Eurostat (table: nrg_bal_s).

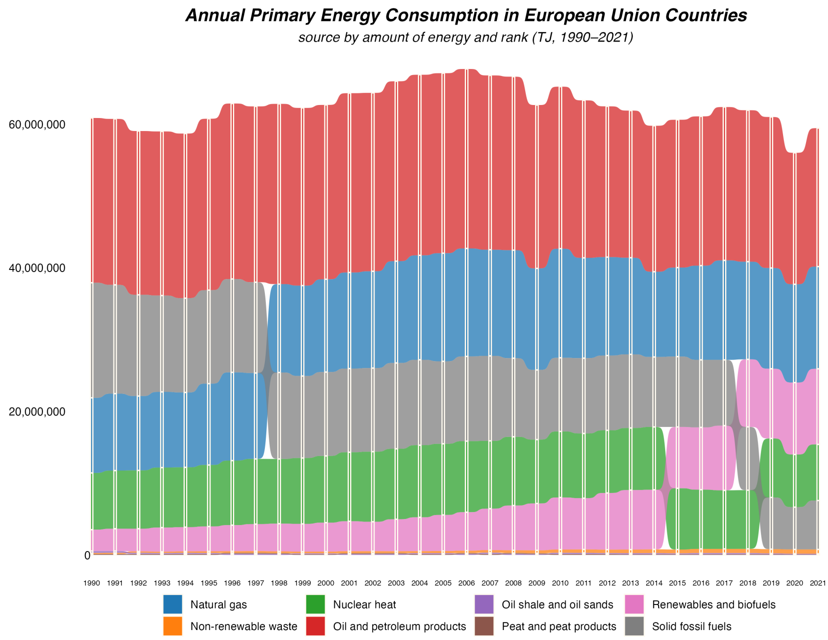

Figure 2. Primary energy consumption. Source: Developed based on data from Eurostat (table: nrg_bal_s).

Summing up the changes in the structure of primary energy consumption in European Union countries, we see that, in 1990, the largest source was oil, accounting for almost 38% of total consumption, followed by solid fossil fuels (26%), natural gas (17%), nuclear energy (13%), renewable energy sources (5%), and other sources with minor shares (Figure 3). By the end of 2021, oil still held the first position, but with a reduced share of just over 32%, followed by natural gas (24%), renewable energy sources (18%), nuclear energy (13%), solid fossil fuels (11%), and other sources of minor significance within the entire European Union (Figure 4).

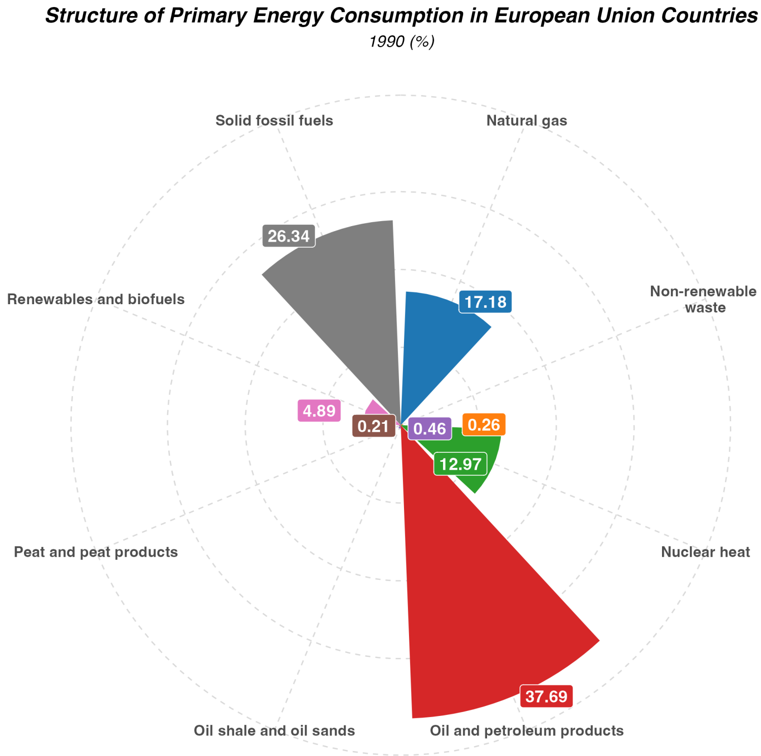

Figure 3. Structure of primary energy consumption in EU27 countries—1990. Source: Developed based on data from Eurostat (table: nrg_bal_s).

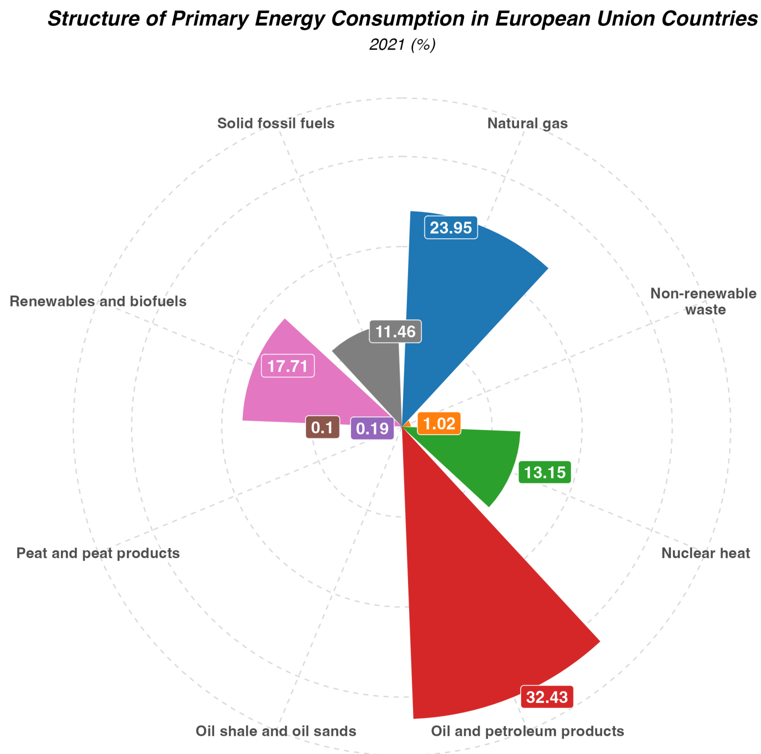

Figure 4. Structure of primary energy consumption in EU27 countries—2021, Source: Developed based on data from Eurostat (table: nrg_bal_s).

The changes in the amount of energy obtained from various sources are illustrated in Figures 1 and 5. Noteworthy is the case of solid fossil fuels, where the most significant change occurred—consumption decreased by over 9.2 EJ. On the other hand, renewable energy sources recorded a substantial increase of more than 7.5 EJ. The decline in the utilization of petroleum oil (3.7 EJ) was similar to the increase in the consumption of natural gas (3.8 EJ). Against this backdrop, the consumption of nuclear energy changed only slightly, by 80 PJ. Among other sources of primary energy, it is worth noting a considerable increase in the use of non-renewable waste (by nearly 0.5 EJ). Although this source remains of marginal significance, it indicates a shift in the European Union's approach to waste management.

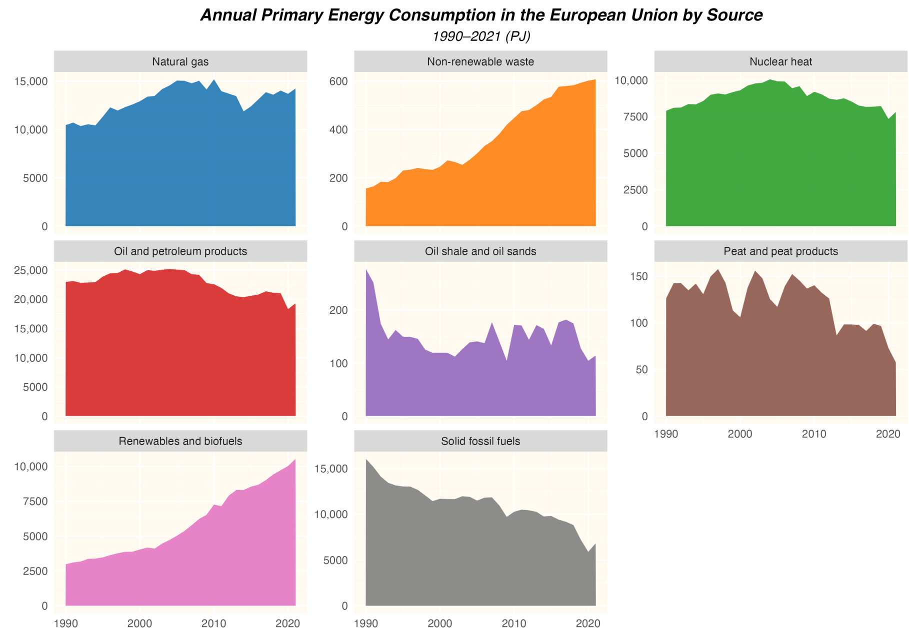

Figure 5. Primary energy consumption per source, Source: Developed based on data from Eurostat (table: nrg_bal_s).

Examining the change in primary energy consumption in individual European Union countries (Figure 6), it can be observed that consumption has increased and decreased in a similar number of states. The largest increase in the period from 1990 to 2021 was recorded in Iceland (over 150%), followed by Norway and Ireland. Conversely, the largest decrease took place in Estonia (nearly 60%), and then in Lithuania and Romania. Not coincidentally, most of the countries experiencing a decline in primary energy consumption are located in Central or Eastern Europe. This decline was largely a consequence of systemic and economic changes, including the transition from energy-intensive centrally planned economies towards market-oriented economies. Among the largest economies in the European Union, only Germany recorded a decline in primary energy consumption, while in other major economies (such as France, Italy, Spain, The Netherlands, and Poland) an increase was noted.

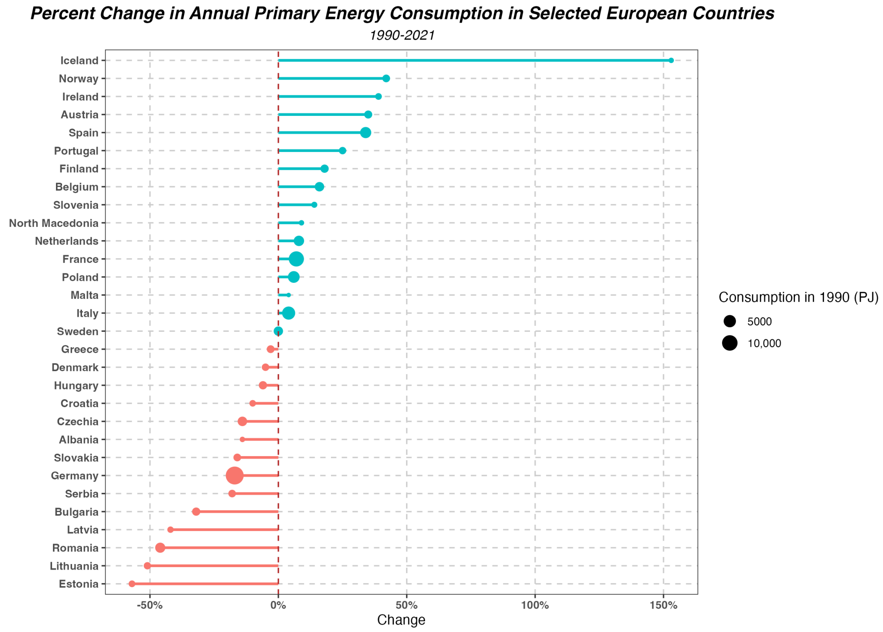

Figure 6. Change in primary energy consumption—countries, Source: Developed based on data from Eurostat (table: nrg_bal_s).

Examining the average proportion of various primary energy sources in the consumption structure of all surveyed countries (Figure 7) listed in the Eurostat database (not limited to European Union members), it is evident that oil remains the predominant source, though its share has decreased from 41% to 34.5%. Renewable energy sources have ascended to the second position, with their contribution surging from just under 10% to over 24%. Natural gas holds the third spot, increasing its share from 15% to nearly 20%. Solid fossil fuels, after descending from the second to the fourth rank, have seen their average contribution to primary energy consumption decline from 24% to just below 13%. Nuclear energy, among the major primary energy sources, occupies the last position, with its share diminishing from slightly above 7% to 6%.

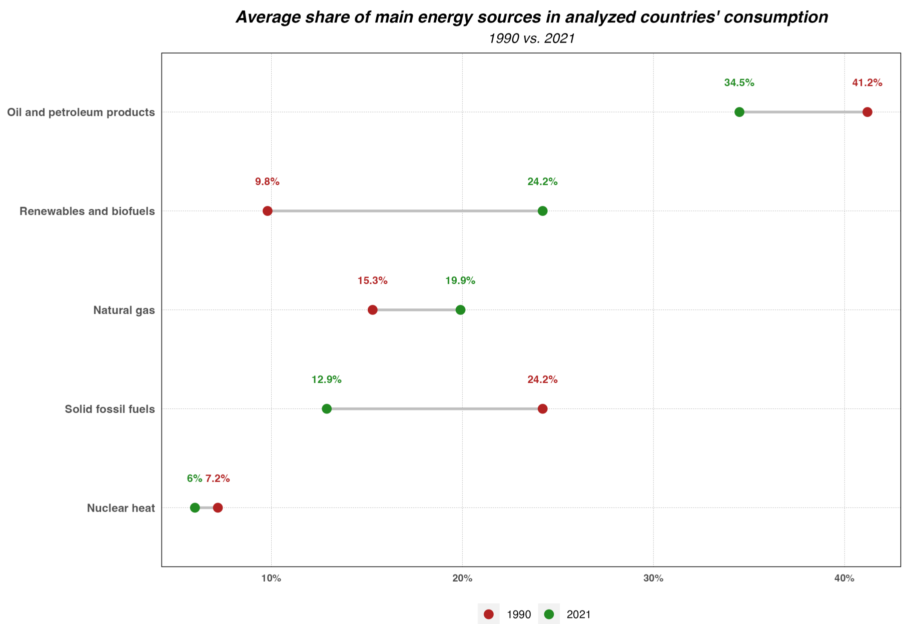

Figure 7. Change in average share of primary energy sources between 1990 and 2021, Source: Developed based on data from Eurostat (table: nrg_bal_s).

4. Cluster Analysis of Primary Energy Consumption Patterns in Selected European Countries

In the article, as previously mentioned, a cluster analysis was conducted for European countries present in the Eurostat database, focusing on the structure of primary energy consumption. The aim of this analysis was to categorize these countries into groups based on similarities in their consumption patterns. The study was conducted for two years—1990, marking the beginning of the analyzed period, and 2021, which is the latest year for which data are available in the Eurostat database. The optimal number of clusters was determined using two previously presented methods: the minimization of WSS (Within-Cluster Sum of Squares) and the Silhouette method.

4.1. Year 1990

Figures 8 and 9 display the results of the analysis of the influence of the number of clusters on WSS and the Silhouette coefficient value. Based on these findings, the authors decided to set the number of clusters at seven.

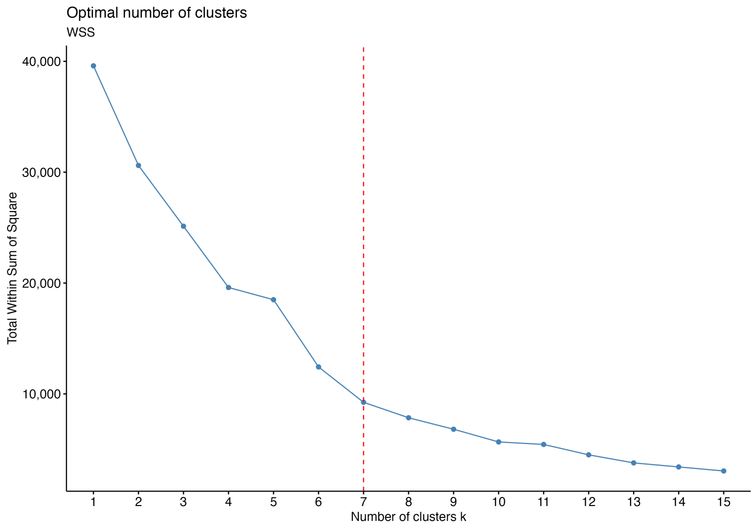

Figure 8. Optimal number of clusters in 1990—WSS minimization.

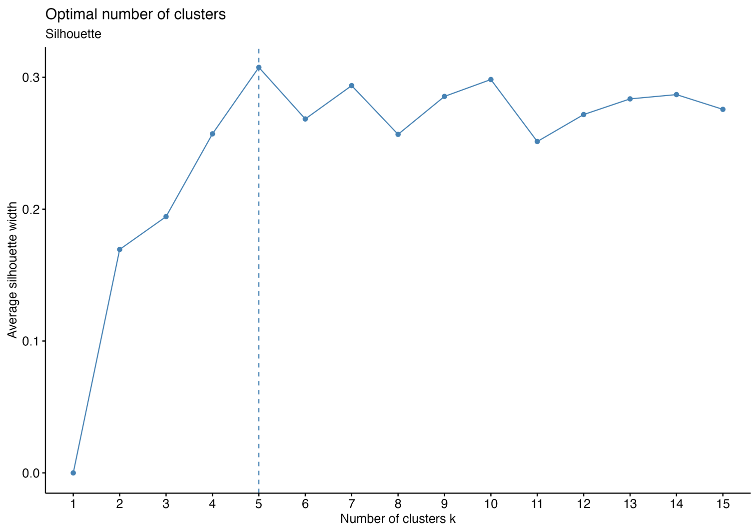

Figure 9. Optimal number of clusters in 1990—Silhouette method.

As a result, seven groups of countries with similar primary energy consumption structures were identified (Table 1). It is important to note that the analysis focused on currently existing countries, some of which might have been part of different national structures in

1990. For instance, the Czech Republic and Slovakia, which, in 1990, constituted a single nation—Czechoslovakia.

Table 1. Countries in clusters in 1990.

Cluster						
1	**2**	**3**	**4**	**5**	**6**	**7**
Czechia	Bulgaria	Albania	Cyprus	Belgium	Iceland	Estonia
North Macedonia	Germany	Austria	Malta	Finland	Norway	
Poland	Hungary	Denmark		France		
Serbia	The Netherlands	Greece		Lithuania		
	Romania	Spain		Sweden		
	Slovakia	Croatia		Slovenia		
	Ukraine	Ireland				
	The UK	Italy				
		Luxembourg				
		Latvia				
		Portugal				
		Turkey				

The first distinct group included the Czech Republic, North Macedonia, Poland, and Serbia. They are characterized by a significant share of solid fossil fuels in primary energy consumption, averaging 61%, and a 25% share of crude oil. Natural gas ranked third at 8%, with other sources being of lesser significance (Figure 10).

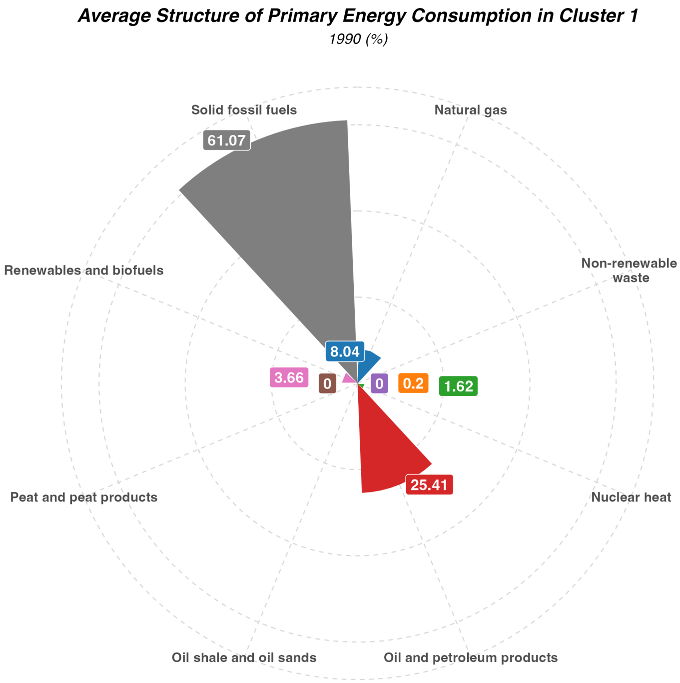

Figure 10. Averages of the first cluster identified during the analysis of data from 1990.

The second group, comprising Bulgaria, Germany, Hungary, The Netherlands, Romania, Slovakia, Ukraine, and the United Kingdom, still had a considerable share of solid fossil fuels (28%). However, crude oil (32%) and natural gas (30%) surpassed it. Among other sources, only nuclear energy had a noticeable share (9%) in primary energy consumption (Figure 11).

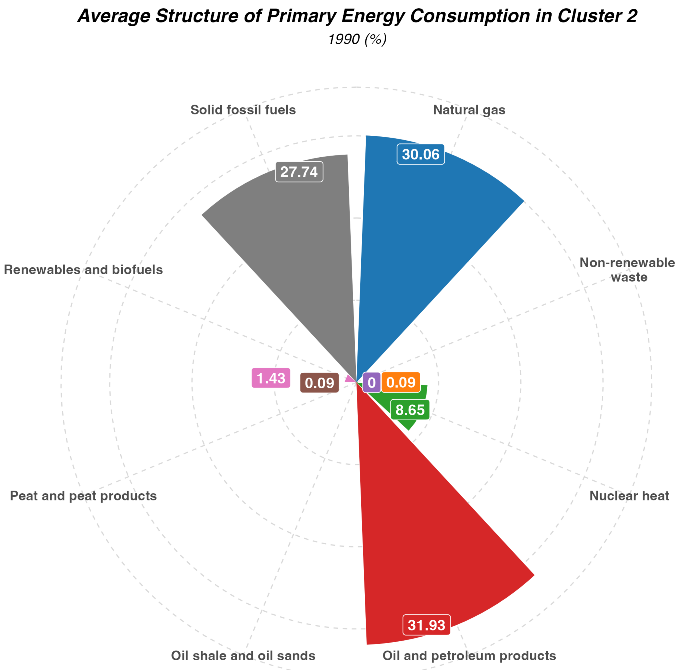

Figure 11. Averages of the second cluster identified during the analysis of data from 1990.

The third group is the largest, consisting of Albania, Austria, Denmark, Greece, Spain, Croatia, Ireland, Luxembourg, Latvia, Portugal, and Turkey. A distinctive feature of this group is the high share of crude oil—51%, followed by solid fossil fuels—22%, natural gas—14%, and renewable energy sources—11%) (Figure 12).

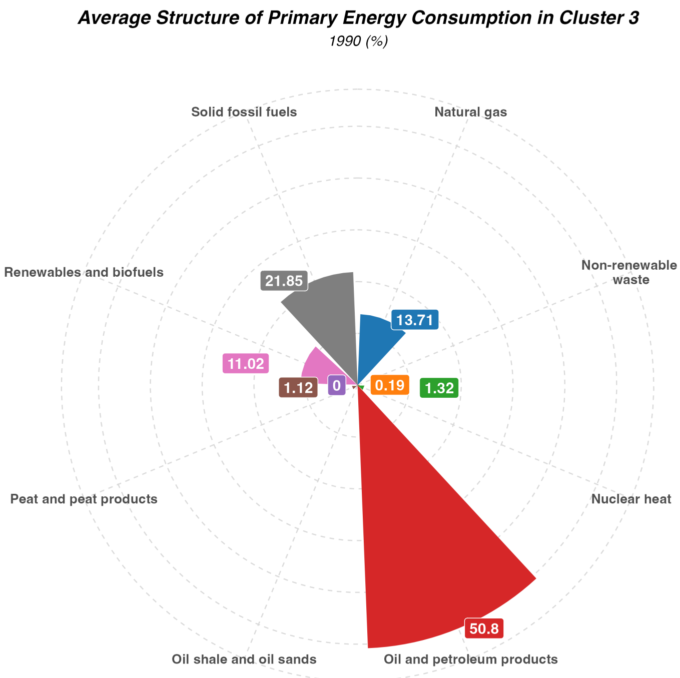

Figure 12. Averages of the third cluster identified during the analysis of data from 1990.

The fourth group consists of two Mediterranean island nations—Malta and Cyprus. They are distinguished by a very high share of crude oil—86%. Solid fossil fuels ranked second at 14%, and other primary energy sources were almost non-existent in 1990 (Figure 13).

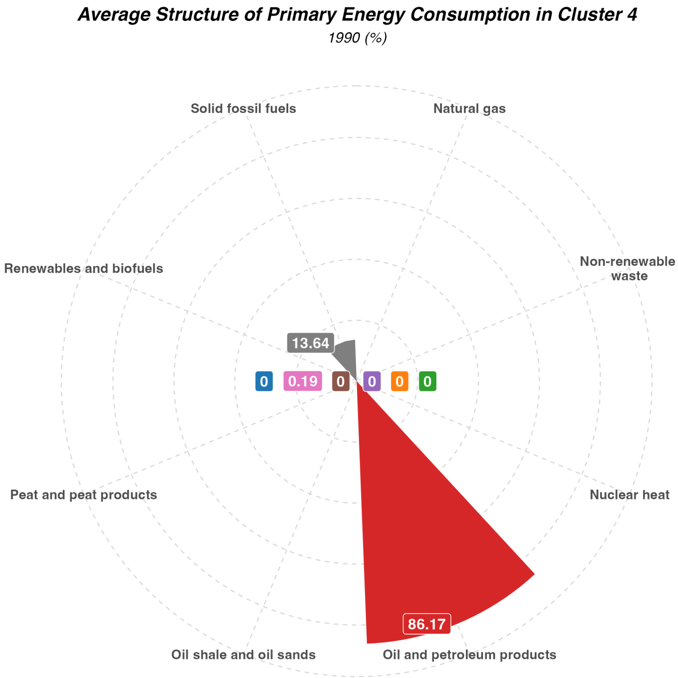

Figure 13. Averages of the fourth cluster identified during the analysis of data from 1990.

The next, fifth group is characterized by a significant share of nuclear energy—27%, which was only surpassed by crude oil—35%. Solid fossil fuels (14%), natural gas (13%), and renewable energy sources (10%) followed in sequence. This group includes Belgium, Finland, France, Lithuania, Sweden, and Slovenia (Figure 14).

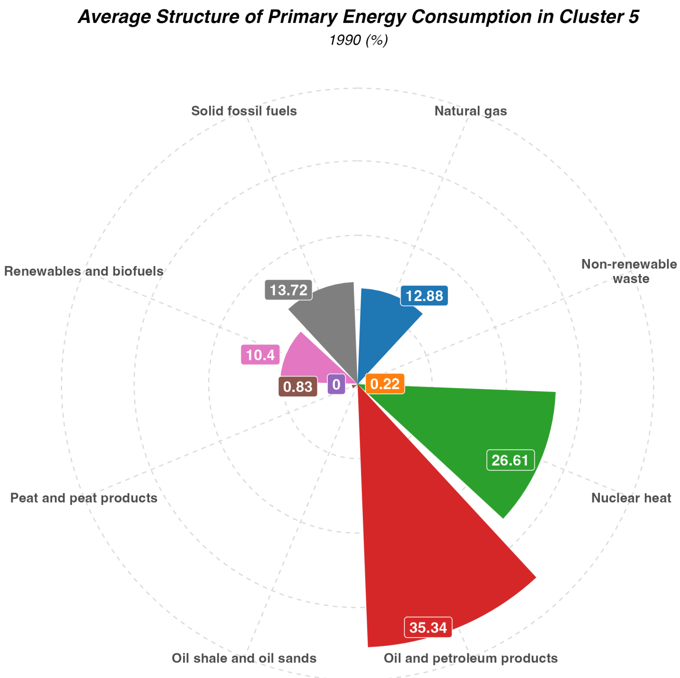

Figure 14. Averages of the fifth cluster identified during the analysis of data from 1990.

The sixth group consists of two Scandinavian countries—Iceland and Norway. Their distinguishing feature in 1990 was a very high share of renewable energy sources, averaging 60% for the group. Crude oil ranked second with a 33% share, while other primary energy sources played a negligible role (Figure 15).

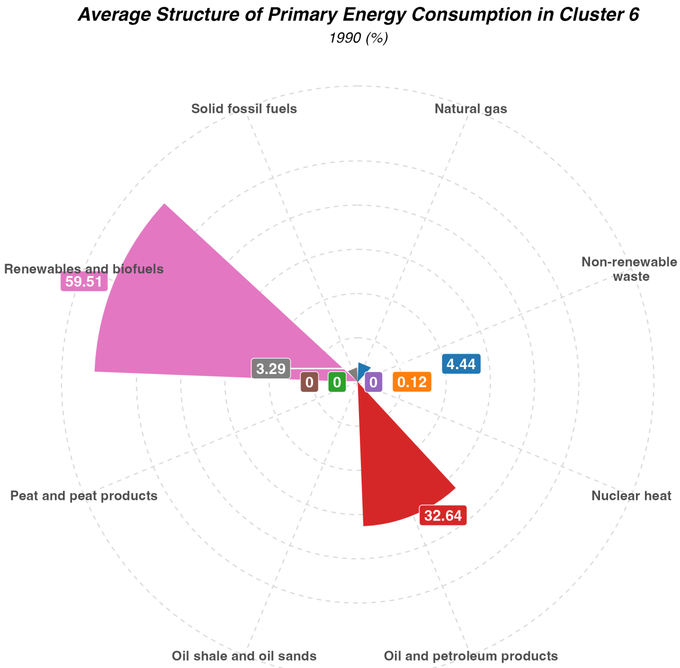

Figure 15. Averages of the sixth cluster identified during the analysis of data from 1990.

The last, seventh group consists of a single country—Estonia. Its consumption structure in 1990 was unique compared to the other analyzed countries, as the main source of primary energy was oil shale—58%, which is abundant in this country. Crude oil ranked second—26%, followed by natural gas—11% (Figure 16).

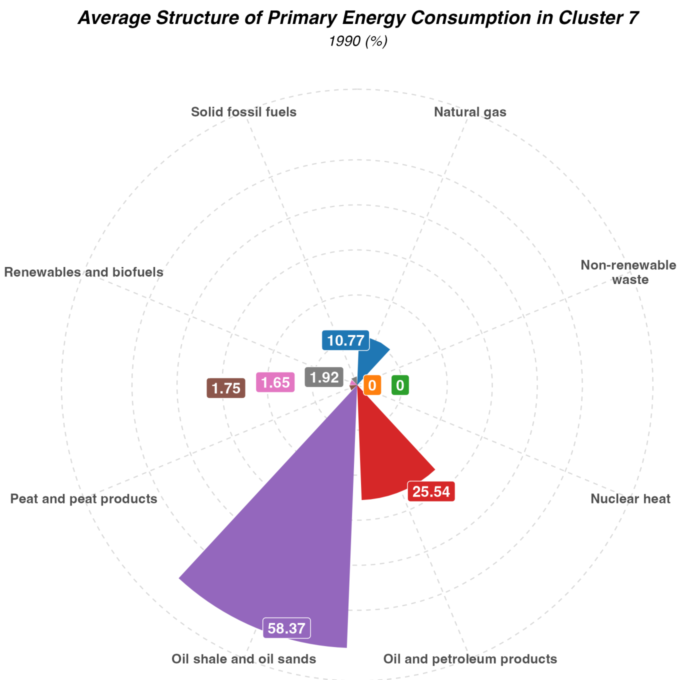

Figure 16. Averages of the seventh cluster identified during the analysis of data from 1990.

Figure 17 presents a map showing the division of countries into specific clusters in 1990.

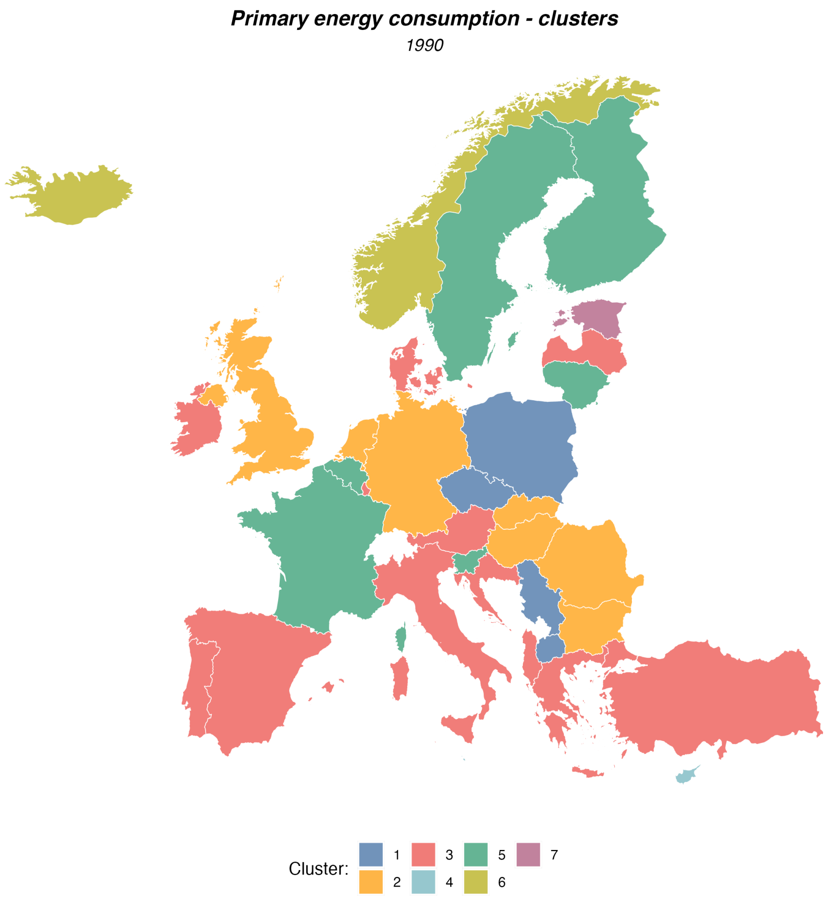

Figure 17. Map showing the analyzed countries divided according to the clusters identified during the analysis of 1990 data.

4.2. Year 2021

During the data analysis for the year 2021, as was the case for the year 1990, two methods suggesting the optimal number of clusters were employed: the minimization of WSS and the Silhouette method (Figures 18 and 19).

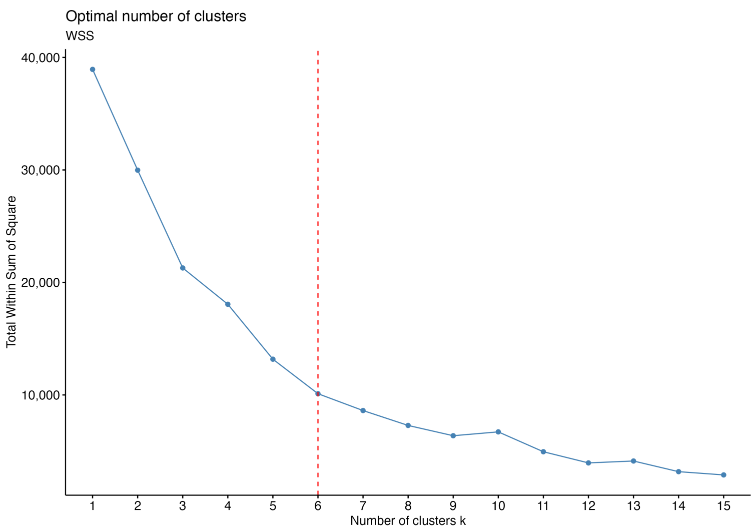

Figure 18. Optimal number of clusters in 2021—WSS minimization.

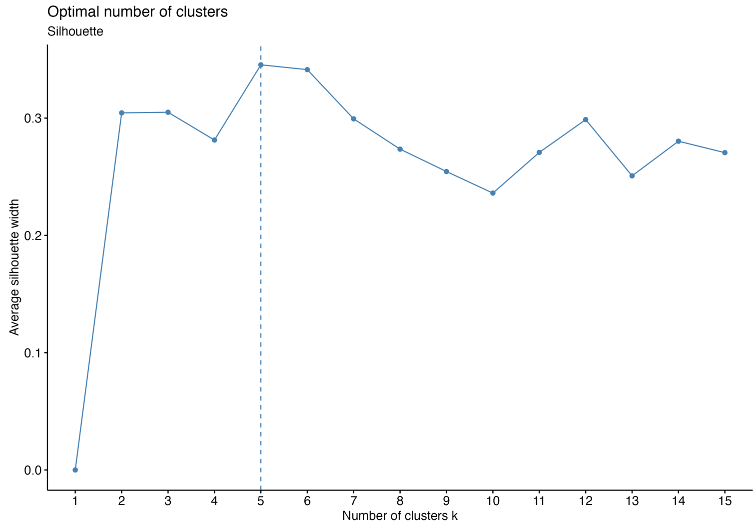

Figure 19. Optimal number of clusters in 2021—Silhouette method.

This time, the authors determined that the number of clusters would be six. The six groups of countries, similar in terms of their primary energy consumption structure, are presented in Table 2.

Table 2. Countries in clusters in 2021.

Cluster					
1	**2**	**3**	**4**	**5**	**6**
Bosnia and Herzegovina	Austria	Belgium	Cyprus	Albania	Estonia
Montenegro	Germany	Bulgaria	Luxembourg	Denmark	
North Macedonia	Greece	Czechia		Finland	
Poland	Spain	France		Iceland	
Serbia	Georgia	Slovenia		Latvia	
Kosovo	Croatia	Slovakia		Norway	
	Hungary			Sweden	
	Ireland				
	Italy				
	Lithuania				
	Moldova				
	Malta				
	The Netherlands				
	Portugal				
	Romania				
	Turkey				

Countries in purple font are transitioned to a group with a different characteristic.

The first group, still dominated by solid fossil fuels (accounting for 41%), includes Bosnia and Herzegovina, Montenegro, North Macedonia, Poland, Serbia, and Kosovo. Oil ranks second in this group (31%), followed by renewable energy sources (19%) and natural gas (8%). Compared to the first group from 1990, where solid fossil fuels also prevailed, a significant decrease in their share is evident, accompanied by an increased significance of renewables. This trend is ubiquitous and pertains to all country groups. Notably, the Czech Republic exited this group due to an increase in nuclear energy utilization, placing it in the third group (Figure 20).

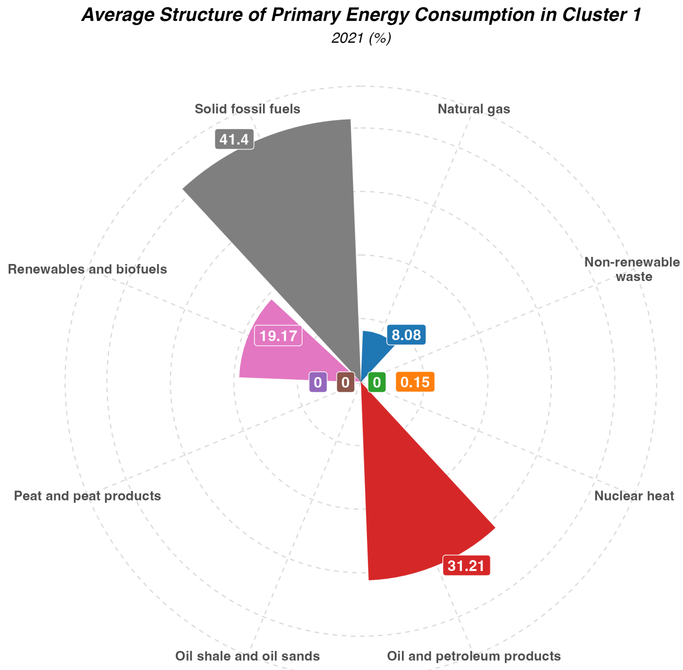

Figure 20. Averages of the first cluster identified during the analysis of data from 2021.

The second group is characterized by a substantial share of oil (38%) and natural gas (32%). Compared to the second group from 1990, there was a significant decrease in the share of solid fossil fuels (7%) and nuclear energy (3%), while the importance of renewables rose to 20%. This largest group comprises Austria, Germany, Greece, Spain, Georgia, Croatia, Hungary, Ireland, Italy, Lithuania, Moldova, Malta, the Netherlands, Portugal, Romania, and Turkey (Figure 21).

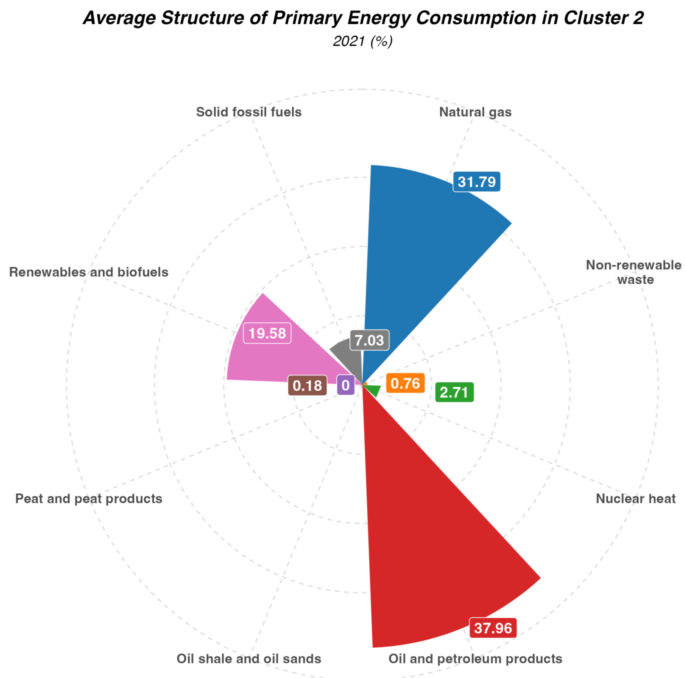

Figure 21. Averages of the second cluster identified during the analysis of data from 2021.

The third group exhibits a highly diversified primary energy consumption structure, with a notable share of nuclear energy (24%, ranking second). Oil occupies the top position

(27%), followed by natural gas (19%), solid fossil fuels (16%), and renewable energy sources (13%, Figure 22).

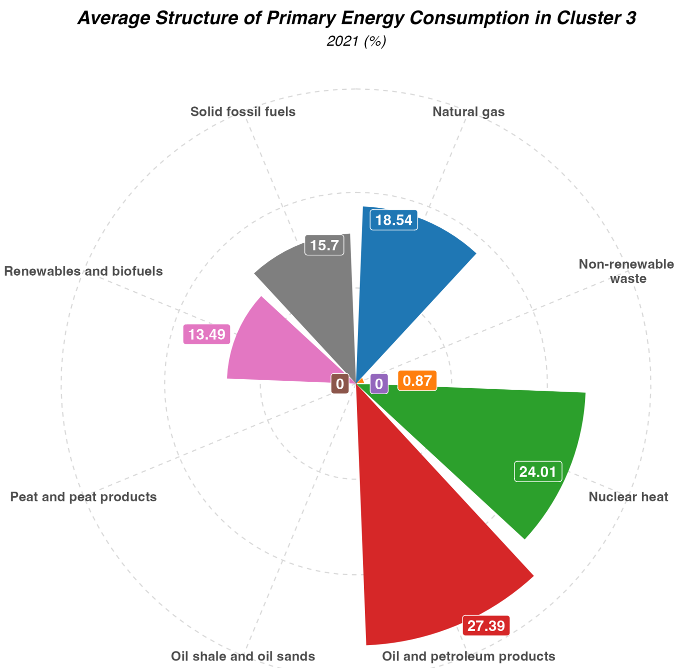

Figure 22. Averages of the third cluster identified during the analysis of data from 2021.

The fourth group consists of Cyprus and Luxembourg, with a predominant share of oil (77%) and significant contributions from renewables energy sources (12%) and natural gas (9%, Figure 23).

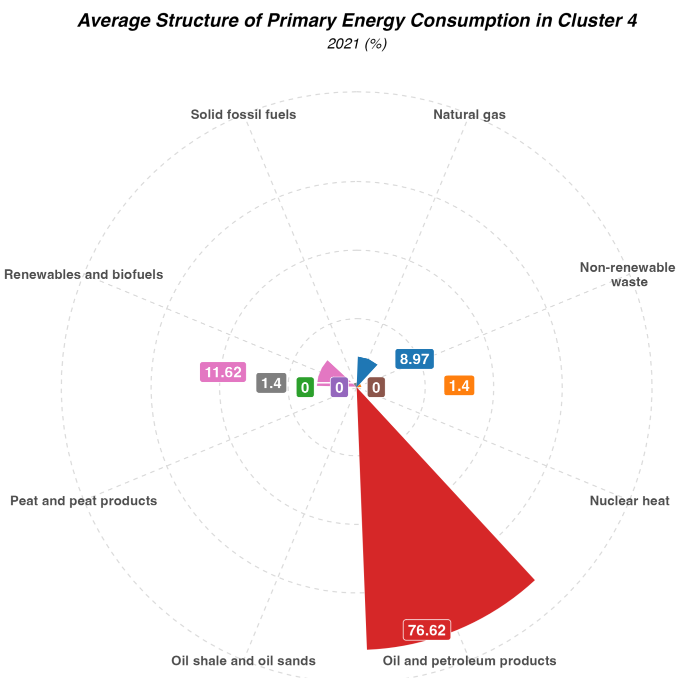

Figure 23. Averages of the fourth cluster identified during the analysis of data from 2021.

The fifth group, encompassing Albania, Denmark, Finland, Iceland, Latvia, Norway, and Sweden, is characterized by a notably high average share of renewable energy sources (51%), followed by oil (28%) and natural gas (9%). It is worth noting that, in 1990, the group of countries with a dominant share of renewable sources consisted only of Norway and Iceland (Figure 24).

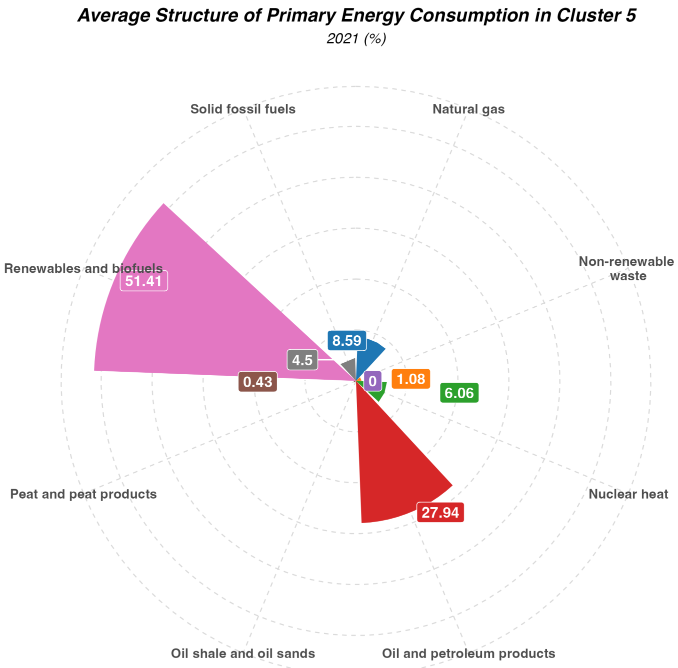

Figure 24. Averages of the fifth cluster identified during the analysis of data from 2021.

The final, sixth group comprises only Estonia, distinguished by its primary energy consumption structure due to the extensive use of oil shales. Their share in total consumption has decreased (to 60%), with a noticeable increase in the share of renewable sources (to 29%). In 2021, natural gas ranked third, accounting for 9% of the consumption (Figure 25).

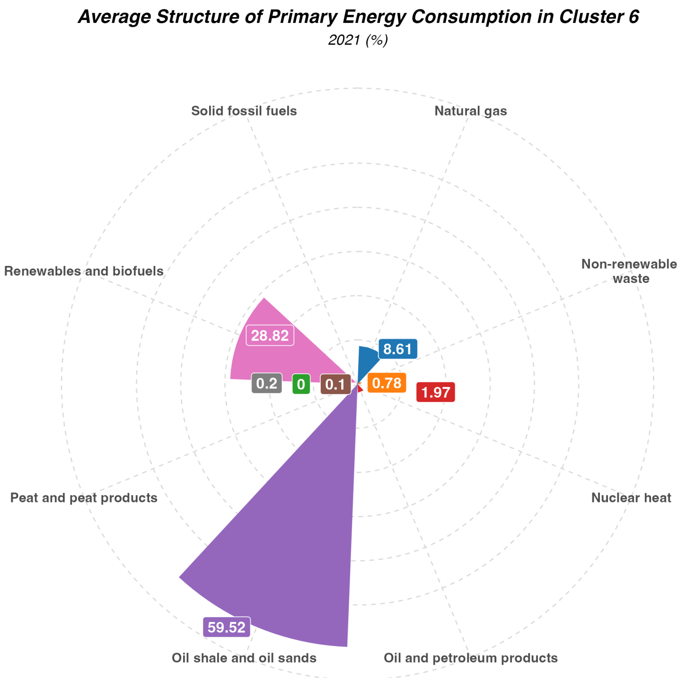

Figure 25. Averages of the sixth cluster identified during the analysis of data from 2021.

Figure 26 presents a map showing the division of countries into specific clusters in 1990.

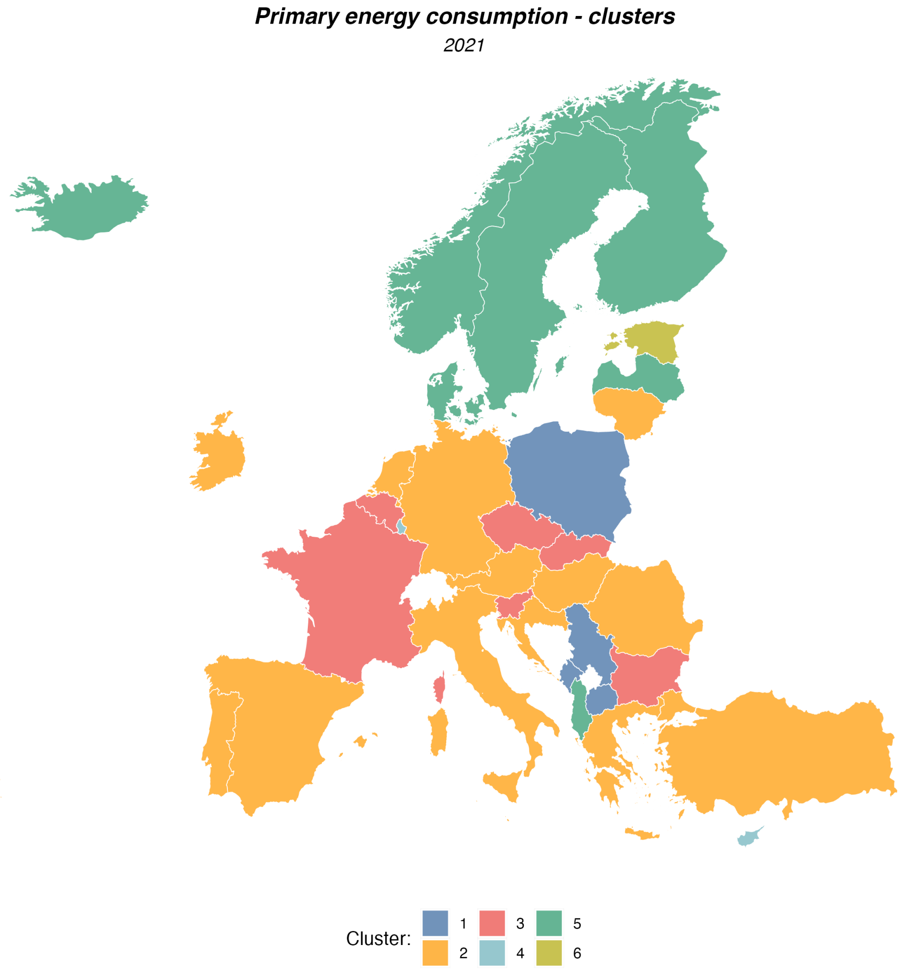

Figure 26. Map showing the analyzed countries divided according to the clusters identified during the analysis of 2021 data.

5. Discussion and Conclusions

Discussing the results of the analysis, we can discern several distinct trends. These include the following:

1. A clear trend of moving away from solid fossil fuels. Even in countries where this remains the primary source of energy, its share in overall consumption has significantly decreased.
2. Renewable energy sources have seen the most substantial growth in share across all groups. This robust trend will undoubtedly continue in the coming years, aligning with the policies of the European Union and individual countries. However, this shift also presents challenges. Most of this growth has been achieved through relatively unstable sources, such as wind and solar energy. This introduces several serious implications, including the need for energy storage, periodic energy shortages or surpluses, and the necessity to balance the energy system with other sources during windless or sunless periods.
3. A noticeable increase in natural gas consumption, which serves as a transitional fuel in the energy transformation process and is well-suited for stabilizing energy systems during renewable energy shortages. It also acts as a good substitute for solid fossil fuels.
4. During the analyzed period, there was a kind of stagnation in the development of nuclear energy. Some countries continued its development, while others decided to gradually phase it out (e.g., Germany). However, overall changes in both consumption volume and share were minimal. This situation may change in the coming years

due to the consequences of Russia's aggression against Ukraine, the loss of energy security in Europe, and the further development of renewable energy sources, which require balancing and backup from alternative sources. As a result, many countries are considering the development of nuclear energy or have already taken steps in this direction.
5. For most countries, oil remains crucial, although its share in total primary energy consumption is slowly decreasing.

From an energy security perspective, it is essential to note that each primary energy source has its advantages and disadvantages. For most countries, it is challenging to identify a single, ideal primary energy source:

1. Renewable sources are politically and ecologically favorable. However, they are typically unstable and require support from other energy sources, at least until effective renewable energy storage technologies are developed and implemented.
2. Solid fossil fuels are relatively easy to use, do not require dedicated, extensive transport infrastructure, and provide stable energy supplies. However, due to CO_2 emissions, they are an unsustainable energy source in the long run, and a shift away from them seems inevitable.
3. Natural gas is a flexible and easy-to-use transitional fuel. However, it requires extensive transport and storage infrastructure and is perhaps the most politicized primary energy source. The consequences of Russia's aggression against Ukraine and its use of natural gas as a geopolitical tool, leading to an energy and economic crisis in Europe, have clearly demonstrated this. Moreover, natural gas is also a fossil fuel, generating CO_2 emissions, and Europe lacks significant reserves.
4. Nuclear energy has faced negative publicity, exacerbated by disasters in Chernobyl and Fukushima, geopolitical issues, and a certain aura of mystery and fear surrounding nuclear technologies. On the other hand, it seems to be an ideal complement to renewable sources. However, the significant investments associated with the development of nuclear energy can be a barrier.
5. Oil is currently a key component of the energy mix for European countries. However, it is also a fossil source responsible for CO_2 emissions, and due to a lack of significant reserves in Europe, it mostly requires import. Its ease of transport, processing, and the high amount of energy carried per volume unit make oil a very convenient primary energy source.

Upon assessing the 2021 energy consumption clusters, several key observations can be made:

1. The first cluster is characterized by a significant reliance on solid fossil fuels. While these sources are often locally available or easily imported, they are becoming increasingly untenable due to environmental, political, and social concerns. This has also led to their diminishing economic viability. Countries in this cluster, notably Poland, are transitioning towards renewable energy sources, increasing natural gas consumption, and planning substantial investments in nuclear energy.
2. The second group predominantly utilizes oil, natural gas, and renewable sources. Given that the majority of their oil and natural gas is imported, it is crucial for these countries to ensure diversified supplies and a well-developed transport and storage infrastructure. The Ukraine conflict highlighted the risks, as seen in Germany, of over-reliance on a single supplier, especially for natural gas.
3. The third cluster boasts the most diverse energy mix in terms of primary energy consumption. However, the relatively high proportion of solid fossil fuels remains a concern. A significant advantage for this group is their use of nuclear energy, ensuring a stable energy supply.
4. The fourth group, comprising two small countries, primarily consumes oil. It i challenging to assess them collectively due to Cyprus's unique geopolitical situation

and Luxembourg's affluent status in Western Europe. Nonetheless, reliance on a single, imported primary energy source is suboptimal.

5. The fifth group is distinguished by its substantial use of renewable energy sources. While this is theoretically ideal, it necessitates backup energy sources, especially when relying on unstable renewables. This issue is less pertinent for Iceland, which benefits from hydro and geothermal energy, and to a lesser extent for Norway and Sweden, which utilize hydropower. However, prolonged droughts can disrupt such energy production. This renewable-centric model seems to be the European goal, but establishing a balanced system with backup energy sources during renewable shortages remains a challenge.
6. The final group consists of a single country, Estonia, which stands out in Europe due to its shale oil reserves. While this ensures energy security for Estonia, it poses environmental, political, and social challenges. Consequently, Estonia is gradually moving away from this primary energy source and increasingly turning to renewables.

Our paper provides a comprehensive, data-driven analysis of the primary energy consumption landscape across European countries from 1990 to 2021. We have identified several key trends, such as a significant move away from solid fossil fuels, a robust growth in renewable energy sources, and an increase in natural gas consumption as a transitional fuel. We also observed a stagnation in the development of nuclear energy and a slow decline in oil consumption. Importantly, our study reveals a trend towards the convergence of primary energy consumption structures among European countries, indicating a collective move towards more diversified and sustainable energy portfolios.

From an energy security perspective, we have discussed the advantages and disadvantages of each primary energy source, emphasizing the need for a well-diversified set of energy sources tailored to a country's specific situation. We also assessed energy consumption clusters for the year 2021, providing insights into the energy security and economic implications for countries in different clusters. For example, countries heavily reliant on solid fossil fuels are transitioning towards more sustainable options, while those dependent on imported oil and natural gas are focusing on diversifying their supplies.

Moreover, our analysis has shown that there is a noticeable trend towards the homogenization of primary energy consumption structures among European countries. This is a significant observation that has implications for both policy-making and future research. It suggests that European countries are increasingly aligning their energy policies and strategies, which could facilitate more coordinated and effective regional responses to energy security challenges.

We also acknowledge that our study has several limitations that should be considered when interpreting the results:

1. Methodological Limitations: We employed the k-means clustering algorithm to categorize countries based on their primary energy consumption patterns. While k-means is a widely used method, it has its limitations. For instance, it assumes spherical clusters and is sensitive to the initial placement of centroids, which could affect the final clustering outcome. Additionally, k-means does not provide a measure of the "goodness of fit" for the chosen number of clusters, which could be a limitation in understanding the robustness of our categorizations.
2. Data Scope: Our analysis is limited to countries for which data is available in the Eurostat database. This means that some European countries that are not part of the Eurostat database were not included in our study. The exclusion of these countries could potentially limit the comprehensiveness of our findings and their applicability to the entire European region.
3. Temporal Limitations: Our study covers the period from 1990 to 2021. While this provides a long-term view, it may not capture very recent policy changes or technological advancements that have not yet significantly impacted primary energy consumption statistics.

4. Lack of Qualitative Data Analysis: Our study is primarily quantitative and does not delve into the qualitative aspects, such as political, social, or economic factors, that might influence energy consumption patterns and energy security in individual countries.

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Abbreviations

The following abbreviations are used in this manuscript:

OPEC	Organization of the Petroleum Exporting Countries
SMR	Small Modular Reactor
IDE	Integrated Development Environment
DBSCAN	Density-Based Spatial Clustering of Applications with Noise
EU27	27 Countries of the European Union
EJ	exajoule
PJ	petajoule
WSS	Within-Cluster Sum of Squares

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