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Europe's Energy Shift: From Fossil Fuels to Renewable Energy

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Abstract

Objectives: This study explores the transformation of energy consumption in Europe between 2002 and 2022, focusing on the declining role of fossil fuels and the increasing significance of renewable and nuclear energy sources. The study also considers how countries with varying levels of economic development adopt different energy strategies and how these strategies correlate with shifts in energy usage. A circular economy approach that includes energy recovery from waste and resource reuse is a complementary aspect of sustainable energy transitions. ***Methods/Analysis:*** The per capita energy consumption data were analyzed through decile classification and cluster analysis to group countries with similar energy profiles. To explore the relationship between GDP and energy use—both total and renewable—linear and exponential regression models were applied. Outlier countries with atypical consumption trends were excluded to improve model reliability. Statistical analyses were conducted using SPSS, and Excel was used to support the visualization process. ***Findings:*** Six distinct clusters of energy consumption patterns emerged. In lower- and middle-GDP countries, renewable energy use showed a stronger exponential correlation with GDP growth than total energy use. While fossil fuel dependence has declined across most countries, the pathways taken have been diverse. High-GDP nations such as Iceland and Norway have demonstrated unique, resource-driven strategies. ***Novelty/Improvement:*** This study introduces a novel methodological blend of decile-based classification and clustering to enable clearer cross-country comparisons of energy use. The results also highlight the importance of excluding statistical outliers to improve regression precision. By integrating insights relevant to circular economy principles, the findings contribute to designing more effective and regionally adapted energy transition strategies.

Keywords:

Energy Consumption;
Renewable Energy;
Fossil Fuels;
Energy Transition;
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1- Introduction

The evolution of Europe's energy consumption is crucial for achieving the continent's sustainability and energy independence. Analyzing energy consumption patterns will help policymakers reduce fossil fuel dependency and promote the expansion of renewable energy sources, thereby strengthening energy security and advancing climate goals.

According to the European Environment Agency, economic recovery has led to an increase in greenhouse gas emissions and energy consumption, particularly in the transportation, industrial, and energy supply sectors. However, the growth of renewable energy has slowed due to the energy supply crisis and high gas prices, resulting in a return to more carbon-intensive fuels [1]. Cluster analyses reveal significant differences in the energy strategies of the European Union (EU) member states, particularly in adopting renewable energy and energy efficiency measures. Achieving the EU's 2030 and 2050 targets requires the development of energy infrastructure and the integration of climate-neutrality considerations [1].

While energy consumption growth is often associated with economic expansion, sustainable development can be achieved through energy efficiency investments that contribute not only to reducing energy consumption but also to enhancing energy security and mitigating environmental impacts [2].

The primary challenges for the EU are to balance economic growth, ensure energy security and achieve environmental sustainability. The dominance of fossil fuels, the slow expansion of renewable energy, and disparities in national energy policies hinder unified progress. Addressing these challenges is essential for meeting climate goals and building sustainable energy systems.

This research aims to analyze trends in European energy consumption, with a particular focus on the reduction of fossil fuel consumption and the expansion of nuclear and renewable energy sources. The findings support the identification of best practices and promote sustainability, energy diversification, and energy independence.

2- Literature Review

This review examines the necessity of transforming European energy systems, focusing on the transition from fossil fuels to renewable and nuclear energy sources. Energy transition is an organized process that not only aims to reduce greenhouse gas emissions but also supports long-term sustainable development [3]. Due to advancements in nuclear technologies, even previously opposing countries may need to reconsider their strategies [4, 5].

Decentralized energy systems, such as solar and wind power, enhance supply security and efficiency while reducing the dependence on fossil fuels [6]. Transformation of the energy mix and adoption of clean technologies are essential for ensuring a sustainable energy supply [7]. To increase energy independence, using renewable energy sources reduces import dependence and improves energy security. Achieving carbon neutrality requires the development of carbon-free technologies [8].

Integrated resource assessments are crucial for establishing a sustainable energy policy and ensuring that energy transition technologies remain viable in the long term [9]. The theory of energy transition examines the role of policy innovations, technological advancements, and market mechanisms in the development of sustainable energy systems [10, 11]. The theory of innovation diffusion highlights the channels through which renewable energy sources are spread and the policy incentives that facilitate their adoption. The relationship between economic growth and energy consumption is complex. Research suggests that economic growth can be decoupled from environmental degradation through appropriate policy measures [12, 13]. Effective decarburization policies support transitioning to low-carbon energy systems, as examined in the EU and Germany [14, 15]. In bioenergy policy development, considering indirect land-use changes can help mitigate undesirable environmental trade-offs [8].

The expansion of renewable energy sources and improvements in energy efficiency contribute to reducing carbon emissions [16]. Microalgal biomass as a sustainable alternative to replacing fossil fuels. Regression analyses and panel studies can assess policy impacts on energy transition [17, 18]. Country-specific measures can significantly accelerate the adoption of renewable energy sources [19].

Technological innovations play a key role in accelerating energy transition. Successful implementation requires global coordination, appropriate regulatory frameworks, and substantial infrastructure investments [20]. The social and economic impacts of the transition include increased energy security and job creation. The future of sustainable energy consumption relies on reducing the carbon footprint and increasing the use of renewable energy [9].

Research related to Sustainable Development Goals increasingly highlights the role of the circular economy, which not only aims to close material loops but also emphasizes energy efficiency and the recovery of energy from waste [21]. Circular models offer opportunities to reduce dependence on primary energy sources by recovering energy from waste—such as organic residues, used oil, and plastics. Bibliometric analyses within the tourism sector also reveal that circular thinking is increasingly integrated into sustainability practices, both in terms of material and energy flows [22]. This is particularly relevant in industries that generate significant waste, where energy recovery from waste can help lower the sector's carbon footprint. Bai et al. [23] used examples from China and demonstrated that government environmental targets—such as promoting the use of recycled materials and energy—play a key role in developing low-carbon development pathways. This approach is also applicable in Europe, particularly in regions in which energy independence and waste management are strategic priorities.

3- Research Methodology

Our analysis was based on energy consumption data from European countries, including the quantity and share of fossil fuel, nuclear, and renewable energy in total energy consumption. The data were examined in kWh per capita for the years 2002 and 2022 [24].

The analysis aims to classify European countries based on their energy consumption structures. After thoroughly reviewing the literature, we developed the following hypotheses, which examine different aspects of energy source distribution, the relationship between economic growth and energy consumption, and the expansion of renewable energy. The research followed a 10-step process in the following order (Figure 1).

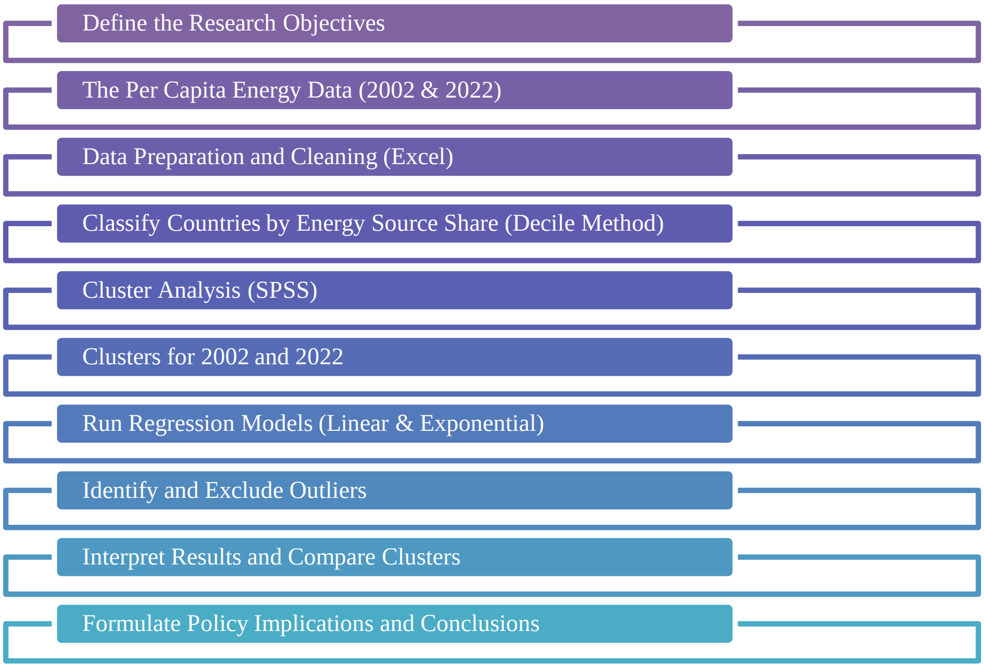

Figure 1. Research process

In the meantime, we also tested the following hypotheses, which we considered realistic.

H1. European countries rely on fossil, renewable, and nuclear energy sources in varying proportions, but some countries exhibit similar energy consumption patterns. These similarities can be identified by cluster analysis.

H2. The relationship between energy consumption and economic growth is non-linear; energy consumption increases faster than GDP growth, as economic development leads to greater energy demand.

H3. Certain high-GDP countries do not fit the general GDP-energy consumption relationship because their energy consumption patterns deviate from the average trend.

H4. Economic growth in countries with low to medium GDP increases renewable energy consumption more significantly than the overall energy consumption.

To test these hypotheses, we applied the following procedures. First, countries were grouped into deciles based on their fossil fuel, nuclear, and renewable energy consumption. This approach enabled a comprehensive analysis of the energy consumption structures, thus improving the clarity and facilitating cross-country comparisons. The decile boundaries were determined based on the data distribution. Based on the results, we identified six distinct clusters for 2002 and 2022. The clusters were named according to their energy consumption strategies (e.g., Fossil Dominance, Renewable Energy Focus, etc.). The comparison revealed how countries' energy consumption strategies have evolved over the past two decades.

Next, the relationship between renewable energy consumption, total energy consumption, and GDP was examined for each country. Linear and exponential regression models were used for the analysis. The exponential model provided more accurate results; however, some countries (Iceland, Norway, Switzerland, Luxembourg, and Ireland) displayed significantly different values, leading to their exclusion as outliers in the final examination.

The analyses were conducted using the SPSS statistical software package, which facilitates the creation of deciles, cluster analysis, and regression model evaluations. Data preparation and visualization were performed using Excel. The examination of the temporal changes in the clusters revealed that some countries maintained or modified their energy consumption strategies between 2002 and 2022. The exponential regression results indicate that the growth of renewable energy consumption follows the GDP expansion at a much more intense rate than fossil fuel or nuclear energy consumption. The separate analysis of outlier countries revealed unique strategies that distinguish these states from the rest. The findings of this study contribute to a deeper understanding of European energy consumption strategies and help identify trends that may shape future energy consumption patterns across Europe.

4- Results

The results are presented in order of the hypotheses. First, the cluster analysis findings are introduced, followed by an analysis of the changes in energy consumption. Next, a comparison of the linear and exponential regression models is provided, followed by an examination of the model without outliers. Finally, a qualitative analysis presents the economic and geographical characteristics of the outlier countries.

4-1- Cluster Formation

Tables 1 and 2 presents the (2002 and 2022) energy consumption and its distribution for the European countries for which data were available.

Table 1. Per Capita Energy Consumption of European Countries in 2002

Country	Fossil consumption per capita (kWh)	Per capita nuclear energy (kWh)	Renewable energy (kWh)	Total (kWh)	Fossil rate	Nuclear rate	Renewable rate
Austria	35145.6	0.0	15210.7	50356.3	69.8%	0.0%	30.2%
Belgium	57679.6	12809.6	339.8	70829.0	81.4%	18.1%	0.5%
Bulgaria	19439.0	7102.3	774.5	27315.8	71.2%	26.0%	2.8%
Belarus	25296.7	0.0	8.4	25305.0	100.0%	0.0%	0.0%
Switzerland	24857.5	10410.0	14515.4	49782.9	49.9%	20.9%	29.2%
Czechia	41477.5	5126.3	868.0	47471.8	87.4%	10.8%	1.8%
Germany	41845.7	5669.0	1673.7	49188.4	85.1%	11.5%	3.4%
Denmark	40237.5	0.0	3779.7	44017.2	91.4%	0.0%	8.6%
Spain	32200.8	4255.3	2471.5	38927.6	82.7%	10.9%	6.3%
Estonia	41689.9	0.0	77.3	41767.2	99.8%	0.0%	0.2%
Finland	47297.5	12007.5	11602.5	70907.5	66.7%	16.9%	16.4%
France	28689.0	20604.1	3172.7	52465.8	54.7%	39.3%	6.0%
United Kingdom	39606.9	4145.4	570.7	44323.0	89.4%	9.4%	1.3%
Greece	32973.6	0.0	944.0	33917.6	97.2%	0.0%	2.8%
Croatia	18859.1	0.0	3809.9	22669.0	83.2%	0.0%	16.8%
Hungary	23760.2	3850.9	69.3	27680.4	85.8%	13.9%	0.3%
Ireland	45528.8	0.0	1040.8	46569.6	97.8%	0.0%	2.2%
Iceland	36687.5	0.0	84617.1	121304.7	30.2%	0.0%	69.8%
Italy	34008.4	0.0	2472.8	36481.2	93.2%	0.0%	6.8%
Lithuania	16304.2	11266.4	296.9	27867.5	58.5%	40.4%	1.1%
Luxembourg	96728.5	0.0	1006.8	97735.4	99.0%	0.0%	1.0%
Latvia	14516.0	0.0	3119.3	17635.3	82.3%	0.0%	17.7%
North Macedonia	12666.0	0.0	1070.1	13736.1	92.2%	0.0%	7.8%
Netherlands	63691.0	682.7	772.9	65146.6	97.8%	1.0%	1.2%
Norway	36309.8	0.0	83431.4	119741.2	30.3%	0.0%	69.7%
Poland	25652.0	0.0	212.0	25864.0	99.2%	0.0%	0.8%
Portugal	25701.7	0.0	2761.0	28462.7	90.3%	0.0%	9.7%
Romania	17503.9	713.1	2163.4	20380.4	85.9%	3.5%	10.6%
Slovakia	29812.8	9354.9	2950.9	42118.6	70.8%	22.2%	7.0%
Slovenia	28390.8	7805.0	5038.7	41234.6	68.9%	18.9%	12.2%
Sweden	27955.5	21372.6	23391.9	72720.0	38.4%	29.4%	32.2%
Turkey	11517.4	0.0	1502.8	13020.2	88.5%	0.0%	11.5%
Ukraine	27234.8	4553.1	587.0	32374.9	84.1%	14.1%	1.8%

Table 2. Per Capita Energy Consumption of European Countries in 2022

Country	Fossil consumption per capita (kWh)	Per capita nuclear energy (kWh)	Renewable energy (kWh)	Total	Fossil rate	Nuclear rate	Renewable rate
Austria	27159.9	0.0	15210.7	42370.6	64.1%	0.0%	35.9%
Belgium	43711.6	9418.1	5713.4	58843.0	74.3%	16.0%	9.7%
Bulgaria	23545.3	6072.7	3899.3	33517.3	70.2%	18.1%	11.6%
Belarus	29259.1	1229.4	380.4	30868.8	94.8%	4.0%	1.2%
Switzerland	15619.0	6615.7	10748.8	32983.4	47.4%	20.1%	32.6%
Czechia	32759.7	7395.7	2894.4	43049.8	76.1%	17.2%	6.7%
Germany	31151.6	1041.6	8325.8	40519.0	76.9%	2.6%	20.5%
Denmark	19704.5	0.0	13363.4	33067.9	59.6%	0.0%	40.4%
Spain	23096.9	3082.1	6817.5	32996.5	70.0%	9.3%	20.7%
Estonia	41223.4	0.0	6372.3	47595.8	86.6%	0.0%	13.4%
Finland	25790.7	11439.9	19541.6	56772.1	45.4%	20.2%	34.4%
France	18967.5	11409.5	4567.9	34944.9	54.3%	32.6%	13.1%
United Kingdom	22270.8	1768.6	5524.6	29563.9	75.3%	6.0%	18.7%
Greece	24323.2	0.0	5667.6	29990.7	81.1%	0.0%	18.9%
Croatia	17103.0	0.0	5952.1	23055.1	74.2%	0.0%	25.8%
Hungary	20338.4	3968.8	2129.6	26436.8	76.9%	15.0%	8.1%
Ireland	29604.4	0.0	6902.4	36506.8	81.1%	0.0%	18.9%
Iceland	31408.0	0.0	138979.1	170387.1	18.4%	0.0%	81.6%
Italy	24294.4	0.0	4600.8	28895.2	84.1%	0.0%	15.9%
Lithuania	20133.8	0.0	3020.5	23154.3	87.0%	0.0%	13.0%
Luxembourg	53171.4	0.0	4395.3	57566.8	92.4%	0.0%	7.6%
Latvia	15091.7	0.0	5582.2	20673.9	73.0%	0.0%	27.0%
North Macedonia	12651.0	0.0	1979.0	14630.0	86.5%	0.0%	13.5%
Netherlands	45617.5	592.0	7497.7	53707.2	84.9%	1.1%	14.0%
Norway	28682.9	0.0	68610.0	97293.0	29.5%	0.0%	70.5%
Poland	26873.6	0.0	2577.3	29450.9	91.2%	0.0%	8.8%
Portugal	18013.1	0.0	7243.0	25256.1	71.3%	0.0%	28.7%
Romania	13507.9	1411.2	3150.2	18069.3	74.8%	7.8%	17.4%
Slovakia	21627.7	7057.5	2844.1	31529.3	68.6%	22.4%	9.0%
Slovenia	21175.5	6615.5	5083.4	32874.4	64.4%	20.1%	15.5%
Sweden	15088.2	12318.7	29873.1	57280.0	26.3%	21.5%	52.2%
Turkey	18837.5	0.0	4252.7	23090.3	81.6%	0.0%	18.4%
Ukraine	11113.4	3911.2	1234.4	16259.0	68.4%	24.1%	7.6%

Due to the large number of examined countries, a graphical representation of the clustering would not have been sufficiently informative. Therefore, deciles were applied based on the energy consumption structure. A country's energy consumption was moved into the next decile if it exceeded the upper threshold of the previous decile. Table 3 presents the energy consumption patterns of the European countries in 2002, classifying them into six clusters based on their share of fossil fuel, nuclear, and renewable energy consumption. Below, we provide a detailed description of each cluster's characteristics.

Cluster 1: Mixed-energy Use

This cluster included Austria, Czechia, Germany, Denmark, Spain, Estonia, Finland, the United Kingdom, Greece, Ireland, and Italy. While these countries had high fossil fuel consumption (6th–9th decile), they also utilized a significant share of renewable energy (4th–9th decile). Nuclear energy usage varied: Finland had exceptionally high levels (10th decile), whereas Austria and Denmark, for example, had lower levels (1st–5th decile). Their energy policies aimed for a balance, combining fossil fuels and renewable sources, with nuclear energy playing different roles across countries.

Cluster 2: Fossil and Nuclear Dominance

This cluster consisted of Belgium and the Netherlands, both of which had extremely high fossil fuel consumption (10th decile) and a significant share of nuclear energy (6th–10th decile). In contrast, the share of renewable energy was minimal (1st–2nd decile). Their energy structure was less diversified, primarily relying on fossil fuels and nuclear energy sources.

Cluster 3: Nuclear and Renewable Energy Dominance

Switzerland, France, Slovenia, Sweden, and Slovakia consumed moderate to low fossil energy consumption (3rd–6th decile) while heavily relying on nuclear (8th–10th decile) and renewable energy (7th–10th decile). Switzerland and Sweden exhibited particularly high values in both categories. Their strategy focused on reducing fossil energy dependence and prioritizing nuclear and renewable sources.

Cluster 4: Fossil Dominance with Low Diversification

Luxembourg fell into this cluster, as its energy consumption was largely dependent on fossil fuels (10th decile), while nuclear energy played a minor role (1st–5th decile), and the share of renewable energy was moderate (4th decile). The country’s energy supply was not highly diversified, relying primarily on fossil fuels.

Cluster 5: Low Fossil Energy Use with Varying Nuclear and Renewable Energy Consumption

Bulgaria, Belarus, Croatia, Hungary, Lithuania, Latvia, North Macedonia, Poland, Portugal, Romania, Ukraine, and Turkey have low fossil fuel energy consumption (1st–4th decile), whereas nuclear energy usage varies significantly across countries (1st–9th decile). The role of renewable energy was moderate, with Croatia showing particularly high values (8th decile). These countries are gradually reducing their dependence on fossil fuels while increasing their focus on renewable energy sources, leading to a continuous diversification of energy structures.

Cluster 6: Renewable Energy Focus

This cluster included Iceland and Norway, which had exceptionally high renewable energy consumption (10th decile) alongside moderate fossil fuel use (7th decile) and minimal nuclear energy utilization (1st–5th decile). Both countries were pioneers in integrating hydropower and geothermal energy, based their energy supply primarily on renewable sources.

Table 3. Per Capita Consumption Assessment by Country in Deciles in 2002

Cluster	Country	Fossil energy (decile)	Nuclear (decile)	Renewable (decile)
0	Austria	7	1–5	9
	Czechia	8	7	4
	Germany	9	8	4
	Denmark	8	1–5	8
	Spain	6	7	7
	Estonia	8	1–5	1
	Finland	9	10	9
	United Kingdom	8	6	3
	Greece	6	1–5	4
	Ireland	9	1–5	5
	Italy	8	1–5	6
2	Belgium	10	10	2
	Netherlands	10	6	1
3	Switzerland	3	10	9
	France	5	10	8
	Slovenia	5	8	8
	Sweden	6	10	10
	Slovakia	6	8	7
4	Luxembourg	10	1–5	4
5	Bulgaria	3	8	3
	Belarus	3	1–5	1
	Croatia	2	1–5	8

	Hungary	3	6	1
	Lithuania	2	9	2
	Latvia	1	1–5	6
	North Macedonia	2	1–5	5
	Poland	4	1–5	2
	Portugal	4	1–5	7
	Romania	2	6	6
	Ukraine	4	7	4
	Turkey	1	7	5
6	Iceland	7	1–5	10
	Norway	7	1–5	10

Table 4 presents clusters formed based on the energy consumption patterns of European countries for 2022. Each cluster reflects the energy source utilization strategy of the respective countries, which is influenced by geographical, economic, and environmental characteristics.

Cluster 1: Green Renewable Energy

This cluster includes only Iceland, which relies primarily on renewable energy sources. The energy supply is predominantly provided by geothermal energy (10th decile), while fossil energy plays only a supplementary role (9th decile). Nuclear energy is not utilized (1st–5th decile). Iceland is an example of how natural energy resources can help achieve sustainable energy independence.

Cluster 2: Fossil-Dominant Countries

Belgium, Estonia, Luxembourg, and the Netherlands belong to this cluster and are heavily dependent on fossil fuel energy (9th–10th decile). Belgium has significant nuclear energy use (9th decile), whereas other countries have lower levels (1st–6th decile). The share of renewable energy is minimal, and the energy mix is mainly based on fossil fuels and nuclear sources. The high reliance on fossil fuels poses challenges for achieving carbon neutrality, although increasing efforts are being made to integrate renewable energy sources.

Cluster 3: Renewable-Focused Countries

This cluster includes Norway, which primarily uses hydropower (10th decile) while also consuming fossil energy (8th decile), but nuclear energy plays a minimal role (1st–5th decile). Its energy strategy is built on natural resources, minimizes environmental impact, and serves as a model for renewable energy-based self-sufficiency.

Cluster 4: Dual-Energy Users

Finland and Sweden form this cluster, where nuclear energy plays a key role (10th decile), while renewable energy consumption is also high (9th–10th decile). The share of fossil fuel energy is low, especially in Sweden (2nd decile). These countries integrate the stability of nuclear energy with the sustainability of renewable energy in their energy mix.

Cluster 5: Low-Energy Consumers

Croatia, Latvia, North Macedonia, Romania, and Ukraine are part of this cluster, with low-energy consumption from both fossil and renewable sources (1st–3rd decile). The role of nuclear energy varies: Romania and Ukraine rely on it moderately, whereas it is barely present in other countries. These countries are less energy-intensive, reflecting their economic structure and level of industrial development. Their low-energy consumption ensures a stable energy mix without a dominant energy source.

Cluster 6: Mixed-Energy Users

This cluster includes Austria, Bulgaria, Switzerland, Czechia, Germany, Spain, France, the United Kingdom, Hungary, Italy, and Turkey. These countries rely on fossil fuel energy to a moderate or high degree (3rd–9th decile), while their nuclear energy use varies—France uses it heavily, whereas it is barely present in others. The role of renewable energy also spans a wide range (1st–9th decile). These countries strive to achieve a balanced energy mix by adapting to economic and environmental challenges.

Table 4. Per Capita Consumption Assessment by Country with Deciles in 2022

Cluster	Country	Fossil energy (decile)	Nuclear (decile)	Renewable (decile)
1	Iceland	9	1–5	10
2	Belgium	10	9	6
	Estonia	9	1–5	7
	Luxembourg	10	1–5	4
	Netherlands	10	6	8
3	Norway	8	1–5	10
4	Finland	7	10	9
	Sweden	2	10	10
5	Croatia	3	1–5	6
	Latvia	2	1–5	6
	North Macedonia	1	1–5	1
	Romania	1	6	3
	Ukraine	1	7	1
6	Austria	7	1–5	9
	Bulgaria	6	8	3
	Belarus	8	6	1
	Switzerland	2	8	8
	Czechia	9	9	3
	Germany	8	6	8
	Denmark	4	1–5	9
	Spain	6	7	7
	France	3	10	4
	United Kingdom	5	7	5
	Greece	6	1–5	6
	Hungary	4	8	2
	Ireland	8	1–5	7
	Italy	6	1–5	5
	Lithuania	4	1–5	3
	Poland	7	1–5	2
	Portugal	3	1–5	8
	Slovakia	5	9	2
	Slovenia	5	8	5
	Turkey	3	1–5	4

The results indicate that the energy consumption structures of certain countries follow similar patterns, supporting our first hypothesis.

4-2- Changes

The energy consumption structures of European countries underwent significant transformations between 2002 and 2022, primarily characterized by a decline in fossil energy use and the increasing share of renewable energy sources. Based on 2022 data, we analyze the energy transition that has taken place in selected countries from each cluster, with a particular focus on the expansion of renewable energy sources.

Austria (Cluster 6) significantly reduced its fossil fuel consumption while increasing its share of renewable energy, which aligns with its energy policy strategy, which primarily relies on hydropower. The country does not use nuclear energy, a decision influenced by anti-nuclear public opinion, policy choices, and a commitment to sustainability [25]. Hydropower has a long history in Austria and remains a key component of energy supply, whereas biomass and solar energy are becoming increasingly important [26]. The Austrian National Energy and Climate Plan (NECP) promotes renewable energy investments in conjunction with sustainable urban planning to facilitate the development of low-carbon energy systems [27].

Norway (Cluster 3) continues to base its energy structure on renewable energy sources, particularly hydropower, which accounts for more than 90% of the country's electricity production [28]. The country's sustainability policies and carbon neutrality goals have driven renewable energy development [29]. Hydropower is not only the backbone of the domestic energy supply but also plays a crucial role in stabilizing the European energy market by integrating variable-output wind and solar power [30]. The Norwegian government remains committed to further developing hydropower and supporting the integration of European electricity networks, thereby enabling energy exports [31]. However, energy policy decisions are influenced by sustainability considerations and economic, political, and national interests [29].

Romania (Cluster 5) has significantly reduced its share of fossil fuels while increasing the use of renewable energy sources, particularly hydropower and biomass. The alignment with the EU's climate policy has facilitated the promotion of sustainable energy production and the reduction of carbon emissions [32]. Hydropower remains the country's most important renewable energy source [33], while biomass—leveraging Romania's extensive forested areas—contributes to energy diversification and reduces import dependence [34]. EU support programs have enabled the development of solar and windfarms, accelerating the expansion of renewable energy infrastructure [35]. Additionally, modernizing energy systems and developing energy storage solutions play crucial roles in the stable integration of renewable energy sources [36].

Belgium (Cluster 2) has gradually reduced its use of fossil fuels in recent years and initiated the phase-out of nuclear energy. However, the timing of this process remains a subject of ongoing political and energy debates. The nuclear phase-out plan for 2015–2025 aimed at the gradual closure of seven nuclear power plants; however, the government has repeatedly adjusted the schedule to ensure energy security [37]. The expansion of renewable energy has been driven primarily by investments in solar and wind power plants, with the aim of diversifying energy supply and meeting EU sustainability targets [38]. Although Belgium has significantly increased its solar and wind energy capacity, these have not fully offset the reduction in nuclear energy, raising challenges for the country's energy security. However, the continuous development of new windfarms and solar energy infrastructure may reduce the country's dependence on fossil and nuclear energy in the long term [39].

Finland (Cluster 4) has made significant progress in reducing fossil energy use while increasing the application of nuclear and renewable energy sources. With the commissioning of the Olkiluoto 3 reactor, the country's nuclear capacity has increased, contributing to its energy security and carbon neutrality goals [40]. In the field of renewable energy, Finland has become one of the largest users of forestry biomass, which accounts for a significant portion of the country's energy consumption [41]. In addition to biomass, the rapid development of wind energy has played a key role in establishing sustainable energy systems [42]. The Finnish government aims to completely phase out coal energy by 2029 while ensuring supply stability and energy independence through a combination of nuclear power and renewable energy [43].

Iceland's energy mix is almost entirely based on renewable energy sources, primarily geothermal and hydropower. Renewable energy sources provide 85% of the country's energy supply, with 66% from hydropower and 19% from geothermal energy [44]. The country is carbon-neutral and aims to achieve full carbon neutrality by 2040 [45]. Its industry and households operate almost exclusively on renewable energy, thereby strengthening energy independence and providing economic benefits [46]. Geothermal energy plays a crucial role in not only electricity generation but also heating systems and industrial applications [47]. Iceland is also focusing on greening the transportation sector, where replacing fossil fuels remains a challenge. Hydrogen and green methanol production using geothermal energy is already underway, thereby supporting sustainable transport [48]. Iceland's renewable energy policy is exemplary and can serve as an inspiration for other countries.

Reducing the use of conventional energy sources is not only important from an environmental perspective but also to decrease the Visegrád countries' dependence on Russian energy sources [49].

We examined the relationship between per capita GDP (at current prices), total energy consumption, and renewable energy use. Based on the data, an exponential correlation proved to be the most appropriate. The inadequate linear relationship is illustrated in Figures 2 and 3. We identified five outliers. In the cases of Iceland and Norway, the total energy consumption and energy derived from renewable sources were exceptionally high (Figures 1 and 2). This is due to their geographical location and the increased energy demand caused by low temperatures. Switzerland, Luxembourg, and Ireland also deviated from the trend line, as these countries exhibited lower energy consumption than expected based on their GDP. This trend is a result of social consensus and political decisions favoring the dominance of energy-efficient economic sectors.

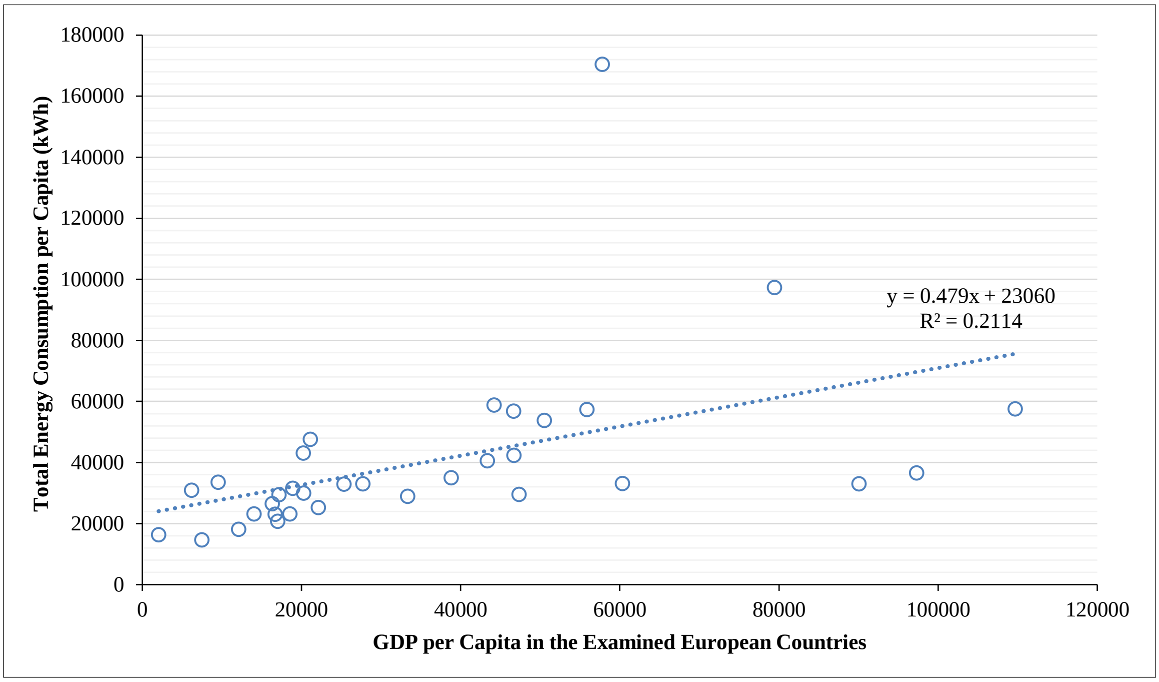

Figure 2. **Total Energy Consumption of the Entire Sample (2022, linear)**

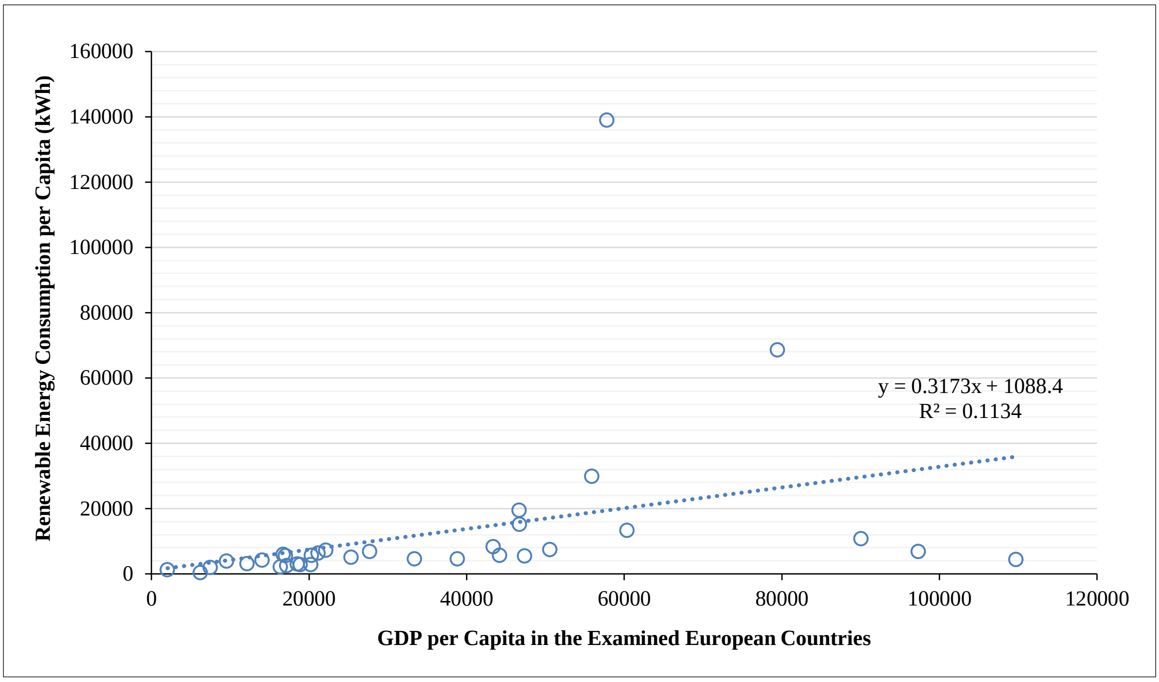

Figure 3. **Renewable Energy Consumption of the Entire Sample (2022, linear)**

Iceland and Norway have exceptionally high energy consumption relative to their GDP, which can be explained by their cold climate and energy-intensive industries (e.g., aluminum smelting, oil and gas extraction).

In contrast, Luxembourg, Switzerland, and Ireland are primarily based on the service sector, which requires less energy. Advanced technologies and strict environmental regulations contribute to increased energy efficiency.

Figures 4 and 5 illustrate the exponential correlation, excluding countries that, due to their high GDP, shape their energy consumption in ways that prioritize national interests. As a result, our second and third hypotheses are confirmed.

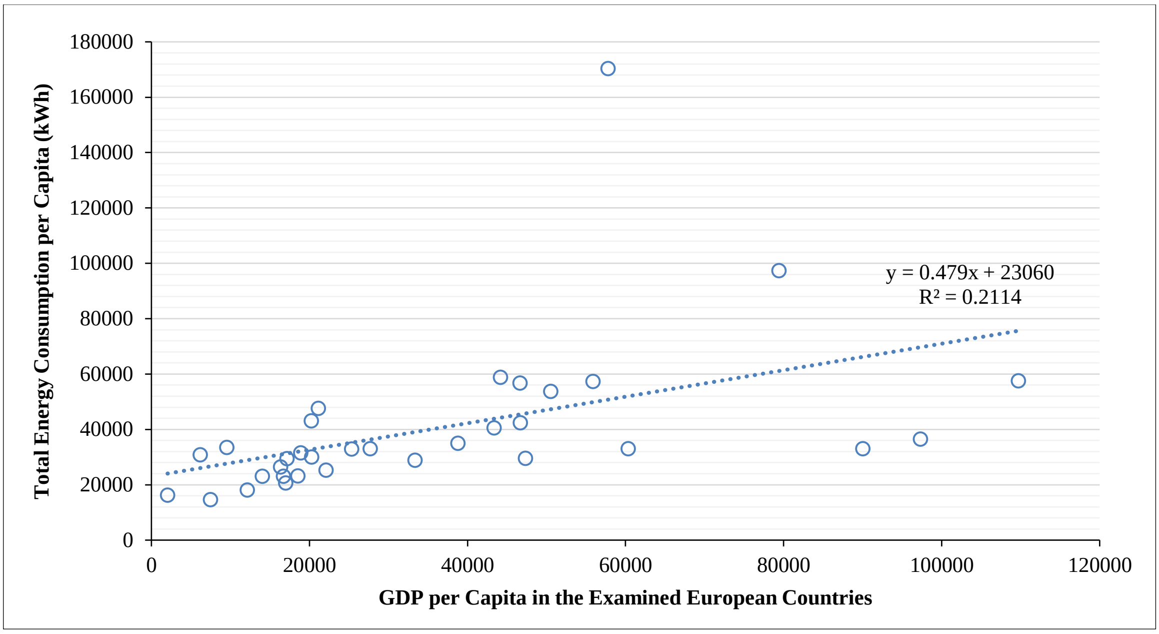

Figure 4. **Total Energy Consumption Without Outliers (2022, exponential.)**

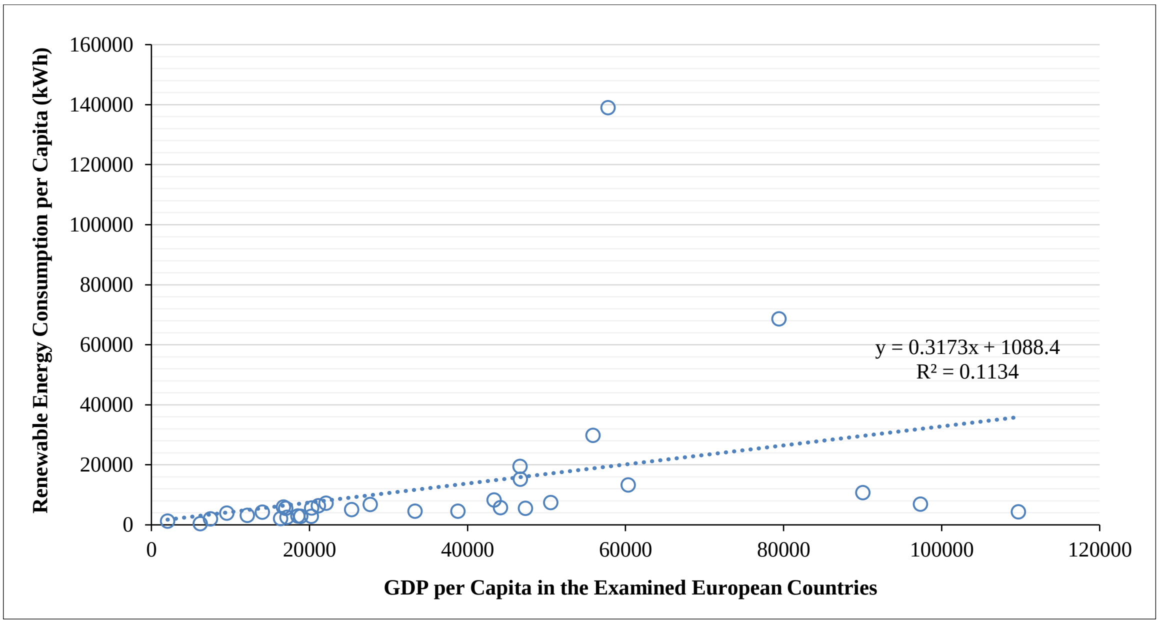

Figure 5. **Renewable Energy Consumption Without Outliers (2022, exponential.)**

Our fourth hypothesis was validated based on the equations presented in Figures 3 and 4 (y = 20381e2E-05x and y = 1582.2e4E-05x). These models were tested and found to be statistically significant ($p < 0.01$). Thus, in countries with low and medium GDPs, economic growth increases renewable energy consumption to a greater extent than total energy consumption.

5- Discussion

Numerous studies in the literature confirm that energy transition involves high investment costs, infrastructural barriers, and geopolitical factors, yet it is essential for developing sustainable energy systems [20]. The transition is influenced by technological, social, and economic factors such as population growth, urbanization, and increasing energy demand [50]. Countries operate in different political and economic environments, which impact energy supply decentralization and new technology adoption [51].

According to the Environmental Kuznets Curve (EKC) theory, industrialization initially increases pollution in the early stages of economic growth, but later, cleaner technologies and stricter environmental regulations reduce pollution levels. However, research suggests that without targeted renewable energy policies, carbon dioxide emissions will continue to rise [16]. The example of Germany's energy transition confirms that targeted renewable energy policies can reduce dependence on fossil fuels and enhance energy independence [15]. In addition, social support and consumer attitudes play crucial roles in energy policy decision-making [52].

Clustering energy consumption helps map national energy strategies and track progress in energy transition. The adoption of renewable technologies has progressed at different rates, thus influencing regional energy policies [53]. Advanced clustering methods have been proposed for identifying electricity consumption patterns. Effective government interventions facilitate the expansion of renewable energy sources [19]. The use of renewable energy is increasing in developing countries [54], whereas European companies are taking on an increasingly significant role in this sector [55].

European countries have reduced their reliance on fossil fuels and increased their share of renewable energy. However, differences persist due to regulatory environments, financial conditions, and the availability of energy resources [55]. The cluster analysis revealed six distinct patterns of energy consumption across European countries, based on per capita fossil fuel, nuclear, and renewable energy use. These clusters highlighted key differences not only in the energy mix but also in the economic structure and policy environments [56]. High-GDP countries, such as Luxembourg, Switzerland, and Ireland, significantly deviated from the general energy–GDP trend, which is largely attributable to their low-energy service-oriented economies and the implementation of robust energy efficiency policies [57]. In particular, Norway's long-standing hydropower infrastructure and Belgium's nuclear phase-out strategy were important national drivers behind shifts in cluster membership [58]. The results also confirm that countries with targeted environmental policies and innovation subsidies tend to move toward more renewable-dominant clusters over time. For instance, Austria's NECP has supported solar and wind development, contributing to its evolving energy profile [59]. Additionally, Romania's transition from fossil fuels to renewable energy highlights how Central and Eastern European countries can realign their energy strategies in line with EU directives and funding mechanisms [60].

The expansion of the circular economy also supports the development of stable and resource-efficient energy management systems, particularly in sectors where long-term technological reliability is crucial. In agriculture, for example, improved yield stability and system performance are closely linked to the reuse and optimization of inputs, which aligns with circular economy principles [61]. Moreover, the successful application of circular approaches depends on not only technological or policy innovation but also the integrity of the supporting scientific knowledge base. As Dadkhah et al. [62] highlighted, the spread of unreliable or hijacked publications poses a serious threat to evidence-based policymaking, potentially undermining innovation in renewable energy and circular solutions. Therefore, strengthening both circular practices and scientific transparency is essential for advancing low-carbon, resilient energy systems.

6- Conclusion

The identification of cluster-based patterns provides a strong foundation for region-specific energy transition strategies and cross-country policy learning, particularly among countries belonging to the same cluster. The identification of cluster-based patterns provides a strong foundation for region-specific energy transition strategies and cross-country policy learning, particularly among countries belonging to the same cluster. The energy consumption patterns of the examined countries indicate that economic growth does not necessarily correlate with a proportional increase in energy consumption. The examples of Luxembourg, Switzerland, and Ireland demonstrate that a knowledge-based, low-energy-intensive economic structure can achieve sustainable GDP growth. However, the reduction of energy consumption, diversification of energy sources, and improvement of energy efficiency are crucial for sustainability.

From a practical perspective, policymakers should closely monitor countries with similar economic and energy policy patterns because their experiences can contribute to the development of effective energy management strategies. Regional cooperation can facilitate the promotion of energy independence and sustainability for states within the same cluster. A limitation of our research is that we did not examine the structure of energy production but only the relationship between energy consumption and GDP. A comprehensive assessment of energy security and sustainability requires considering import dependency and energy infrastructure, highlighting the need for further research in this field.

Recent policy developments reflect the EU's dual objectives of energy resilience and climate neutrality. The EU's 2050 long-term strategy places emphasis on investing in renewable energy and efficiency as the cornerstones of a low-carbon future [63]. To support this transformation, the Clean Industrial Deal proposes €100 billion in public-private financing to enhance the competitiveness of clean technologies and reduce energy bills [64]. In addition, Wang et al. [58] highlight the growing geopolitical risks that threaten energy security and urge policymakers to integrate green innovation as a resilience strategy. Similarly, Rastegar et al. [65] stressed that environmental policy and subsidies are key drivers of renewable energy innovation, especially in regions where fossil fuel dependence is still high. Therefore, future energy policies must strive for balance: ensuring supply security while reducing environmental impact and accelerating the transition to a low-carbon economy. This calls for coordinated actions, shared innovations, and mutual learning across national borders to develop more resilient and sustainable energy systems.

7- Declarations

7-1- Author Contributions

Conceptualization, S.J. and B.G.K.; methodology, S.J. and K.S.A.; software, S.J. and L.D.D.; formal analysis, S.J. and K.S.A.; investigation, S.J., S.M.S., D.P.S., K.S.A., and B.G.K.; resources, S.M.S., D.P.S., N.P.N., and L.D.D.; data curation, S.J. and B.G.K.; writing—original draft preparation, S.J. and K.S.A.; writing—review and editing, S.J., S.M.S., D.P.S., K.S.A., N.P.N., B.G.K., and L.D.D.; visualization, S.J., S.M.S., and L.D.D.; supervision, S.M.S. and N.P.N.; project administration, S.M.S. and N.P.N.; funding acquisition, N.P.N. All authors have read and agreed to the published version of the manuscript.

7-2- Data Availability Statement

The data presented in this study are available on request from the corresponding author.

7-3- Funding and Acknowledgments

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7-4- Institutional Review Board Statement

Not applicable.

7-5- Informed Consent Statement

Informed consent was obtained from all subjects involved in the study.

7-6- Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancies have been completely observed by the authors.

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