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Clustering analysis of energy consumption data in EU regions and other countries of the world

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Abstract

This study aims to analyze energy consumption patterns across selected nations from Africa, America, Asia/Middle East, and Europe, with a focus on the types of energy sources used. Covering 46 countries, the research spans the years 2000 to 2018 and examines the distribution and changes in energy consumption by source and type. The regions studied include diverse countries such as Austria, Sweden, Czechia, and Croatia in Europe; Algeria, Egypt, and South Africa in Africa; China, India, and Saudi Arabia in Asia/Middle East; and Brazil, Canada, and the United States in the Americas, with Australia and New Zealand representing Oceania.

Utilizing data from the BP Statistical Review of World Energy and the SHIFT Data Portal, along with key indicators maintained by Our World in Data, the study employs methods such as descriptive statistics, cluster analysis using k-means, and time-series clustering with dynamic time warping (DTW). The analysis highlights regional similarities and variances in energy use, providing new insights into the complex relationship between energy consumption patterns and factors such as economic growth, national policies, and geopolitical contexts.

This research addresses a significant gap in the existing literature by offering a detailed comparative analysis of how different nations manage and consume energy. It contributes to the broader discourse on sustainable energy policies and economic development in the face of global energy challenges.

Keywords: energy, clustering, energy consumption, energy policy, sustainable energy, clustering analysis, k-means, dynamic time warping, energy production, EU, economic development, energy efficiency, comparative analysis

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1. Introduction

Energy is fundamental to all societal activities, driving sectors such as transportation, agriculture, and various industries. Despite the critical reliance on energy, there remains a significant dependency on non-renewable sources, making effective power management increasingly essential. Different nations consume varying amounts of energy, with regional cooperation and policy-driven efforts towards energy convergence showing mixed success [1-3, 6-10].

In pursuit of sustainable development, countries worldwide are focusing on reducing emissions and enhancing energy efficiency. However, the adoption of cleaner, less harmful energy sources like renewables varies significantly due to factors like industry structure, technological advancement, and economic maturity [11-16]. Developing countries often follow the developmental footsteps of their developed counterparts but frequently lag in incorporating energy efficiency into their growth models [17-20].

1.1 Problem statement

While existing academic literature extensively covers the relationship between economic growth and energy consumption, it sparsely addresses the dynamics between a nation's economic development stage and its adoption of various energy sources such as fossil fuels, nuclear energy, and renewables. This research gap is notable, particularly in studies encompassing a diverse range of countries [21-26].

1.2 Aims and objectives

This thesis aims to analyze the energy mix consumed across selected nations and years, focusing on nuclear, fossil, and renewable energy sources based on the following objectives:

- Classify countries into clusters based on their energy source consumption (fossil, nuclear, renewables).
- Delineate the characteristics of each cluster.
- Explore the similarities in energy consumption patterns across countries within each cluster, segmented by source and year.

1.3 Scope of work

The scope of this thesis encompasses an analysis of energy consumption in 44 countries from 2000 to 2018. The selected countries include:

- Europe: Austria, Belgium, Czechia, Croatia, Denmark, Finland, France, Germany, Greece, Italy, Ireland, Latvia, Luxembourg, Netherlands, Norway, Poland, Romania, Hungary, Slovakia, Slovenia, Sweden, Switzerland, Russia, Ukraine, and the United Kingdom.
- Africa: Algeria, Egypt, South Africa.
- Middle East/Asia: China, India, Iran, Indonesia, Japan, Kuwait, Saudi Arabia, Turkey, Qatar.
- Americas: Brazil, Canada, Mexico, United States.
- Oceania: Australia, New Zealand.

2. Literature review

2.1 Economic growth and energy consumption

The interrelationship between economic growth and energy use is critical in assessing a nation's developmental trajectory. Many studies underscore that as economies grow, their energy requirements evolve, reflecting changes in industry structures and technological advancements. Acaravci and Ozturk [27] found a direct correlation between GDP growth, energy consumption, and CO_2 emissions across 19 European countries, suggesting that economic development stages significantly influence energy use patterns.

2.2 Sectoral energy consumption trends

The consumption of energy varies significantly across different sectors, influenced largely by the GDP per capita. Judson et al. [28] highlighted that in Western European countries, GDP per capita has a prolonged relationship with energy consumption, particularly in major industrial sectors. Such trends indicate that as technology progresses, the industrial demand for energy decreases, peaking during early development stages and diminishing as advancements stabilize. This transition underscores a shift towards sustainability as sectors evolve to incorporate more efficient energy use practices.

2.3 Technological advancements and structural changes

Technological advancements and structural changes within economies play a pivotal role in modulating energy intensity. Studies by Ma and Stern [30] on China and by Mulder and de Groot [8] across OECD countries illustrate that technological progress leads to reduced energy intensity over time. However, these improvements are not uniform across all sectors or regions, with significant variations influenced by each country's specific economic and industrial conditions.

2.4 Global trends in energy transition

The global shift towards low-carbon energy is shaped by both regional and international policies, including commitments under the Paris Agreement. The transition process is complex, influenced by economic, structural, and environmental factors unique to each region. Innovative analytical methods like the k-means clustering technique have been refined to address these variations, allowing for a nuanced understanding of regional energy consumption patterns [34-36].

2.5 Challenges in energy clustering and analysis

Despite advancements in clustering algorithms, such as the development of the Seeded-k-means and MinMax k-means, significant challenges remain, particularly in the temporal complexity and accuracy of data categorization [37, 38]. These challenges highlight the need for ongoing research to refine data integration techniques and improve the reliability of energy consumption analyses.

3. Methodology

This section details the methods and materials used for analyzing the energy consumption patterns among various nations from 2000 to 2018.

3.1 Overview of energy data

The data for this study was sourced from the BP Statistical Review of World Energy, SHIFT Data Portal, and key indicators maintained by Our World in Data. These sources provide a consistent methodological framework, allowing for comparable energy consumption analyses across different states. For clarity in presentation, state names were abbreviated in all graphical data representations.

3.2 K-means clustering

K-means clustering, a well-known unsupervised learning algorithm, was employed to analyze energy consumption by source (fossil, nuclear, and renewable) for all nations in 2018. This method is widely used in data analytics for clustering large datasets and is particularly effective due to its simplicity and efficiency. The algorithm organizes the dataset into a predetermined number of clusters K, aiming to minimize the within-cluster sum of squares, which is the sum of squared distances between items and the corresponding centroid [33, 36].

Formula:

$$min \sum_{j=1}^{K} \sum_{\substack{i:x_i \\ \text{is assigned to } j}} d(x_i, \mu_j) = min \sum_{j=1}^{K} \sum_{i=1}^{n} a_{i,j} \, ||x_i - \mu_j||^2$$

where: $a_{i,j}$ *is a binary coefficient that, depending on cluster assignment, can have a value of one or zero.*

3.3 Descriptive analysis of clusters

Following the clustering, a descriptive analysis was conducted to examine the proportion of energy used by the source within each cluster. This analysis provided insights into the typical energy consumption patterns by source for the nations within each cluster, highlighting significant trends and deviations.

3.4 Time series clustering

The third phase of the study utilized dynamic time warping (DTW) to analyze the time series of global energy consumption by source from 2000 to 2018. DTW is advantageous for time series data as it can accurately measure similarities between sequences that may vary in time or speed. Unlike simple Euclidean distances, DTW can align sequences that are similar but out of phase, and thus provide a more accurate measure of similarity between time-varying data.

Formula:

$$DTW(X,Y) = W_{min} \sum_{l=1}^{k} w_l, w_l \in W$$

where: $w_{i,l}$ is the element of the optimal warping path between two time series X and Y and k is the length of the path

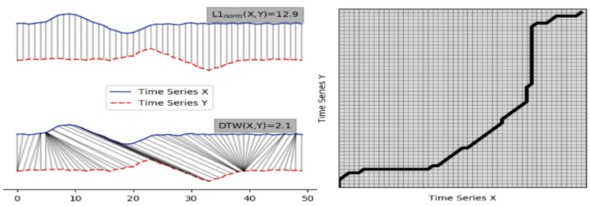

Figure 1: In (a), the DTW distance and L1-norm distance for the time series X and Y are shown. In (b), the ideal warping path selected by DTW is shown.

4. Results and discussion

This section elaborates on the findings from the data analysis and discusses the implications within the context of global energy consumption trends.

4.1 Descriptive analysis (2000 - 2018)

The analysis began with a Pearson correlation coefficient calculation to determine the relationships between energy consumption per capita, GDP, and population across various nations from 2000 to 2022. Notable patterns emerged from the data, revealing significant variability in how changes in population and GDP impact energy consumption. For instance, while countries like India and Algeria showed a very high positive correlation (above 0.98), indicating that increases in population correspond with increases in energy consumption, countries such as the United Kingdom and France exhibited strong negative correlations, suggesting that energy consumption per capita decreased as population increased.

- Positive correlations: In countries with rapidly growing economies and populations such as India and China, energy consumption has increased alongside these factors.
- Negative correlations: Conversely, in many developed countries, increases in population have not corresponded with increases in per capita energy consumption, possibly reflecting more efficient energy use or demographic trends like aging populations.

Figures 2a and b illustrate these trends across selected countries, highlighting the diverse energy consumption patterns that challenge uniform policy application across different regions.

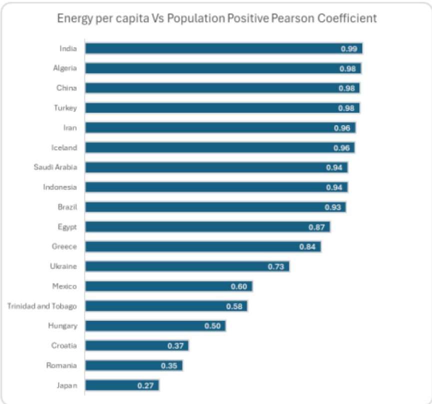

Figure 2a: Positive Pearson correlation between population and energy consumption per capita by country

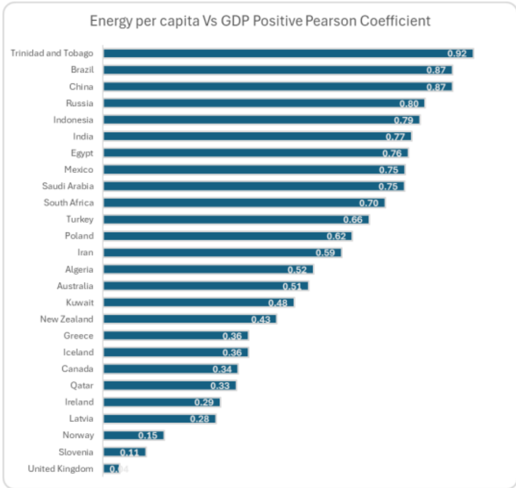

Figure 3a: Positive Pearson correlation between GDP and energy consumption per capita by country

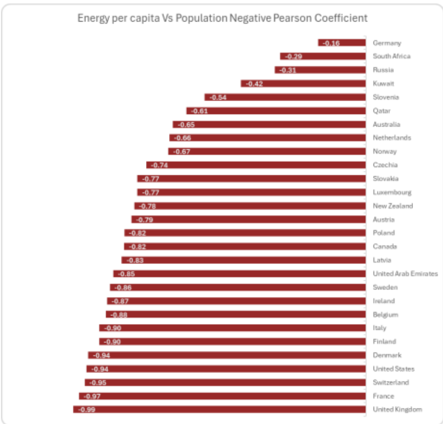

Figure 2b: Negative Pearson correlation between population and energy consumption per capita by country

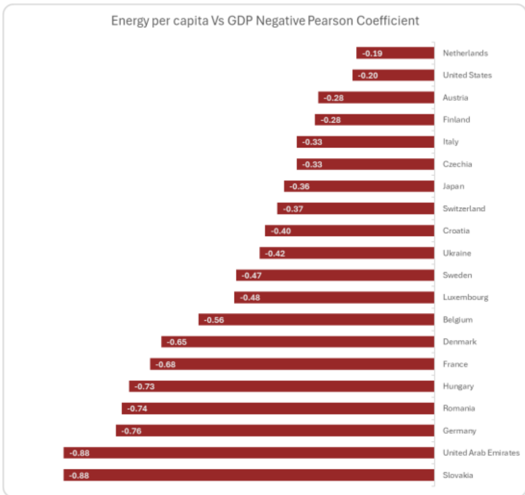

Figure 3b: Negative Pearson correlation between GDP and energy consumption per capita by country

Figures 3a and 3b present the correlations between GDP and energy consumption, illustrating how economic growth interfaces with energy use

4.2 Energy mix clustering (2018)

The aim is to classify countries into distinct clusters based on their energy consumption patterns. This categorization helps in identifying groups of countries that have similar energy usage profiles, which can be crucial for comparative analysis and policy formulation. Using the k-means clustering algorithm, countries were grouped based on their proportionate consumption of fossil fuels, nuclear energy, and renewables in 2018. This unsupervised learning technique identifies centroids within a dataset and assigns each data point (in this case, a country) to the nearest cluster, based on Euclidean distance.

4.2.1 Exploratory analysis

- Data preparation: The dataset included the percentage share of fossil, nuclear, and renewable energy consumption for each country. Data cleaning was performed to handle any inconsistencies or missing values.
- Cluster formation: The number of clusters was determined using the elbow method, which helps to identify the point where adding another cluster does not significantly improve the variance explained by the clusters.

4.2.2 Cluster formation and characteristics

Using the k-means clustering algorithm, the 2018 data on energy consumption by source was analyzed to identify groups of countries with similar energy profiles. Five distinct clusters were identified, demonstrating varied reliance on fossil fuels, nuclear power, and renewable energy sources:

- Cluster 0 and Cluster 3: Dominated by countries with high fossil fuel consumption, these clusters represent nations where fossil energy remains the predominant source. Specifically, Cluster 0 shows an overwhelming 96.6% reliance on fossil fuels, while Cluster 3 has a slightly lower dependence at 82.2%. These clusters underscore the ongoing reliance on traditional energy forms in many parts of the world.
- Cluster 1: This cluster includes Finland, France, Sweden, Slovakia, and Switzerland—countries known for their balanced energy mix. Fossil fuels account for 51.12% of energy use, with significant contributions from both nuclear (24%) and renewable sources (25%). This group exemplifies a transition phase towards more sustainable energy sources while maintaining a strong base in nuclear energy.
- Cluster 2 (Island and Norway): Notably distinct, this cluster is characterized by its high renewable energy usage, accounting for 72.7% of its total energy consumption. Its geographic and socio-economic characteristics make it unique, hence termed an "outlier" cluster. The prominence of renewable energy in this cluster is indicative of successful policy implementations and a strong commitment to sustainable energy practices.
- Cluster 4: Contains countries with a moderate mix of all energy sources, with no single source overwhelmingly dominant. This cluster highlights a transition in energy

practices, with renewable energy making up a significant 32% of the mix.

4.2.3 Detailed analysis of cluster dynamics

Table 1: Average values of individual clusters across energy mix

Variable	Clusters				
	0	1	2	3	4
Fossil Energy Consumption	97%	51%	27%	82%	67%
Nuclear Energy Consumption	0%	24%	0%	7%	1%
Renewable Energy Consumption	3%	25%	73%	11%	32%

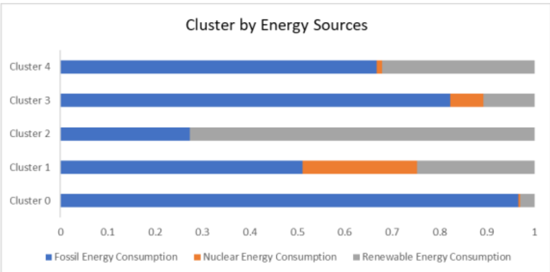

Figure 4: Average values for each cluster, based on the energy mix (2018)

Table 1 and Figure 4 above provides a breakdown of the average energy consumption by source for each cluster, illustrating the diversity within the clusters:

- Fossil energy consumption: Ranges from a high of 97% in Cluster 0 to a low of 27% in Cluster 2.
- Nuclear energy consumption: Cluster 1 stands out with a 24% contribution from nuclear energy, the highest among all clusters.
- Renewable energy consumption: Cluster 2 leads with 73%, highlighting its heavy investment in renewable resources.

4.2.4 Implications and insights

This clustering reveals significant insights into global energy consumption patterns:

- **Policy and economic implications**: The varied clustering indicates that while some countries are advancing towards more sustainable practices (Clusters 1 and 2), others remain heavily dependent on fossil fuels (Clusters 0 and 3). This disparity suggests the need for tailored policy approaches that consider each cluster's unique characteristics and challenges.
- **Technological and environmental impact**: Clusters with higher renewable usage can serve as benchmarks for technological innovation and environmental sustainability. In contrast, fossil fuel-dominated clusters may require more aggressive interventions to transition towards greener alternatives.
- **Future projections and strategy development**: Understanding these clusters helps predict future trends and develop strategies that align with both national and global energy goals. It can also facilitate more targeted international cooperation and support, especially for countries in clusters transitioning towards sustainable energy.

4.3 Time-series clustering (DTW)

This section conducts a time-series clustering analysis from 2000 to 2018 to identify consistent historical patterns in energy usage, breaking down the results for fossil, nuclear, and renewable energy sources. The focus here is on fossil energy consumption per capita.

4.3.1 Fossil energy consumption per capita clustering analysis

Methodology and clustering execution

Using the elbow method, an optimal cluster number was determined for analyzing the fossil fuel consumption per capita across the studied period. The k-means clustering algorithm, which seeks to minimize within-cluster variances, identified five distinct clusters. This process, illustrated in Figure 5, shows the sum of squared distances for different numbers of clusters, supporting the decision for five clusters as most effective for representing the data without unnecessary complexity.

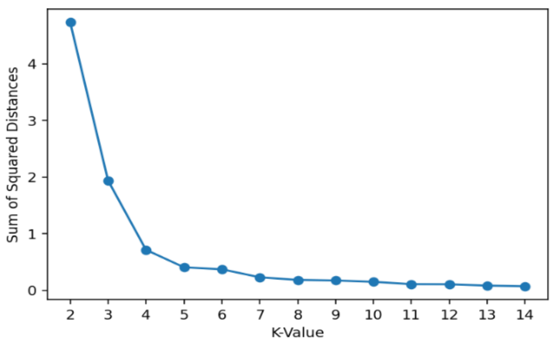

Figure 5: The sum of squared distance for different number of clusters (Fossil DTW)

Cluster descriptions and dynamics

- **Cluster 0 (moderate stability):** Comprising Brazil, France, and Switzerland, this cluster exhibits moderate fossil fuel dependency with a slight decrease over the period, maintaining average consumption around 52%. This indicates a gradual transition away from fossil fuels, aligning with global sustainability trends.

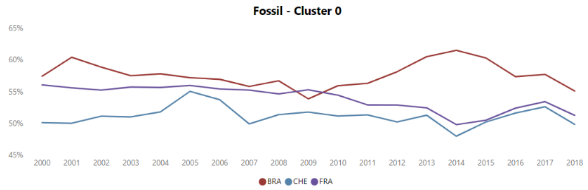

Figure 6a: Countries in Cluster 0 (Fossil DTW)

- **Cluster 1 (high dependency reduction):** Including countries like Australia, Ireland, and Greece, this cluster initially had the highest per-capita fossil fuel usage, around 97%. Notably, these countries have made significant reductions in fossil fuel dependency, demonstrating effective energy transition policies.

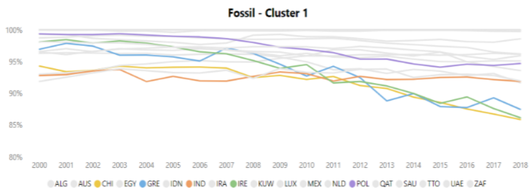

Figure 6b: Countries in Cluster 1 (Fossil DTW)

- **Cluster 2 (significant reductions):** Featuring Denmark and Italy, this cluster started with high fossil consumption but saw substantial reductions. Denmark, for example, reduced its fossil dependency from 93% in 2000 to 73% in

2018, a reflection of aggressive national policies toward a fossil-free future.

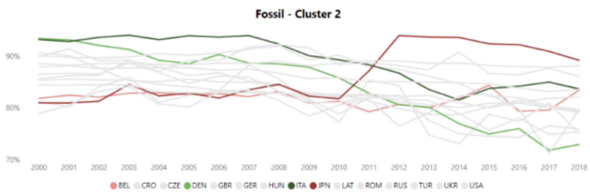

Figure 6c: Countries in Cluster 2 (Fossil DTW)

- **Cluster 3 (gradual reduction):** Countries in this cluster, including Finland, New Zealand, and Austria, have moderately decreased their fossil fuel consumption, with most changes being incremental over the years.

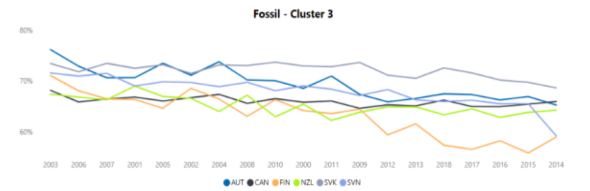

Figure 6d: Countries in Cluster 3 (Fossil DTW)

- **Cluster 4 (Scandinavian success):** Consisting solely of Scandinavian countries—Iceland, Norway, and Sweden—this cluster has the lowest and most rapidly declining fossil energy consumption, emphasizing the region's leadership in sustainable energy usage.

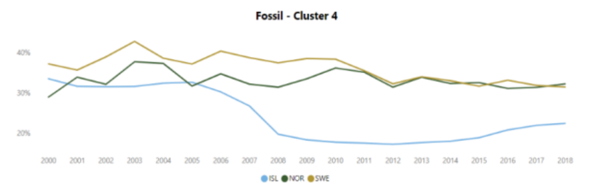

Figure 6e: Countries in Cluster 4 (Fossil DTW)

Figures 6a-6e and Figure 7 provide detailed visual and quantitative insights into these clusters, showcasing the trajectory of fossil energy consumption changes over the years. Each figure corresponds to a specific cluster, depicting the geographical distribution and specific energy consumption profiles.

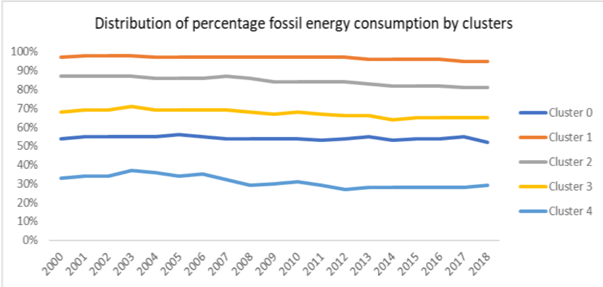

Figure 7: Graphical representation of the average values of individual clusters (Fossil DTW)

Discussion of findings

The clustering analysis reveals significant variances in how different countries manage and adapt their fossil fuel consumption strategies. The data illustrates a clear trend towards reduced reliance on fossil fuels, particularly in countries with stringent environmental policies and high societal engagement in sustainability goals.

Implications for policy and practice

- The results from Cluster 1 and Cluster 2 are particularly instructive for countries still heavily reliant on fossil fuels, showing that substantial reductions are achievable with robust policy frameworks and public engagement.
- Cluster 4's success underscores the potential impact of comprehensive, community-supported renewable energy initiatives, which could serve as a model for other regions aiming to decrease their fossil fuel dependence.

4.3.2 Nuclear energy consumption per capita clustering analysis

Methodology and clustering execution

The nuclear energy consumption per capita was analyzed using the elbow method to identify the optimal number of clusters, with results indicating that five clusters would provide the most meaningful segmentation. This clustering choice, based on the k-means algorithm, ensures that the selected clusters capture significant variations in nuclear energy consumption patterns among the nations studied, as confirmed by the absence of negative values in the sum of squared distances, depicted in Figure 12 below.

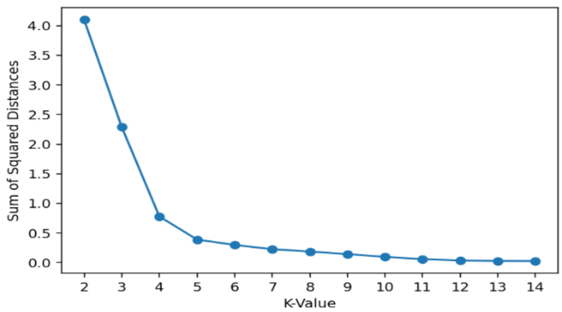

Figure 8: The sum of squared distance for different number of clusters (Nuclear DTW)

Cluster descriptions and dynamics

- **Cluster 0 (low nuclear utilization):** This cluster comprises countries like Brazil, China, India, Mexico, the Netherlands, and South Africa, which have relatively low nuclear energy consumption, averaging 1.3% per capita. These countries have generally maintained or slightly adjusted their nuclear energy shares, reflecting a cautious or strategic approach to nuclear energy utilization.

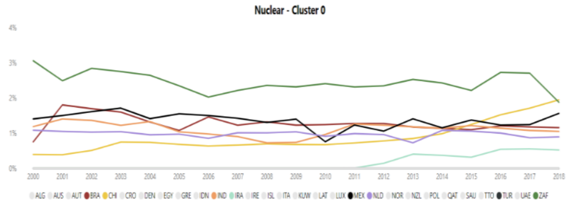

Figure 9a: Countries in Cluster 0 (Nuclear DTW)

- **Cluster 1 (moderate and stable utilization):** Including Slovakia, Sweden, and Switzerland, this cluster shows a moderate but stable reliance on nuclear energy, with shares slightly declining in Slovakia and Switzerland but increasing in Sweden, from 25.6% in 2000 to 28.3% in 2018. This trend underscores Sweden's continued commitment to nuclear power as a significant energy source.

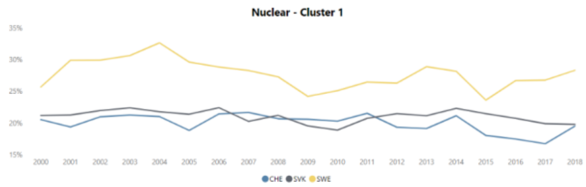

Figure 9b: Countries in Cluster 1 (Nuclear DTW)

- **Cluster 2 (high impact events):** Featuring countries like Germany and Japan, this cluster experienced significant reductions in nuclear energy use following the Fukushima disaster in 2011. Germany and Japan's drastic cuts from higher levels of nuclear utilization reflect the profound impact of nuclear accidents and public opinion on energy policy.

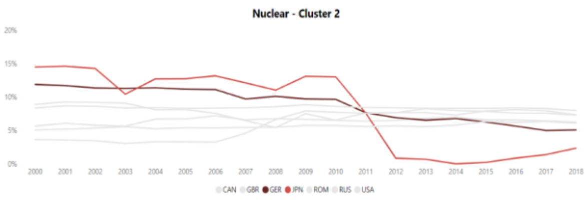

Figure 9c: Countries in Cluster 2 (Nuclear DTW)

- **Cluster 3 (high reliance on nuclear):** France is the sole member of this cluster, showcasing the highest reliance on nuclear energy, where nuclear power constitutes 70% of its electricity production. France's consistent and high nuclear energy share highlights its strategic choice to depend heavily on nuclear energy for its national energy security.

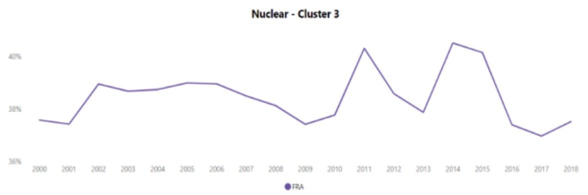

Figure 9d: Countries in Cluster 3 (Nuclear DTW)

- **Cluster 4 (varied adjustments):** This cluster includes Belgium, Czechia, Finland, Hungary, Slovenia, and Ukraine, with diverse adjustments in nuclear energy shares. Notably, Czechia and Ukraine increased their nuclear energy consumption, while Belgium saw a significant reduction, illustrating different national strategies towards nuclear energy amidst evolving economic, political, and environmental contexts.

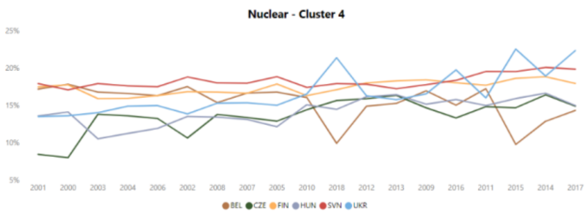

Figure 9e: Countries in Cluster 4 (Nuclear DTW)

Figure 10 below offers a quantitative breakdown of the average nuclear energy consumption per capita across each cluster, providing a basis for comparative analysis and benchmarking.

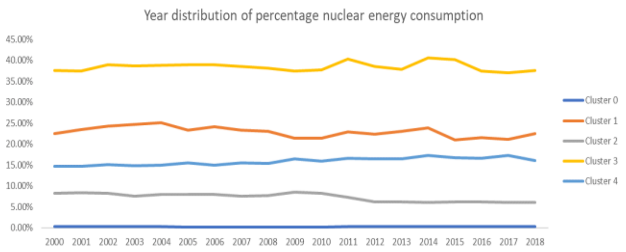

Figure 10: Graphical representation of the average values of individual clusters (Nuclear DTW)

Implications for policy and future research

This detailed clustering analysis provides crucial insights into how different countries manage their nuclear energy resources, influenced by policy decisions, public opinion, and critical events. It highlights the importance of:

- **Policy flexibility:** Adapting nuclear energy policies in response to technological advancements, safety considerations, and public sentiments.
- **Strategic energy planning:** For countries like France, maintaining a high level of nuclear energy utilization underscores the importance of strategic long-term energy

planning for national security and energy independence.

- **Risk management:** The significant reductions in nuclear energy usage in Germany and Japan post-Fukushima highlight the need for robust risk management strategies and public engagement in nuclear energy policy.

4.3.3 Renewable energy consumption per capita clustering analysis

The renewable energy consumption per capita analysis utilizes the elbow method, similar to previous sections, to determine the ideal cluster size for analyzing trends from 2000 to 2018. Although the method suggested four clusters as optimal, five were chosen to maintain consistency with the other sections of energy source analysis. This decision allows for a detailed comparison across different energy types while maintaining methodological consistency.

Methodology and clustering execution

- Elbow method application: The determination of cluster sizes was guided by the elbow method, which identifies the point where adding more clusters does not significantly improve the model's performance. This analysis is visualized in Figure 11.

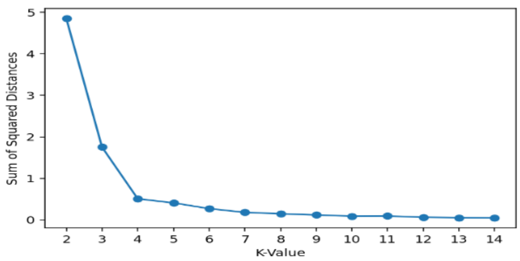

Figure 11: The sum of squared distance for different number of clusters (Renewable DTW)

- Cluster formation: Utilizing the k-means clustering algorithm, countries were grouped based on their renewable energy consumption per capita. The principal component transformation was applied to the dataset before clustering to enhance the separation and interpretability of the results.

Cluster descriptions and dynamics

- **Cluster 0 (emerging renewable adoption):** This cluster includes 17 countries with relatively low but growing renewable energy consumption, ranging from 1% to 7%. Egypt is notable for a decrease in its renewable share, likely due to increasing energy demands outpacing renewable energy developments.

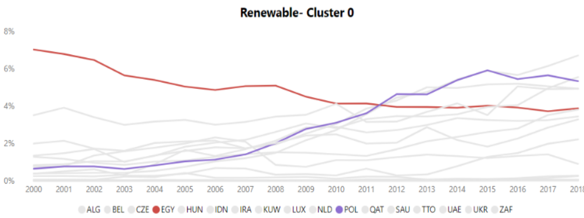

Figure 12a: Countries in Cluster 0 (Renewable DTW)

- **Cluster 1 (significant renewable usage):** Comprising five nations, this cluster exhibits a substantial use of renewable energy, averaging 34.33%. This cluster demonstrates successful integration of renewables into their energy mix, showing significant progress over the study period.

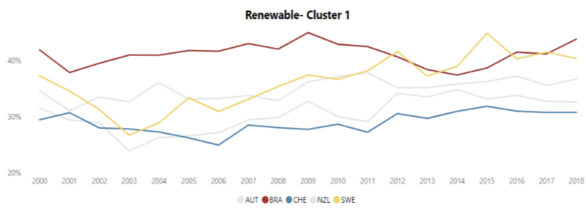

Figure 12b: Countries in Cluster 1 (Renewable DTW)

- **Cluster 2 (moderate renewable users):** This cluster features countries like Denmark, which has shown remarkable growth in renewable usage, increasing from 6.5% in

2000 to 27% in 2018. The cluster's average renewable share is 20.22%, with slight decreases observed in Canada and Latvia.

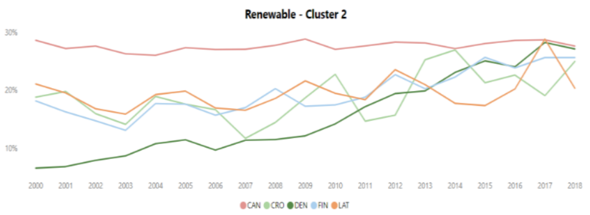

Figure 12c: Countries in Cluster 2 (Renewable DTW)

- **Cluster 3 (high renewable adoption):** Iceland and Norway represent this cluster, with the highest renewable usage among all clusters, averaging 71.4%. Norway shows a decrease in share, contrary to Iceland, which increased its renewable energy consumption significantly.

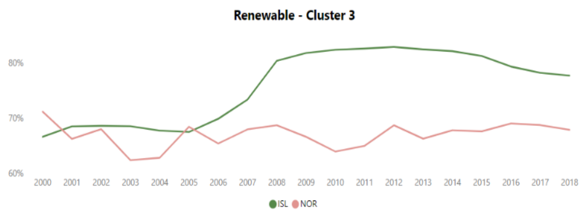

Figure 12d: Countries in Cluster 3 (Renewable DTW)

- **Cluster 4 (gradual adopters):** Includes diverse countries such as France, the United States, and Russia, with an average renewable share of 7.63%. Despite being modest, the increase in renewable energy usage across these countries indicates a slow but steady shift towards more sustainable energy sources.

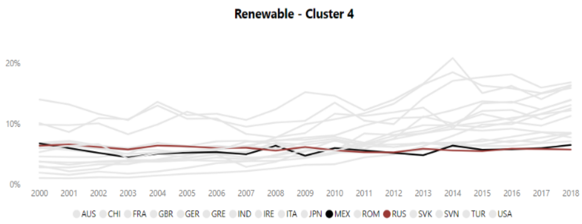

Figure 12e: Countries in Cluster 4 (Renewable DTW)

Implications for policy and future research

- **Policy insights:** The data from Cluster 1 and Cluster 3 can provide valuable insights for other countries aiming to increase their renewable energy share. Policies that encourage investment in renewable technologies, as seen in Iceland and Denmark, can serve as models for similar initiatives worldwide.
- **Future research directions:** Understanding the barriers that prevent higher adoption in clusters with lower renewable energy shares, such as those in Cluster 0 and Cluster 4, could be crucial. Research could focus on economic, regulatory, and technological challenges that these countries face.

5. Conclusion

This study has contributed to the understanding of the complex relationships between energy consumption, GDP, and population growth. Contrary to initial expectations, our findings indicate that the correlation between these variables is not as significant as might be presumed. However, the use of Pearson correlation as the primary analytical method, while straightforward, has its limitations and predominantly focuses on linear relationships. Future studies should explore causality, which could offer deeper insights into the dynamics and directions of these relationships [42].

Environmental considerations and economic growth

It is essential to consider environmental impacts in the context of economic growth. The long-term consequences of the energy sources used are increasingly influencing both energy output and GDP growth. With rising energy demand, reducing carbon dioxide emissions has become imperative. This necessitates a shift away from environmentally harmful fossil fuels. Interestingly, even regions heavily dependent on conventional energy sources, such as the Middle East, recognize the urgent need to mitigate climate change. These areas are uniquely positioned to harness abundant renewable resources, like solar energy, which could serve as a significant supply for other regions globally [43].

Renewable energy sources such as wind, hydrothermal, and biomass not only offer sustainability but also boast attributes like abundance, cleanliness, minimal environmental impact, and low production costs. The shift towards renewables, however, involves considerable upfront investment and complex feasibility assessments, which can be particularly challenging for less developed nations [39].

The 2018 Energy mix and future directions

The analysis of the 2018 energy mix across various nations highlights significant disparities. Countries like Kuwait, Saudi Arabia, and Iran show a predominant reliance on conventional energy sources, whereas nations like Canada, Brazil, and Sweden have made substantial progress in integrating renewable sources into their energy mix. This shift is critical, as high CO_2 emissions and the rising costs associated with traditional fuel extraction not only incur financial penalties but also negatively impact GDP growth [44].

Strategic energy policies in Europe

European countries exhibit diverse energy policies but share a strategic focus on enhancing energy efficiency and increasing renewable energy output. For instance, Austria aims to achieve carbon neutrality by 2040 and heavily relies on hydropower, which, while currently significant, has a limited potential for expansion [40]. France, leveraging its position as a major exporter of low-emission nuclear energy, continues to invest in measures to combat climate change [41]. Italy, heavily dependent on energy imports, is implementing a climate plan expected to reduce greenhouse gas emissions significantly by 2030 through renewable energy and improved energy efficiency.

Implications and future research

The variability in energy policies and their implications for national economies underscores the necessity of continued research in this area. Understanding how energy policies impact macroeconomic indicators is crucial for planning and forecasting. As such, future studies should delve into the economic impacts of shifting energy policies and explore how changes in the energy sector could affect long-term economic sustainability.

This research underscores the importance of a multidisciplinary approach to studying energy economics, one that incorporates environmental science, policy analysis, and economic forecasting to address the pressing challenges of our time.

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