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STRATEGIC DIRECTIONS FOR ENERGY EFFICIENCY BASED ON INTELLECTUAL DECARBONIZATION: A CLUSTER ANALYSIS

The object of research is the processes of substantiating strategic directions for energy efficiency on the basis of intelligent decarbonization and sustainable development based on cluster analysis, taking into account international experience and challenges of the global environment. The problem that has been addressed is the lack of a systematic approach to clustering countries by energy efficiency, which also takes into account indicators of intelligent decarbonization. This makes it difficult to develop targeted strategies to improve energy efficiency and decarbonization, especially given the specifics of AI and innovative technologies in different countries.

The essence of the study results is to identify five clusters of the selected countries such as USA, India, Japan, China, Ukraine, Romania, Hungary, Poland, Czech Republic, Turkey, Portugal, Belgium, Greece, Sweden, Spain, Norway, Austria, Finland, Italy, France, The Netherlands, Germany, Switzerland, United Kingdom using cluster analysis based on the following indicators:

1. Applied AI research score.
2. Government Strategy AI: Strategy score.
3. Commercial Ecosystem AI: Companies score.
4. Energy intensity.
5. Carbon dioxide emissions from energy.

Cluster 1 includes India and Ukraine, countries with high energy intensity and significant CO_2 emissions, but with the potential to develop intelligent decarbonization. Cluster 2 is represented by the United States, a leader in AI and innovation, with low energy intensity but high CO_2 emissions due to its advanced industry. Cluster 3 covers countries with low energy intensity and low CO_2 emissions but weak AI development. Cluster 4 includes China, a country with a high level of AI research and commercial ecosystem, but high energy intensity and CO_2 emissions due to intensive industry. Cluster 5 covers countries with medium to high AI development, low to medium energy intensity, and varying levels of CO_2 emissions. The key principles of energy efficiency in these clusters are identified and strategic priorities for the development of energy efficiency in modern countries are defined.

The results obtained can be used in practice to develop energy efficiency and decarbonization strategies at the national and international levels.

Keywords: *energy efficiency strategy, energy efficiency policy, economic decarbonization, intelligent decarbonization, artificial intelligence, energy policy.*

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1. Introduction

In today's conditions, when energy resources are becoming increasingly limited and environmental challenges are becoming global, ensuring energy efficiency and decarbonization of the economy is becoming one of the key priorities for most countries. The growing need to reduce greenhouse gas emissions, use energy resources efficiently and switch to renewable energy sources requires a comprehensive approach that combines innovative technologies, government policies and international cooperation. One of the most promising tools for achieving these goals is intelligent decarbonization, which involves the use of artificial intelligence (AI) and other advanced technologies to optimize energy consumption and minimize the anthropogenic impact on the environment. According to the analysis of scientific papers in the Scopus bibliographic database, 465 articles were identified in the context of energy efficiency research, taking into account decarbonization and sustainable development, for the period from 2001 to 2025. Moreover, an intensive growth of research was observed from 2019 to 2024, as evidenced by an increase in the number of papers by more than 13 times – from 11 papers in 2019. Using the software tool VOSviewer 1.6.20, based on the analysis of these publications by keywords, 6 clusters were identified, marked with colors that unite the publications (Fig. 1): cluster 1 (red), cluster 2 (green), cluster 3 (blue), cluster 4 (yellow), cluster 5 (purple), cluster 6 (blue).

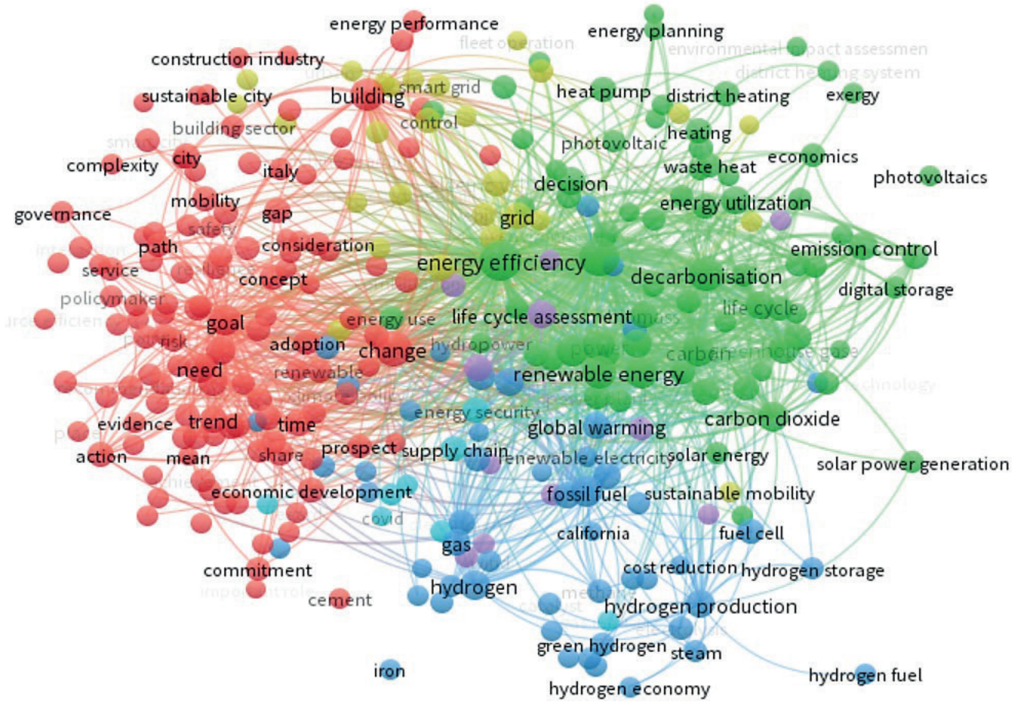

Fig. 1. Visualization of clusters of publications in the Scopus bibliographic database by keywords in the field of energy efficiency

Cluster 1 brings together 125 articles that explore the interconnection of artificial intelligence, circular economy, energy innovation and digitalization. Cluster 2 includes 75 articles with a focus on economic analysis of energy efficiency and environmental impact assessment of different types of energy. Cluster 3 contains 52 articles that explore the development of a green economy, the introduction of hydrogen technologies, and carbon capture technologies. Cluster 4 includes 29 articles on the integration of innovative energy systems into industry. Cluster 5 contains articles on the study of energy security and the development of alternative energy sources. Cluster 6 contains 1 article on management of traditional energy sources. The areas of application in these studies are quite diverse.

The study [1] used economic and mathematical modelling to examine emissions, GDP, population, and energy consumption in ASEAN countries. It concluded that energy efficiency reduces CO_2 emissions and is vital for sustainable energy development, along with decarbonization. The study also highlighted that energy efficiency curbs growing energy demand, while decarbonization cleans up energy supply. The study [2] investigated the definition, characterization and implementation of Positive Energy Districts as a concept for the development of urban areas. These districts are aimed at creating areas that produce more energy than they consume, while reducing environmental impact and improving the quality of life of residents. Their main goal is to ensure sustainable energy consumption, increase energy efficiency and reduce CO_2 emissions. The research also explored key elements of their provision, such as energy efficiency, energy flexibility, e-mobility, soft mobility, and low-carbon generation. It is determined that ensuring Positive Energy Districts (PED) requires the development of data analysis and integration, as well as digital twins of districts and cities. Proper stakeholder involvement, integrated sustainability approaches, and innovative business models are also essential for promoting market integration of technologies and PED solutions. Further research is needed to enhance energy efficiency and support decarbonization efforts. The study [3] analyses regional initiatives, using multivariate regression analysis to assess how existing regional green energy initiatives, their dependence on fossil fuels, and specific energy targets shape their progress towards achieving the EU Green Deal goals. To achieve energy efficiency goals, current research emphasizes smart decarbonization technologies. In particular, study [4] emphasizes the efficiency of energy load management to reduce carbon emissions through the use of artificial intelligence in warehouse systems, which demonstrates the validity of intelligent decarbonization. The study [5] focuses on examining the key prerequisites for achieving intellectual decarbonization, drawing on the experiences of European countries, and in relation to energy security. The study [6] states that Efforts towards electrification will alter electricity demand patterns, but they must also support the deployment of renewable energy generation. To achieve this, intelligent coordination of millions of resulting distributed energy resources is essential. This paper outlines the challenges and opportunities of smart electrification as a key strategy for enabling decarbonization and the transition to clean energy. The above justifies the relevance of further development of approaches to energy efficiency, taking into account current trends and multidisciplinary approaches.

Thus, *the aim of research* is to identify the key principles of ensuring energy efficiency of the economy, based on the needs of decarbonization, through the use of cluster analysis, which takes into account the international experience of innovative development of the energy sector, current challenges of the global environment and the peculiarities of the development of artificial intelligence and innovative technologies that will determine the potential of intelligent decarbonization, taking into account the specifics of the strategic development of cluster countries.

2. Materials and Methods

The object of research is the processes of substantiating strategic directions for energy efficiency on the basis of intelligent decarbonization and sustainable development based on cluster analysis, taking into account international experience and challenges of the global environment. Therefore, the research was divided into the following stages:

1. Study of current scientific publications on the development of approaches to energy efficiency and current trends in the development of artificial intelligence for energy efficiency and economic decarbonization, taking into account global sustainable development goals.

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2. Substantiation of energy efficiency indicators based on the principles of intelligent decarbonization and sustainable development and identification of countries for cluster analysis based on the selected indicators. Thus, the following indicators were used for the analysis:

– Applied AI research score;
– Government Strategy AI: Strategy score;
– Commercial Ecosystem AI: Companies score;
– Energy intensity, exajoules/billion US dollars;
– Carbon dioxide emissions from energy, million tons.

The countries selected for analysis are the leading countries with experience in implementing energy innovations to ensure energy efficiency growth, Ukraine's neighbors and potential partners, namely: USA, India, Japan, China, Ukraine, Romania, Hungary, Poland, Czech Republic, Turkey, Portugal, Belgium, Greece, Sweden, Spain, Norway, Austria, Finland, Italy, France, The Netherlands, Germany, Switzerland, United Kingdom.

3. Conducting a cluster analysis using the *k*-means method [7]. This is an iterative method that forms clusters in which the sum of Euclidean distances from the center to the cluster elements is minimal. For better visualization, the PCA (Principal Component Analysis) method was used.

Before applying the *k*-means algorithm, the data were standardized to prevent the dominance of big data at different dimensional scales, distances from centroids and between clusters are calculated in proportion to the significance of the variables, not their scale, and the impact of abnormal values or high variance on the calculations is reduced. The method of data standardization (*z*-score) was chosen:

$$z=\frac{x-\mu}{\sigma}, \quad (1)$$

where z – standardized value (after scaling); x – initial value of the variable; μ – the average value of a variable (mean); σ – the standard deviation of a variable.

The Elbow method was used to determine the optimal number of clusters. The value of k was chosen at the "elbow", i. e. at the point after which the distortion/inertia begins to decrease linearly.

4. Determination and interpretation of the analysis results with additional presentation of individual data in the form of a bubble chart.

5. Identification of key strategic practices for energy efficiency in the countries under study and provision of recommendations for the development of approaches to energy efficiency.

In the course of the study, the R programming language and the RStudio development environment were used.

3. Results and Discussion

To determine the principles of energy efficiency in the selected countries, a cluster analysis was conducted and indicators were selected that characterize the level of energy efficiency of the country, taking into account the potential for smart decarbonization.

The development of innovative approaches to energy efficiency is now key to reducing the use of fossil fuels and increasing the decarbonization of the economy. According to the International Energy Agency's research on achieving carbon neutrality in the energy sector by 2050, accelerating energy efficiency improvements will reduce oil demand by up to 70 % and gas demand by up to 50 % by 2030. It is established that from 2010 to 2022, the increase in energy intensity contributed to a cumulative reduction in global CO_2 emissions by almost 7 gigatons (Gt). It is determined that it is the acceleration of electrification and the increase in technical efficiency based on the introduction of innovations that contribute to the acceleration of energy efficiency. Since 2019, investments in energy efficiency have increased by almost 50 %. According to IEA research, in some cases, efficiency investments lead to a rapid reduction in energy intensity, while in other cases it is possible that other factors, such as increased industrial production, may not immediately achieve a positive result. On the path to carbon neutrality, investments in improving the efficiency of buildings, transport and industry are projected to triple from 660 billion USD today to around 1.9 trillion USD in 2030. Therefore, the Energy intensity indicator was selected as the basic indicator for the cluster analysis to assess energy efficiency and calculated as the ratio of primary energy consumption to GDP (exajoules/billion US dollars). Energy intensity can be interpreted as an approximate indicator of the energy efficiency of the national economy, which reflects the amount of energy required to produce one unit of gross domestic product.

According to Eurostat data, Fig. 2 shows the dynamics of energy intensity of the EU-27, as well as 4 EU countries (Slovakia, Bulgaria, Estonia, Malta – with relatively high energy intensity and 3 EU countries with relatively low energy intensity – Italy, Portugal, Ireland). In general, all EU countries are showing a gradual decline in energy intensity. The average energy intensity of EU countries decreased by 60 % from 2000 to 2023. This is due to the fact that in Europe, there is a general shift from industry to a service economy, accompanied by a reduction in energy intensity in the industrial sector due to the transition to less energy-intensive activities and production methods, the closure of inefficient enterprises and the introduction of more energy-efficient technologies.

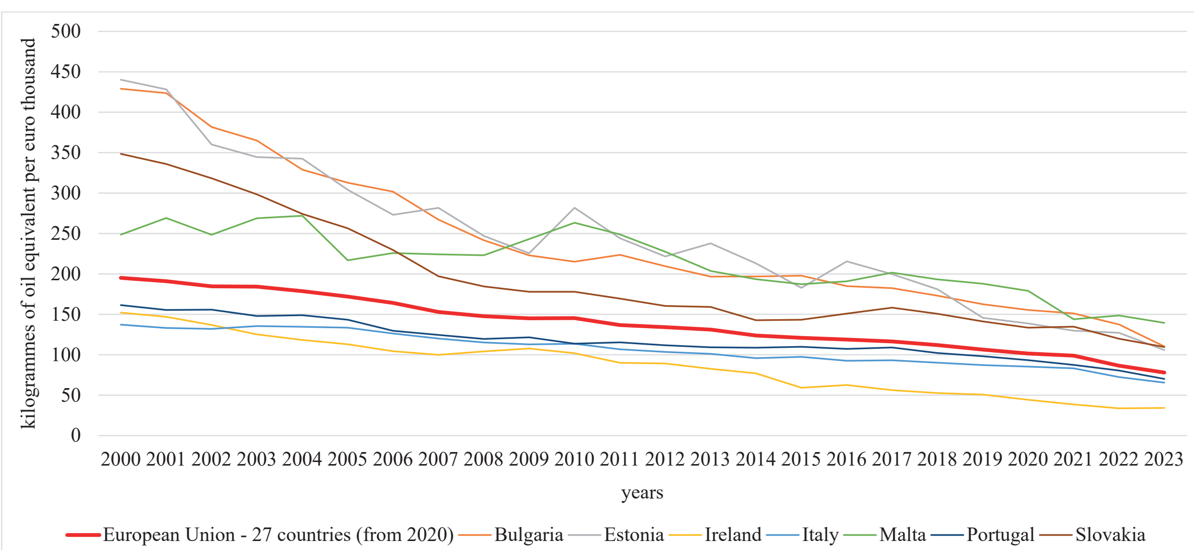

Fig. 2. Dynamics of energy intensity in the EU-27 and selected countries, kilograms of oil equivalent per euro thousand [8]

In general, in the structure of the main energy consuming sectors in the EU (Fig. 3), transport ranks first (31 %), followed by households (27 %) and industry (25 %), which explains that it is in these sectors that innovative energy efficiency management technologies are being introduced.

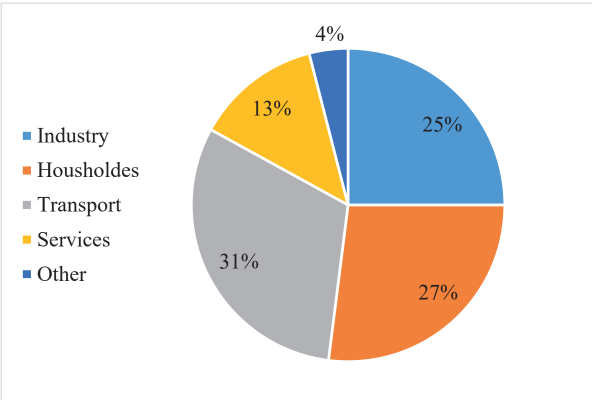

Fig. 3. Final energy consumption by sector, EU, 2022, %

Today, in the context of Industry 5.0, artificial intelligence is an effective solution for reducing energy intensity and promoting decarbonization. The importance of artificial intelligence is being recognized globally and the foundations for its correct use and dissemination are being formed. For example, the first global AI Safety Summit was held in November 2023 in the United Kingdom, where the EU and 28 countries participating in the summit, including Ukraine, signed the Bletchley Declaration. It defines the common agreement and responsibility regarding the risks, opportunities and further process of international cooperation in the field of security and AI research, in particular, by expanding scientific cooperation [9]. In turn, on 13 March 2024, the European Parliament approved the Artificial Intelligence Act that ensures safety and compliance with fundamental rights while boosting innovation, which is the first comprehensive attempt to regulate artificial intelligence (AI) at the global level [10]. This forms the basis for its development, in particular, for the expansion of its use in the energy sector. Innovative solutions for managing the challenges of unstable electricity generation have been built on the basis of AI due to its unique capabilities of analyzing large amounts of data, forecasting demand, and optimizing energy systems. Artificial neural network-based methods allow for efficient modelling of power generation, identification of optimal resource management strategies, and reduction of CO_2 emissions by improving system efficiency. Today, artificial intelligence is being actively implemented in various areas of economic activity, including the energy sector, which, according to research [5], will allow achieving a high level of energy efficiency in the future and is the basis for ensuring intelligent decarbonization. That is why it is possible to choose the following indicators for cluster analysis: Applied AI research score; Government Strategy AI: Strategy score; Commercial Ecosystem AI: Companies score. These indicators are part of the Global AI Index, which became the first index to benchmark nations on their level of investment, innovation, and implementation of artificial intelligence [11]. According to the study, this index consists of three main pillars: implementation, innovation and investment and seven sub-pillars, namely talent, infrastructure, operating environment (related to implementation), research and development (related to investment), which are divided into 122 indicators. The Applied AI research score assesses the level of specialized applied research and researchers, including the number of publications and citations in reputable academic journals. Government Strategy measures the depth of national governments' commitment to artificial intelligence, examining spending commitments and national strategies. Commercial Ecosystem AI: Companies score assesses the level of business initiatives based on artificial intelligence. Since, according to research, decarbonization is also an indicator of energy efficiency, this justified the choice of Carbon dioxide emissions from energy as another indicator for cluster analysis.

The input data according to these indicators are summarized in Table 1.

Table 1

Input data for cluster analysis of selected countries for 2023

Country	Applied AI research score	Government Strategy AI: Strategy score	Commercial Ecosystem AI: Companies score	Energy intensity, exajoules, billion US dollars	Carbon dioxide emissions from energy, million tons
USA	100.00	80.7	100	0.00340	4639.7
India	31.80	80.40	10.7	0.01094	2814.3
Japan	14.40	80.90	8.2	0.00414	1012.8
China	96.30	55.40	28.7	0.00959	11218.4
Ukraine	2.80	56.8	0.5	0.01242	105.3
Romania	4.40	34.8	0.0	0.00365	59.9
Hungary	6.10	50.9	0.8	0.00428	39.10
Poland	7.5	60.9	1.9	0.00509	270.3
Czech Republic	9.2	70.3	1.5	0.00443	82.9
Turkey	9.7	89.7	1.6	0.00626	411.1
Portugal	12.80	44	2.0	0.00329	39.70
Belgium	12.80	42.3	2.6	0.00358	103.3
Greece	13.60	34.5	0.8	0.00452	59.4
Sweden	15.7	36.7	4.4	0.00368	35.8
Spain	16.10	89.5	3.7	0.00349	246.8
Norway	17.60	67.4	2.9	0.00410	34
Austria	18.10	59.9	2.4	0.00080	53.8
Finland	18.90	70.2	4.3	0.00406	31.70
Italy	19.70	67.1	3.7	0.00259	301.3
France	20.40	71.8	6.4	0.00284	254.6
The Netherlands	21.10	66.1	4.4	0.00298	156.1
Germany	28	73.7	7.2	0.00298	571.9
Switzerland	30.20	29.20	6.9	0.00128	32.7
United Kingdom	34.3	94.9	16.8	0.00206	327.3

For the data presented here, according to the methodology used, it is possible to conclude that the optimal number of clusters for the data is 5 (Fig. 4).

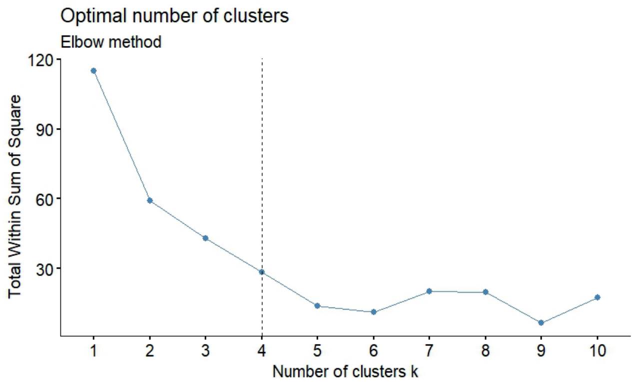

Fig. 4. Criterion for selecting the number of clusters

The results of the clustering have the following numerical characteristics, presented in Table 2.

Table 2

Within cluster sum of squares by cluster (WSS)

Clusters	1	2	3	4	5
WSS	2.370095	0.000000	2.521567	0.000000	9.046878

WSS is the total square distance between points and their centroid in each cluster. The value for each cluster shows how tightly the data is grouped around the center. Clusters 1 and 3 look compact, while cluster 5 contains more points, is wider and less homogeneous ratio:

$$\frac{Between_{SS}}{Total_{SS}} = 87.9\,\%, \qquad (2)$$

where $Between_{SS}$ – the sum of the squared deviations between the cluster centroids and the common centroid (the center of all data); $Total_{SS}$ – the total sum of the squared deviations between each point and the common centroid; $\frac{Between_{SS}}{Total_{SS}}$ – shows how well the clusters separate the data. A high proportion (87.9 %) means that the clustering explains the variation in the data well, as a value closer to 100 % indicates a good clustering.

For better visualization, it is possible to use the PCA (Principal Component Analysis) method, which reduced the space to two dimensions with principal component axes PC_1 and PC_2:

$$PC_1 = -0.59 \cdot X_1 - 0.19 \cdot X_2 - 0.52 \cdot X_3 - 0.2 \cdot X_4 - 0.55 \cdot X_5,$$
$$PC_2 = -0.14 \cdot X_1 - 0.28 \cdot X_2 - 0.35 \cdot X_3 + 0.84 \cdot X_4 + 0.28 \cdot X_5, \qquad (3)$$

where X_1 – applied AI research score; X_2 – strategy score; X_3 – companies score; X_4 – energy intensity; X_5 – carbon dioxide emissions from energy.

PCA transforms the data so that most of the variation in the data is contained in the first few principal components (PC_1, PC_2 others). Therefore, using only PC_1 and PC_2 allows to represent most of the information in the data.

According to the results of the analysis, 5 clusters were obtained (Fig. 5). Cluster 1 unites such countries as India and Ukraine. Cluster 2 covers the USA. Cluster 3 includes Romania, Hungary, Portugal, Belgium, Greece, Sweden, Switzerland. Cluster 4 is formed from China. Cluster 5 includes Japan, Poland, Czech Republic, Turkey, Spain, Norway, Austria, Finland, Italy, France, The Netherlands, Germany, United Kingdom.

Despite different levels of economic development, India and Ukraine are grouped in Cluster 1, and these two countries have the highest energy intensity among the surveyed countries, which indicates inefficient energy use. In relation to GDP, the cluster countries have a fairly high level of carbon dioxide emissions from the country's energy sector. At the same time, India has significantly higher CO_2 emissions due to its large population and intensive industrial production, while Ukraine shows lower figures due to its smaller industry. The high energy intensity in this cluster is caused by several factors. These include the complex industrial structure and reliance on outdated energy technologies. Heavy industrial sectors consume large amounts of energy and have a high share of fossil fuel usage, especially coal. This leads to increased carbon dioxide emissions from energy production. Additionally, there are challenges with energy networks and high energy demand in agriculture, particularly in India. The war in Ukraine, caused by Russia's full-scale military invasion, has severely damaged the country's energy infrastructure. Russian attacks have led to the loss of energy capacities, higher restoration costs, and increased energy consumption for the defense industry.

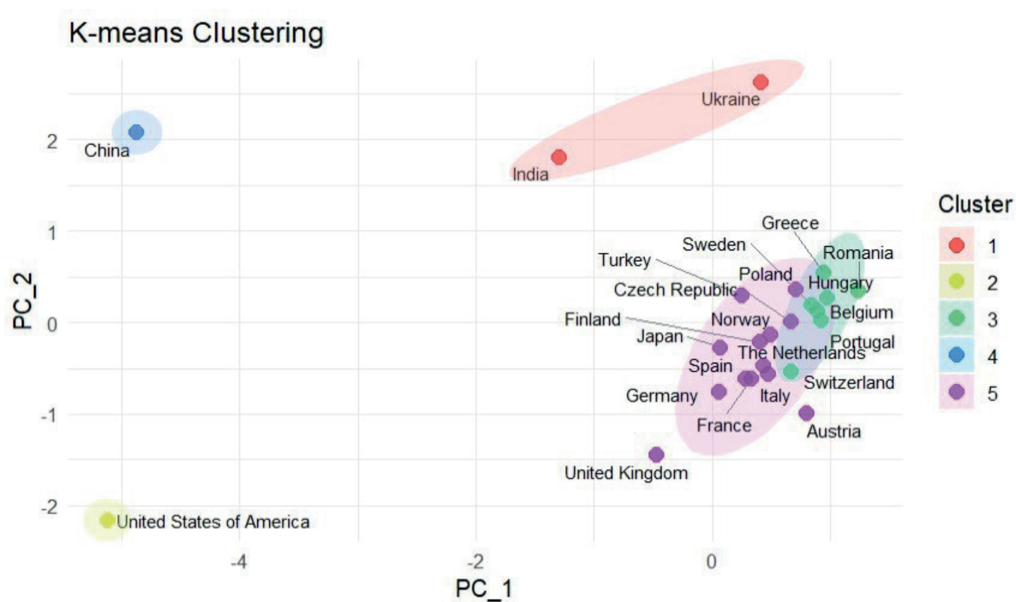

Fig. 5. Clusters of countries based on selected indicators of energy efficiency based on intellectual decarbonization

At the same time, production in less energy-intensive industries has declined, negatively impacting overall energy intensity. At the same time, it is possible to note the relatively high government support for AI development in the cluster, and in India, a relatively high number of studies in this area, which indicates the potential for the development of intellectual decarbonization. Both India and Ukraine are shaping the framework for renewable energy development. In India, several government programs and strategies support energy development. The National Mission on Enhanced Energy Efficiency (NMEEE) focuses on creating fiscal instruments to encourage energy efficiency. It also aims to transform the energy efficiency market through innovative measures and reduce energy intensity in energy-intensive sectors. The Jawaharlal Nehru National Solar Mission (JNNSM), also known as the National Solar Mission, is another key initiative. It is led by the Government of India and State Governments to promote solar power. Its goal is to establish India as a strategic leader in solar energy. According to the Energy Strategy of Ukraine until 2050, the main mission in the energy sector is to support the sustainable development of the national economy. This will be achieved by ensuring access to reliable, sustainable, and modern energy sources. The strategy also states that by 2050, the energy sector should aim to be as close as possible to climate neutrality. A key priority in this process is ensuring energy security. Therefore, the cluster countries share the need to invest in technologies to improve energy efficiency and decarbonization.

Cluster 2 includes only one country, the United States, which stands out from the rest. The United States is the world's second largest energy consumer and one of the world's largest CO_2 emitters, but it is also a global leader in technology and innovation. The US is a global leader in AI, with the highest rankings in applied AI research, a developed government strategy to support AI, and a highly developed commercial AI ecosystem. The relatively low energy intensity indicates a high level of energy efficiency, but the US also has relatively high carbon dioxide emissions from energy due to its developed industry and power sector. The US has seen a rapid increase in investment in clean energy, which has led to its leading position in the renewable energy market, electric vehicles, batteries, electrolysers, heat pumps [12] and is also a leader in biofuel production. The rate of energy efficiency improvement is expected to reach 4 % in 2023. Domestic coal consumption has fallen to a historic low. In 2023, total CO_2 emissions from energy combustion in the US decreased by 4 %, even though the economy grew by 2.5 %, with the electricity sector accounting for more than 60 % of the emissions reduction. That is why it can be argued that energy efficiency policy in this cluster of the US is aimed at achieving energy efficiency through the development of innovations. Among the favorable policy factors is The National Action Plan for Energy Efficiency, a public-private initiative aimed at creating a sustainable, strong national commitment to energy efficiency through the joint efforts of gas and electricity companies, regulators, and other partner organizations. Signed into law in 2022. The CHIPS and Science Act provides 170 billion USD to support the research, innovation, and production of semiconductors and semiconductor support materials. These semiconductors are widely used in clean energy applications, including electric vehicles, energy monitoring and storage, smart heating and lighting systems. Countless computer systems are used to design, monitor, and control the production and use of clean energy. All together they drive the world's most advanced manufacturing and energy-efficient technologies. An innovation to support the development of clean energy was the creation of The Office of Manufacturing and Energy Supply Chains (MESC) [13], which is to strengthen economic and national security by eliminating vulnerabilities in the US energy supply chains and formulate policies to ensure clean energy technology manufacturing. The Bipartisan Infrastructure Law was developed, which defines the need for each state to develop a State Carbon Reduction Strategy to reduce carbon emissions from transport. The US Bureau of Energy Resources (ENR) [14] outlines key principles of US energy policy. These principles include supporting decarbonization, sustainability, and energy access. They also focus on promoting energy security, securing mineral supply chains, implementing sanctions, and advancing US goals in international organizations.

Cluster 3 (Romania, Hungary, Portugal, Belgium, Greece, Sweden, Switzerland) includes countries with medium or low AI development, relatively low energy intensity, and low CO_2 emissions. These countries demonstrate efficient energy use and a relatively small environmental footprint. Despite the weak AI Commercial Ecosystem, they have the potential for further development through investments in technology and energy efficiency. Common features in energy efficiency policies include a shift to renewable energy sources, effective strategic energy efficiency programs, a service sector dominated by industry, and investments in infrastructure modernization. Countries such as Sweden and Portugal have significantly increased the share of renewable energy sources in their energy mix. This reduces dependence on conventional energy resources and reduces overall energy intensity, with renewables accounting for 67.8 % of energy generation in Sweden. Sweden is a world leader in decarbonization and plans to reduce greenhouse gas emissions by another 59 % by 2030 compared to 2005, and to achieve zero carbon emissions in the economy by 2045 [15]. In Portugal, the share of renewable sources in energy generation is 55.5 %. Portugal is an international leader in the integration of wind generation, and auctions are contributing to the rapid deployment of photovoltaic systems and batteries [16].

Cluster 4 (China) includes only one country, which differs significantly from the others. China has a high level of AI research and a developed level of commercial AI development infrastructure, but the government's AI development strategy is weaker than in the US. High energy intensity and CO_2 emissions are associated with intensive industrial production. This cluster highlights China's uniqueness as a country with strong technological potential but a significant negative environmental impact. That is why China is implementing a comprehensive energy strategy that includes the development of renewable energy sources, nuclear power, and reducing dependence on fossil fuels. In 2024, the country installed more than 230 GW of new solar capacity, bringing the total capacity to approximately 850 GW, with the goal of reaching 1 TW by mid-2025. China is also developing areas of AI implementation in the energy sector, including optimization of energy system management, energy demand forecasting, renewable energy management, and development of smart grids.

Cluster 5 (Japan, Poland, Czech Republic, Turkey, Spain, Norway, Austria, Finland, Italy, France, the Netherlands, Germany, and the UK) includes countries with medium or high AI development, low or medium energy intensity, and varying levels of CO_2 emissions. These countries demonstrate a balance between AI development and energy efficiency. They have a fairly high level of government AI strategies and commercial infrastructure, which indicates their potential for further development. The low energy intensity in many countries in this cluster underlines their efficiency in energy use. Germany's carbon dioxide emissions are relatively high compared to other countries in the cluster – 571.9 million tons. This was influenced by the fact that in 2023, Germany provided 46 % of its electricity from fossil fuels, which resulted in higher per capita emissions than the global average. The German Climate Act sets a framework for achieving zero emissions by 2045. To achieve the ambitious goal set out in Germany's Energiewende energy strategy by 2030, 80 % of all electricity must come from renewable energy sources (and 100 % by 2035), and coal must be completely phased out. This is a priority for further development and decarbonization. Norway is also one of the leading countries in the cluster. Norway is actively investing in new technologies to improve energy efficiency and reduce emissions. This includes developing carbon capture and storage (CCS) technologies and improving fossil fuel extraction technologies, and investing in smart grids that use AI technologies to automate processes and increase efficiency. Norway is the world leader in electricity generation from hydropower, which accounts for about 98 % of the country's total electricity production. In 2022, the share of renewables in Norway was 95.6 %. Energy technology and innovation will play an important role in Norway's energy transition, in particular to leverage the existing strengths of its energy sector in new areas such as CCS and hydrogen [17].

Based on the results of the analysis of these clusters, the following key strategic areas of energy efficiency can be identified:

– increasing the share of renewable sources in the overall energy balance, which helps to reduce dependence on fossil fuels and reduce energy intensity;
– using artificial intelligence to optimize energy systems, forecast energy demand and manage electricity generation, which helps to increase resource efficiency and reduce CO_2 emissions;
– implementation of innovative solutions to manage the volatility in electricity generation based on the analysis of large amounts of data;
– development of strategies to decarbonize the energy sector and reduce CO_2 emissions, which is an important indicator of energy efficiency; implementation of government programs and strategies that support the development of energy efficient technologies and stimulate their use at all levels of the economy;
– participation in international initiatives and agreements aimed at improving energy efficiency and sustainable development on a global scale.

Practical significance. The results of the study have significant practical potential by providing an analytical basis based on the proposed indicators and implementing a cluster approach that will allow the development of effective energy efficiency strategies at the national and international levels using the potential of artificial intelligence for decarbonization. The cluster approach allows government agencies, international organizations and businesses to identify specific areas of energy efficiency policy development, taking into account the specifics of country development, and use benchmarking approaches to offer effective solutions and develop international cooperation.

Limitations of the study. One of the main limitations of the study is the availability and relevance of data for all the countries under consideration, as well as the limited data sample. It is necessary to regularly update the analytical indicators to maintain the relevance of the results. In addition, taking into account technological and economic changes, the indicators can be expanded in the future to improve practical solutions, which will deepen the analysis and justification of energy efficiency strategies.

Impact of martial law conditions. The war in Ukraine has had a significant impact on the study, as access to up-to-date national data on energy efficiency and innovation is limited. Energy security has become a priority for government policy, which may shift the focus of decarbonization strategies. At the same time, military challenges are stimulating the development of renewable energy sources, which may form the basis for new energy efficiency strategies in the post-war period.

Prospects for further research. A promising area for further research is to determine the relationship between the level of digitalization, the development of artificial intelligence, and the effectiveness of measures to reduce CO_2 emissions, and to expand the indicators in these components. Analyzing the effectiveness of international environmental initiatives and their impact on different clusters could also be a useful area for further research.

4. Conclusions

The study identified key strategic areas for energy efficiency based on intelligent decarbonization, including the use of artificial intelligence (AI) and other advanced technologies. To achieve the research objective, clusters of countries were identified by the level of energy efficiency, AI development, and environmental impact, which allowed to characterize the main principles of cluster development in the direction of energy efficiency.

The study results showed that countries can be grouped into five clusters that differ in terms of energy efficiency, AI development, and CO_2 emissions. This clustering can be useful for developing strategies aimed at improving energy efficiency and decarbonization for each group of countries. For example, countries in cluster 1 need to invest in AI technologies and energy efficiency, while countries in cluster 5 can serve as a role model for others due to their balance between technological development and environmental responsibility.

One of the key findings of the study is that intelligent decarbonization, including through the use of AI, is an important tool for achieving energy efficiency and reducing CO_2 emissions. This is confirmed by the example of countries that have already achieved significant success in this area, such as the United States, Germany, and Norway. At the same time, countries with less developed technologies, such as India and Ukraine, have significant potential for implementing innovative solutions.

The findings can be used in practice to develop national and international strategies aimed at improving energy efficiency and decarbonization. In particular, governments, international organizations, and the private sector can use clustering data to develop targeted programs aimed at investing in AI, renewable energy, and innovative technologies. This will not only reduce CO_2 emissions but also ensure sustainable economic development.

Considering the results of the study, it is worth noting that it is needed for international cooperation to achieve global energy efficiency and decarbonization goals. Countries with different levels of development can share experiences, technologies and resources to accelerate the transition to clean energy.

Overall, the study confirms that intellectual decarbonization is a key tool for overcoming global energy and environmental challenges. It also demonstrates that clustering countries by energy efficiency and AI development can become the basis for developing effective strategies aimed at achieving sustainable development and reducing anthropogenic impact on the environment.

Conflict of interest

The authors declare that they have no conflict of interest regarding this study, including financial, personal, author-ship or other nature, which could affect the study and its results presented in this article.

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Data availability

The manuscript has no related data.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the presented work.

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