Global Energy Systems Modeling: Structure and Environmental Impacts

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Abstract: The global energy landscape undergoes transformative changes characterized by unprecedented challenges in climate and geopolitical dynamics. This study analyzes energy systems across 66 countries using machine learning methods, based on comprehensive energy performance and environmental indicators. Using the K-means clustering method, three distinct country clusters were identified. The baseline cluster includes 62 countries with moderate energy parameters. China forms a unique cluster, characterized by exceptionally high total energy consumption and maximum carbon emissions, yet relatively low per capita consumption. The third cluster comprises the United States, the Russian Federation, and India, which are distinguished by diversified energy policies with high nuclear and natural gas consumption. Statistical analysis reveals robust correlations between primary energy consumption and environmental indicators, with correlation coefficients exceeding 0.9. The research demonstrates that primary energy consumption patterns and fuel balance structure, rather than emission volumes directly, are primary determinants of environmental impact. Coal-based energy generation emerges as the predominant source of anthropogenic environmental challenges globally. These findings underscore the urgent necessity for developing individualized national energy transition strategies that account for each country's unique energy profile and economic circumstances. The methodology established provides a framework for evidence-based policy formulation toward sustainable energy futures.

1 INTRODUCTION

Energy systems today are at a critical point of transformation that will determine the future fate of humanity and the planet. Global challenges related to climate change and geopolitical upheavals put forward new requirements for understanding and managing energy processes [1]. According to the World Meteorological Organization, 2023 was unprecedented in climate history - the warmest over the entire period of instrumental observations, with a global temperature increase of almost 1.5°C [2]. Such cardinal changes create a complex mosaic of challenges for the world community: from environmental consequences to the transformation of economic models.

The modern energy landscape is characterized by paradoxical trends: simultaneous growth in fossil fuel consumption and unprecedented development of renewable energy. The International Renewable Energy Agency report confirms that the share of green electricity continues to grow rapidly, creating a real alternative to traditional energy models [3].

According to the International Energy Agency, there were radical changes in industry indicators. In 2023, global energy demonstrated impressive dynamics of recovery and growth, returning to pre-coronavirus development trends [4]. A key feature of the past year was a significant revival in energy markets, primarily due to the weakening of logistics constraints and the restoration of economic activity. China played a decisive role in this process, canceling strict anti-epidemic restrictions and significantly increasing energy consumption. Statistics demonstrate unprecedented indicators: global oil consumption exceeded 100 million barrels/day for the first time; coal demand reached a historical maximum; renewable energy consumption grew six times faster compared to overall primary energy consumption; electricity demand increased 25% more intensively than total primary consumption [5]. These trends confirm the gradual transformation of the global energy landscape with the strengthening of renewable sources and diversification of energy portfolios of various countries.

At the same time, according to global monitoring studies, approximately 750 million people, every tenth inhabitant of the planet, are still deprived of basic access to electricity. This makes elementary needs impossible: lighting homes, storing food, and protection from rising temperature loads. Moreover, about 2.6 billion people continue to use extremely toxic biofuel sources for heating and cooking, such as charcoal, coal, and organic animal waste. In 2023, researchers recorded significant geographical differences in the relationships between regional population size and energy consumption volumes, which underscores the uneven nature of global energy development [4].

Today, studies aimed at a comprehensive understanding of structural transformations in global energy, and identification of regional characteristics and patterns of national energy systems development are gaining particular relevance. The purpose of our study is to analyze trends and patterns of modern energy profile formation in countries worldwide, identifying systemic interconnections between fuel balance structure, consumption volumes, and carbon emission levels. The obtained knowledge can provide a theoretical basis for countries to develop effective energy policies aimed at achieving a balance between economic development and environmental sustainability.

2 RELATED WORKS

Research on risks and opportunities created by the energy transition has been the focus of scholarly debates in recent years. Many scholars have dedicated work to identifying the main factors shaping the future of the global energy system [6–7]. O. A. Osobajo et al. investigated the impact of energy usage and economic growth on CO_2 emissions. The findings showed that the study variables (population, capital stock, and economic growth) are mutually linked to CO_2 emissions, whereas energy consumption has a one-way causal effect [8]. M. Ahmed et al. examined the relationship between energy consumption and CO_2 emissions (CO_2e) across China, India, and the USA. The study analyzed key factors including population growth, energy consumption per capita, and income levels. Their findings revealed a significant correlation between energy consumption per capita (p.c.) and CO_2 emissions in these countries [9]. M. Kameni Nematchoua and J. A. Orosa investigated strategies for reducing CO_2 concentrations and minimizing energy demands at the district level [10]. The researchers J. Li et al. examined the relationship between CO_2 emissions, energy consumption, mortality, life expectancy, and GDP in the top five carbon-emitting countries, revealing a strong positive correlation between CO_2 emissions and energy consumption [11]. However, most scientific research in this field relates to regional studies [12–15]. Further research on the efficiency and environmental performance indicators of countries' energy systems remains relevant for developing effective energy strategies.

3 METHODOLOGY

Analysis of global carbon dioxide emission trends demonstrates a clear correlation between primary energy consumption volumes and the level of anthropogenic CO_2 emissions. China has the maximum primary energy consumption level (Fig. 1).

China also significantly leads other countries in carbon dioxide emissions from energy [4]. The USA, India, and Russia are next in the ranking of countries with high primary energy consumption. This trend is associated with intensive industrial development and high electricity consumption in these countries, where traditional fossil energy sources such as coal, oil, and natural gas, the main sources of greenhouse gas emissions, predominate.

However, no correlation has been established between carbon dioxide emissions and energy dependence on primary energy consumption p.c. of countries worldwide (Fig. 2). This confirms the complexity and multi-factor nature of energy transformation processes in the modern global economic space and requires further research.

To identify groups of countries with similar energy consumption and environmental impact models, we conducted a cluster analysis of 66 countries worldwide based on selected indicators of efficiency and environmental friendliness of countries' energy systems [4].

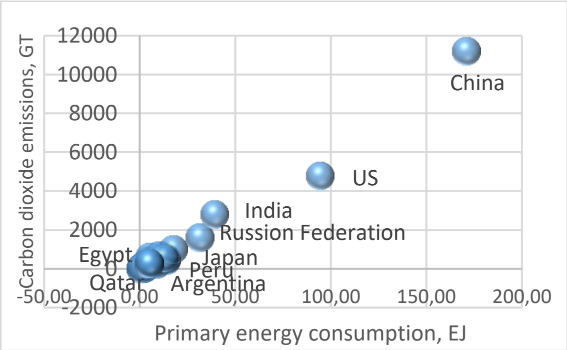

Figure 1: Chart of carbon dioxide emissions from energy dependence on primary energy consumption.

3.1 Data and Variables

The data set comprised efficiency and climate sustainability metrics of energy infrastructures from 66 countries worldwidey, presented in Table 1.

The countries include: Canada, Mexico, US, Argentina, Brazil, Chile, Colombia, Ecuador, Peru, Trinidad and Tobago, Venezuela, Austria, Belgium, Czech Republic, Finland, France, Germany, Greece, Hungary, Italy, Netherlands, Norway, Poland, Portugal, Romania, Spain, Sweden, Switzerland, Turkiye, Ukraine, United Kingdom, Azerbaijan, Belarus, Kazakhstan, Russian Federation, Turkmenistan, Uzbekistan, Iran, Iraq, Israel, Kuwait, Oman, Qatar, Saudi Arabia, UAE, Algeria, Egypt, Morocco, South Africa, Australia, Bangladesh, China, China Hong Kong SAR, India, Indonesia, Japan, Malaysia, New Zealand, Pakistan, Philippines, Singapore, South Korea, Sri Lanka, Taiwan, Thailand, Vietnam.

Empirical research was conducted using Rapid Miner software [16] based on the values of the aforementioned indicators, published in the official report "2023 Statistical Review of World Energy" [4]. *K*-means clustering [17] was used to identify homogeneous models of energy behavior and environmental impact of countries worldwide. This enabled grouping countries with similar energy consumption characteristics and carbon dioxide emissions into homogeneous groups.

Table 1: Study variables.

Variable	Variable
CDEE, Gt	Carbon dioxide emissions from energy
CDEEPMF, $GtCO_2e$	Carbon dioxide equivalent emissions from energy, process emissions, methane and flaring
ENGF, $GtCO_2e$	Emissions from natural gas flaring
PEC, EJ	Primary energy consumption
PECPC, EJ	Primary energy consumption p.c.
Consumption by fuel:	
CC, EJ	Coal
CH, EJ	Hydroelectricity
CNG, EJ	Natural Gas
CNE, EJ	Nuclear Energy
CO, EJ	Oil
CR, EJ	Renewables

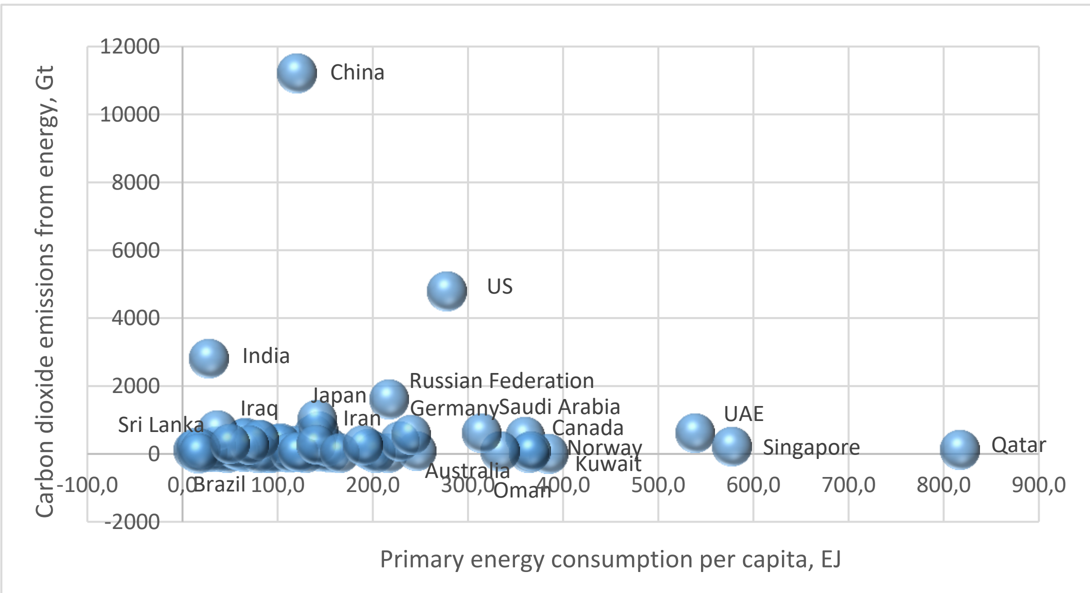

Figure 2: Chart of carbon dioxide emissions from energy dependence on primary energy consumption per capita.

3.2 Method

K-means clustering represents a fundamental unsupervised machine-learning technique for partitioning datasets into predetermined clusters [17]. The method minimizes within-cluster variability by iteratively assigning data points to the nearest centroid and recalculating cluster centers. At its core, the algorithm seeks to reduce the total within-cluster sum of squared distances, which can be expressed mathematically as the objective function:

$$J = \sum_{k=1}^{K} \sum_{x \in C_k} \left\| x - \mu_k \right\|^2, \tag{1}$$

where K denotes the number of clusters, C_k represents a specific cluster, x indicates individual data points, and μ_k represents the cluster centroid. The Euclidean distance between a point and its cluster centroid is calculated using the standard distance formula:

$$d(x, \mu_k) = \sqrt{\sum_{i=1}^{n} \left(x_i - \mu_{k_i} \right)^2}. \tag{2}$$

The clustering process involves several iterative steps beginning with centroid initialization. Initially, K centroids are randomly selected from the dataset, with each centroid representing the initial cluster center. The algorithm then alternates between two primary operations: assignment and update.

In the assignment phase, each data point is assigned to the closest centroid using the Euclidean distance. Mathematically, this assignment can be represented as:

$$C_i = arg \min_j \left\| x_i - \mu_j \right\|^2. \tag{3}$$

The update phase recalculates cluster centroids by computing the arithmetic mean of all points assigned to each cluster:

$$\mu_j = \frac{1}{C_j} \sum_{x_i \in C_j} x_i. \tag{4}$$

Convergence is achieved when centroids stabilize, typically determined by minimal changes in cluster assignments or reaching a predefined maximum number of iterations. The overall optimization is expressed through the convergence criterion:

$$|J(t+1) - J(t)| < \varepsilon, \tag{5}$$

where ε represents a small threshold value indicating minimal change between successive iterations.

4 RESULTS AND DISCUSSION

As a result of applying the k-means clustering method, 3 groups of countries were identified with distinct models of energy behavior and environmental impact (Fig. 3). The optimal number of clusters (k=3) was determined using the elbow method. The largest differences in mean cluster values were found in the variables CDEEPMF (carbon dioxide equivalent emissions from energy, process emissions, methane and flaring) and CDE (carbon dioxide emissions from energy). However, the variables PEC (primary energy consumption) and CNG (natural gas consumption) have the greatest influence on the distribution of countries into groups (Fig. 4). This means that the structure and scale of the energy system are the primary determinants of environmental impact. Emissions are a secondary consequence of overall energy consumption and energy balance diversification.

Cluster No. 0 included all 62 analyzed countries worldwide, except for China, the Russian Federation, and India. This group is characterized by significantly lower mean values for all analyzed indicators compared to countries in other clusters, except primary energy consumption p.c. (Table 2).

Table 2: Cluster Means.

Variable	Cluster 0	Cluster 1	Cluster 2
PECC	152.827	119.800	246.950
PEC	4.711	170.740	62.785
CDEE	263.141	11218.400	3206.450
ENGF	2.900	4.900	40.200
CDEEPMF	282.011	12603.500	1367.900
CO	1.720	32.730	21.535
CNG	1.212	14.570	24.120
CC	0.907	91.940	6.015
CNE	0.275	3.900	4.635
CH	0.315	11.460	2.045
CR	0.383	16.130	4.440

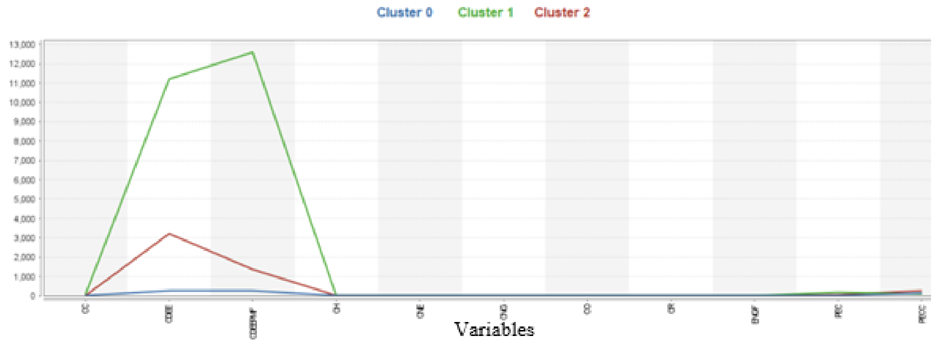

Figure 3: Centroid chart.

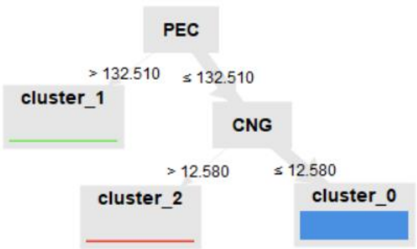

Figure 4: Cluster tree.

Cluster No. 0 effectively represents the “baseline” group of countries with moderate energy and environmental parameters.

Cluster No. 1 included only China. Its energy policy is characterized by significantly higher values, compared to the average of other identified country clusters, in the following indicators: primary energy consumption, coal consumption, oil consumption, hydroelectricity consumption, carbon dioxide emissions from energy, and carbon dioxide equivalent emissions from energy, process emissions, methane, and flaring. At the same time, China has the lowest primary energy consumption p.c. compared to the average values of this indicator in the other two clusters. This indicates the specificity of its energy model – high total consumption with relatively low p.c. consumption.

Cluster No. 2 included the USA, Russian Federation, and India. The average values of nuclear energy consumption, natural gas consumption, emissions from natural gas flaring, and primary energy consumption p.c. for countries in this group are significantly higher than the corresponding averages in the other two identified clusters. This cluster represents countries with a diversified and intensive energy policy.

To assess the model's resilience, we conducted a sensitivity analysis by introducing controlled variations in the input data (±5%) and re-executing the clustering. Results showed stability of the main clusters with an average object reassignment error of 4.2%, confirming the reliability of the classification. This indicates sufficient model robustness to minor changes in input data and the validity of the obtained results.

The obtained estimates confirm the hypothesis of the heterogeneity of global energy systems and the need for an individual approach to assessing their efficiency and environmental impact. The results of the empirical analysis demonstrate the complex interaction between energy consumption and emissions indicators during country clustering. Although the largest statistical differences between clusters are observed in carbon dioxide emissions indicators, which reflect the ecological aspect of energy systems, the determining factors for grouping countries were the volumes of primary energy consumption and natural gas. This means that the structure and scale of the energy system are the primary determinants of environmental impact. This result emphasizes the systemic nature of the relationship between economic scale, energy policy, and environmental impact, where total energy consumption serves as a fundamental basis for further differentiation.

Table 3 presents the correlation assessments between each pair of variables included in the cluster model.

A strong direct relationship was identified between primary energy consumption and the following indicators: carbon dioxide emissions from energy (0.992), renewables consumption (0.970), oil consumption (0.939), and carbon dioxide emissions from energy (0.904); carbon dioxide emissions from energy and renewables consumption (0.961); carbon dioxide emissions from energy and carbon dioxide equivalent emissions from energy, process emissions, methane, and flaring (0.934); coal consumption and carbon dioxide equivalent emissions from energy (0.986); coal consumption and carbon dioxide emissions from energy (0.946); oil consumption and renewables consumption (0.908). A strong positive

Table 3: Correlations.

	CDEE	CDEEPEF	CH	CNE	CNG	CO	CR	ENGF	PEC	PECC
CC	0.946	0.986	0.889	0.468	0.406	0.714	0.888	0.042	0.904	-0.057
CDEE		0.934	0.884	0.693	0.671	0.898	0.961	0.185	0.992	0.006
CDEEPEF			0.885	0.442	0.427	0.697	0.856	0.154	0.893	-0.056
CH				0.527	0.486	0.727	0.897	0.120	0.878	-0.009
CNE					0.870	0.875	0.731	0.270	0.764	0.100
CNG						0.872	0.661	0.555	0.743	0.131
CO							0.908	0.263	0.938	0.071
CR								0.070	0.970	-0.017
ENGF									0.221	0.006
PEC										0.019

correlation is observed between hydroelectricity consumption and the following indicators: coal consumption (0.889), carbon dioxide equivalent emissions from energy, process emissions, methane, and flaring (0.885), and carbon dioxide emissions from energy (0.884). Primary energy consumption correlates with carbon dioxide equivalent emissions from energy, process emissions, methane, and flaring (0.893) and hydroelectricity consumption (0.878); hydroelectricity consumption correlates with oil consumption (0.908)

The results of the correlation analysis reveal systemic interconnections between various parameters of the energy system, demonstrating that a change in one indicator almost determines changes in others. The exceptionally strong relationship between primary energy consumption and carbon dioxide emissions, as well as renewable energy sources, confirms a direct dependence between the scale of energy consumption and environmental impact.

In particular, the strong correlation between coal consumption and carbon emissions indicates that coal-based energy remains a major source of anthropogenic environmental impact. The high correlation of hydroelectricity consumption with emission indicators and the consumption of fossil energy sources is noteworthy, suggesting systemic complementarity between different energy sectors in a global context.

These findings confirm the complex nature of energy systems, where changes in one parameter trigger cascading changes in other components.

5 CONCLUSIONS

The study presents a comprehensive analysis of global energy systems, uncovering fundamentally new aspects of the interrelationship between the scale of energy consumption, the structure of the fuel balance, and environmental impacts. The application of cluster analysis made it possible, for the first time, to systematically differentiate countries into three unique groups representing fundamentally different models of energy behavior.

Particularly notable is the unique model of China, which has developed a distinctly specific energy consumption strategy: extremely high total volumes combined with relatively low p.c. consumption. It was found that China represents a unique cluster characterized by the highest indicators of primary energy consumption, coal-based generation, hydroelectricity, and carbon dioxide emissions.

The key scientific outcome of the study is the identification of systemic patterns within the global energy landscape. It was found that primary energy consumption and the structure of the fuel balance are the determining factors of environmental impact, rather than emission volumes directly. The clustering of countries revealed the heterogeneity of global energy systems: from the moderate model of developed countries to China’s unique strategy of extremely high total consumption, and the diversified energy policies of the United States, Russia, and India.

Russia’s full-scale invasion of Ukraine has further highlighted global energy challenges, demonstrating the critical dependence of European countries on Russian fossil fuels. The study shows that the Russian Federation belongs to the group of countries with diversified and intensive energy policies, characterized by high levels of nuclear and gas generation. Geopolitical upheavals have underscored the urgent need to accelerate the transition to renewable energy sources as a strategy for ensuring national and economic security.

Europe’s energy dependence on Russia has caused widespread consequences for the energy balance of other regions. Following Russia's invasion of Ukraine, a global redistribution of energy flows occurred, with Asian countries, especially China and India, increasing purchases of Russian energy resources at reduced prices. This led to increased competition in liquefied natural gas markets, where European countries began seeking alternatives to Russian gas, creating additional pressure on suppliers from the Middle East, Africa, and the United States. At the same time, this accelerated the development of renewable energy in many regions of the world and stimulated the diversification of energy sources in developing countries seeking to reduce their vulnerability to geopolitical upheavals.

The study empirically confirmed exceptionally strong correlations between key parameters of energy systems. In particular, it was established that primary energy consumption almost determines the levels of carbon emissions, renewable energy consumption, and oil consumption, with correlations exceeding 0.9. A particularly important scientific conclusion is that coal-based energy remains the primary source of anthropogenic impact, emphasizing the urgent need for the transformation of energy models.

The results obtained hold significant theoretical and practical value for shaping effective national and global energy transition strategies. The study convincingly demonstrates that balancing economic development and environmental sustainability requires an individualized approach that accounts for each country's unique characteristics. The presented cluster analysis methodology can be successfully adapted for further studies on the dynamics of global energy systems.

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