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Magdalena LAZAREK-JANOWSKA[1], Paweł WŁOCH[2]

ANALYSIS OF CLUSTERING OF ENERGY PRICE QUOTATIONS FROM THE DAY-AHEAD MARKET (DAY-AHEAD-TRADING) OF THE POLISH POWER EXCHANGE (TGE) IN POLAND IN 2022-2023 USING THE K-MEANS METHOD

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Electricity on the Polish Power Exchange (TGE) is traded on both the Day-Ahead Market (DAM) and the futures market. On the DAM, sellers and buyers submit bids for next-day energy delivery. The European market has a wide range of suppliers, and energy prices depend on the prices prevailing in other countries. In contrast, the futures market involves trading contracts for future energy deliveries, often scheduled for the following year. This means that producers have to predict the energy production costs many months in advance. This approach changes the perception of electricity as a commodity in the market. There are many factors influencing energy prices on the Polish Power Exchange. The most important include fuel prices, Emissions Trading System emission prices, weather conditions, etc. The aim of this article is to present the results of applying the clustering technique to assess energy price quotations on the DAM of the TGE from the perspective of a year of stable quotations (2023) and a year of anomalies (2022, caused by Russia's military aggression against Ukraine). Based on the research conducted, it can be stated that k-means clustering analysis is used in the analysis of the energy market in Poland. For the period from January 1, 2022, to December 31, 2023, the optimal number of clusters was defined as four, which is related to the demand for energy produced from conventional sources. This result is justified by the price formation mechanism on the TGE the so-called Merit Order principle, which considers the impact of renewable energy displacing energy from the most expensive units. Further analysis should focus on other factors affecting energy prices, such as CO2 emission allowance quotations, raw material prices, and weather conditions.

Keywords: clustering, k-means method, Polish Power Exchange

[1] West Pomeranian Business School – Academy of Applied Sciences, Faculty in Szczecin. ORCID: 0009-0004-1553-4512.
[2] West Pomeranian Business School – Academy of Applied Sciences, Faculty in Szczecin. ORCID: 0009-0009-3190-4882.

1. INTRODUCTION

The Polish legal system allows energy trading in three main segments[3]. The assumption of efficient energy trade should ensure a country's energy security. Efficiency, in this context, refers to the uninterrupted continuity of energy supply in response to consumer demand. One of the trading methods discussed is trading on the Polish Power Exchange as part of the Day Ahead Market quotations. Prices are formed in accordance with the Merit Order principle, which is used in many energy markets in European countries. As renewable energy continues to develop, there is a noticeable trend of increasing penetration of the energy market by energy from renewable sources (Merit Order Effect, Kusz, 2017), which consists in crowding out energy from conventional sources with energy from renewable sources. Figure 1 shows an example of aggregated curves for determining the transaction price of energy.

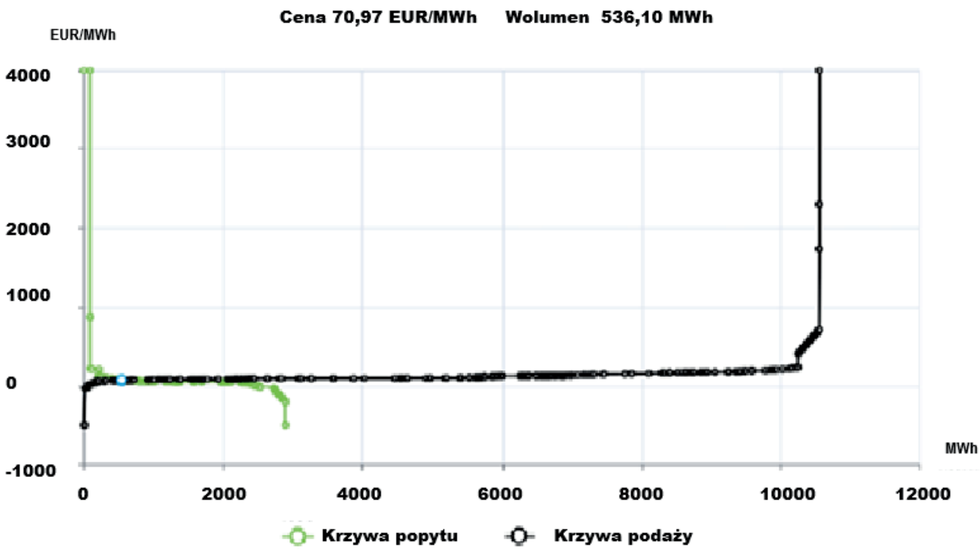

Fig. 1. Aggregated curves of energy purchase and sale offers (TGE SA)

According to the data, energy trading on the exchange accounts for approximately 20% of the total energy volume in the system. While this represents a significant element of the overall market, it is essential to explore the factors influencing

[3] Cf. contractual, in which trading takes place in the form of contracts concluded directly between market participants; stock exchange, where trading takes place in the form of transactions and contracts concluded on the energy exchange or through it and with the help of commercial and technical operators; balancing, in which the transmission system operator balances the difference between the supply and current demand for electricity using balancing offers.

the substitution of conventional energy sources with renewable energy. Identifying these drivers and barriers can provide valuable insights into the transition toward sustainable energy systems.

In accordance with the effective electricity trade and the primary objective of the national power system, ensuring an uninterrupted supply of electricity in the required amounts for consumers at all times, it is worth analyzing energy demand trends in Poland on working days, Saturdays and Sundays during the summer and winter solstices (fig. 2). As can be seen, annual energy demand oscillates between 12.3 and 24.8 GW. However, daily variability is equally important and can amount to nearly 7.7 GW.

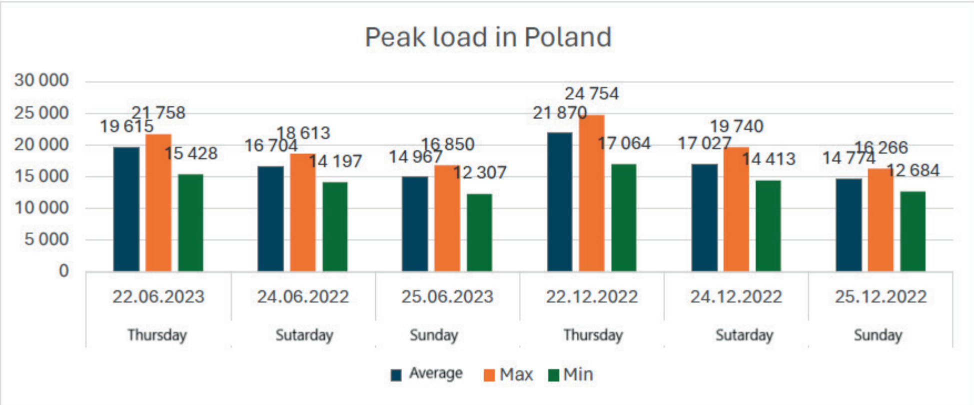

Fig. 2. Electricity demand on working days, Saturdays and Sundays during the summer and winter solstice (own study based on data from PSE SA)

In accordance with applicable legal regulations, energy generated from renewable energy sources has priority in terms of its introduction into the national power system. However, due to the obligation to ensure the safe operation of the National Power System, in 2023, PSE SA. implemented, for the first time, preventive exclusions of certain renewable energy units. This is due to the operating parameters of conventional power units, which, in order to maximize durability, are subject to a technical minimum, which collectively forms the rotating reserve of the system, below which the output of conventional units should not be reduced (Trzeszczyński, Dobosiewicz, Stanek, 2019). According to the PSE announcement dated April 23, 2023, the rotating reserve was at the level of 9 GW of generating capacity, but this value varies depending on the season. Table 1 presents a summary of the types of generation operating in the National Power System in Poland.

Table 1. Capacity of the types of generating units operating in the National Power System in June 2023

Energy source	Capacity [MW]
JWCD	27 770
Stone coal	*16 114*
Brown coal	*8 249*
Gas	*3 407*
nJWCD	8 773
Stone coal	*7 450*
Brown coal	*128*
Gas	*1 195*
Hydro	2 504
Wind	9 698
Photovoltaics	16 190
Biomass	275
Heating oil	747
Coke oven gas	158
Sum	66 115

Source: own study based on data from PSE SA.

An important mechanism to take into account in network balancing is cross-border electricity exchange with neighboring countries. Analysis of the data published by PSE S.A. indicates a strong correlation between domestic photovoltaic units and electricity exchanges with Lithuania and Slovakia (Włoch, 2023).

Taking into account the operational characteristics of the power system, which require that electricity be consumed at the moment production, the capacity for integrating privileged renewable energy is determined by three factors, i.e., momentary demand, rotating reserve, and the momentary cross-border exchange capacity.

An equally important phenomenon in the period under study was Russia's military aggression against Ukraine, which resulted in a rapid change in fuel suppliers for industrial energy. As a result, Figure 3 shows the TGeBASE_WAvg index, illustrating the volatility of energy prices over the past two years.

In accordance with the aim of this article, the following factors shaping energy prices on the Polish Power Exchange can be indicated.

Energy prices

Analyzing the data below regarding the average energy prices on the Polish Power Exchange[4] for the 2022-2023 period[5], the energy price in August 2022 (PLN 1,391 / MWh) should be considered an anomaly. The direct cause of this market distortion can be attributed to the summer period, during which many customers contracted energy in futures contracts, e.g., quarterly, and the remaining European customers were actively seeking new fuel supply markets. Increased demand and the resulting lack of raw material guarantees resulted in rising prices by producers. This increased demand, coupled with uncertainty regarding fuel availability, led to a shortage of raw material guarantees, ultimately driving producers to raise prices.

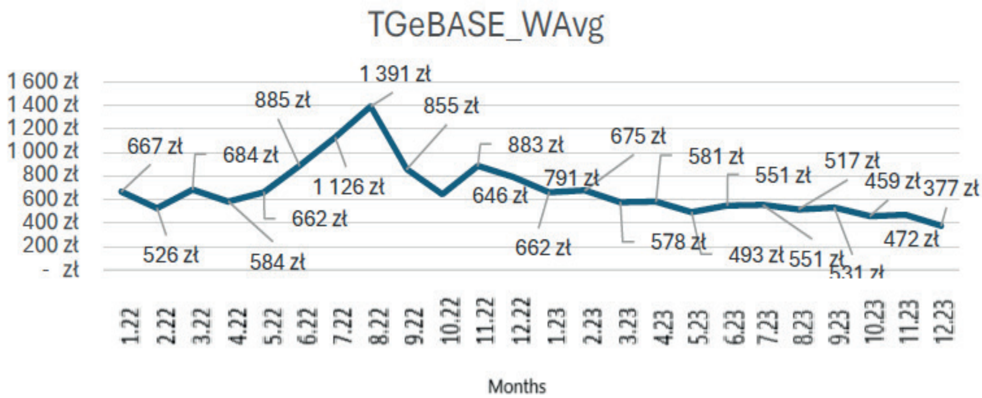

Fig. 3. Average energy price on the Polish Power Exchange in the period 2022-2023 (own study based on data from TGE SA)

[4] Energy price data were obtained from official reports of the Polish Power Exchange (TGE) and Polskie Sieci Elektroenergetyczne (PSE SA), as well as from analytical platforms such as Investing.com (Investing, 2024). Indicators such as TGeBASE_WAvg were used to track energy price dynamics. Additionally, we will emphasize the differences between the pricing mechanisms of the Day-Ahead Market and the futures market. As noted by Loumakis et al. (2019), the Day-Ahead Market is more susceptible to short-term supply and demand fluctuations, whereas futures contract prices depend on forecasts related to energy production costs and geopolitical conditions.

[5] Historical data show that before 2022, energy prices on TGE's Day-Ahead Market exhibited a steady upward trend. However, several key factors accelerated this increase after 2021, including: Rising CO_2 emission allowance prices – According to Investing.com, ETS allowance prices increased from around €25/t in 2020 to over €80/t by the end of 2021, significantly impacting the cost of coal- and gas-based energy production (Investing, 2024). Supply chain disruptions – Gas supply disruptions, combined with Gazprom's market strategies, led to rising energy prices across Europe in 2021. Rapid development of renewable energy – The increasing share of renewables, especially solar and wind power, introduced greater volatility in electricity prices due to their intermittent nature.

The price of CO_2 emissions

In each variable, an equally important factor influencing energy prices is the cost of CO_2 emission allowances. Figure 4 presents the quotations for CO_2 emission futures contracts.

Fig. 4. Quotations of CO2 emission futures contracts
(https://pl.investing.com/commodities/carbon-emissions, access date: 29.01.2024)

Fuel prices

Another factor influencing energy prices is fuel prices. Figure 5 presents the development of coal prices in Rotterdam.

Fig. 5. Coal futures quotations in Rotterdam
(https://pl.investing.com/commodities/rotterdam-coal-futures, access date: 29.01.2024)

The description presented in this way indicates various factors in shaping energy prices on the Polish Power Exchange.

2. K – MEANS METHOD

Machine learning is being applied in an increasing number of new areas. The entry point for applying this methodology is the availability and quality of the dataset. One of the biggest challenges these days is the method of data collection, which translates into its subsequent possibility of analysis. Among the various machine learning techniques, the focus is on k-means clustering.

The k-means method is widely used in data analysis across various fields. The advantage of the k-means method is its intuitive and simple computational approach. The subject of the analysis is a set of n objects (e.g., a sample representing energy prices, with its characteristic of the day and the price for a given day), each described by m features (also known as diagnostic variables). The aim of the analysis is to find the optimal division of the initial set of objects into k subsets, where the quality criterion of the division is maximixing the inter-group variance of diagnostic variables (or equivalently, minimizing the intra-group variance). In the k-means method, the distance between objects is determined using the Euclidean distance or its square (the specificity of the algorithm means that the results are the same in both cases) (Markowska M., Sobolewski M.).

This approach enables the analysis of a dataset to isolate characteristic subsets. Thanks to the use of IT tools, it is also possible to perform analyses on three-dimensional datasets. Energy prices were obtained directly from the Polish energy market, Towarowa Giełda Energii SA, specifically from the "Fixing I" values on the day-ahead market. Additionally, data on energy demand, imports, and exports were sourced from the transmission system operator, Polskie Sieci Elektroenergetyczne SA.

The collected data covers the years 2022 and 2023, aiming to illustrate how energy markets responded during the war crisis (Russia–Ukraine) and the post-war period. The data covers full calendar years, as this represents a complete cycle of energy price and demand fluctuations influenced by seasonal variations. These fluctuations are driven by weather conditions, including temperature, heating demand, and daylight duration, all of which impact the balance between energy demand and supply. As shown in Figure 2, electricity demand varies significantly by season, reflecting shifts in consumption patterns and the broader energy market dynamics.

For the purposes of the analyses, a data standardization process was carried out to focus on variance and ensure that each variable was the same. For this purpose, each set was scaled so that the value of zero corresponds to the value of the arithmetic mean, the value of –1 corresponds to the value of the arithmetic mean minus the standard deviation, and the value of 1 corresponds to the mean plus one standard deviation. Table 2 presents the standardized values for each subset.

Table 2. Values of the arithmetic mean and standard deviation for individual sets

	2022-2023			2022			2023		
	Energy price [PLN]	Conventional energy demand	Import/ export	Energy price [PLN]	Conventional energy demand	Import/ export	Energy price [PLN]	Conventional energy demand	Import/ export
Average	649,41	15 514,14	185,80	787,89	16 575,54	–105,35	510,86	14 452,29	476,72
Standard deviation	334,97	3 641,93	1 016,38	392,35	3 389,60	695,05	179,27	3 575,66	1 189,11

Source: own study based on data from PSE SA.

The first dataset examined covered the period from January 1, 2022 to December 31, 2023. Figure 6 provides a graphical representation of the "elbow analysis". As observed, the analysis identifies a distinct breakpoint (the so-called elbow) at 4 clusters, indicating that 4 clusters should be considered the optimal number for segmenting the data.

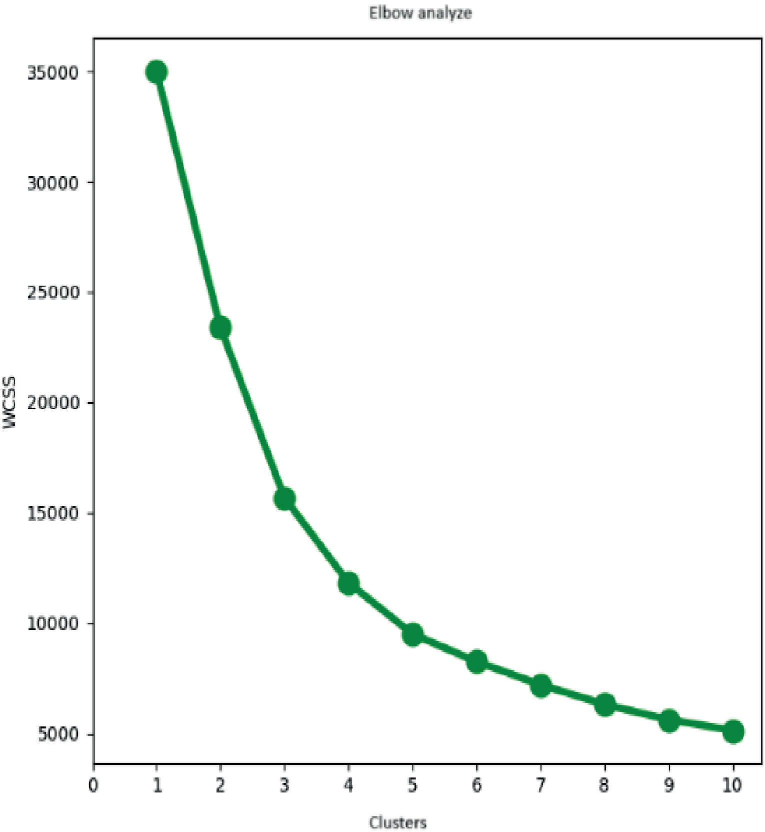

Fig. 6. Graphical presentation of the elbow analysis for data from the period 2022-2023 (own study)

Figure 7 presents the result of energy price clustering in relation to the demand for black energy. The locations of the centroids are marked in yellow.

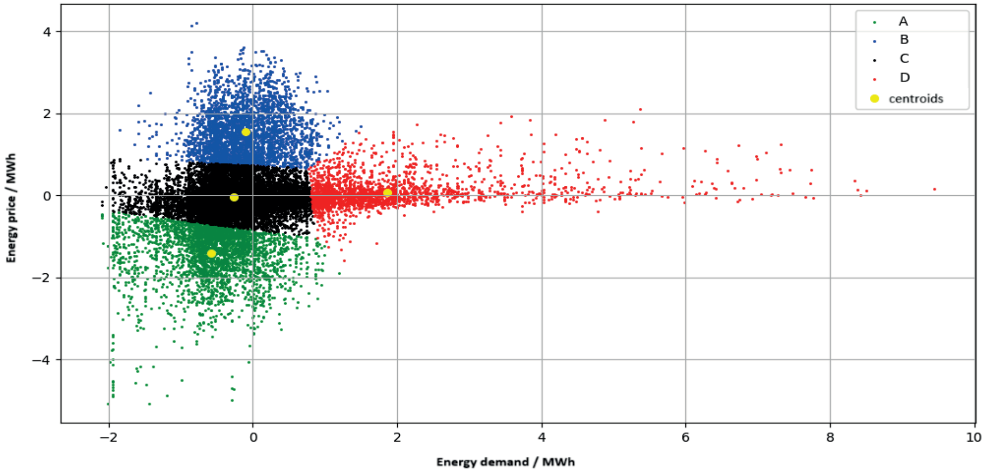

Fig. 7. Clustering of energy price data in relation to the demand for black energy in the period 2022-2023 (own study)

Figure 8 presents the result of clustering cross-border energy exchange in relation to the demand for black energy.

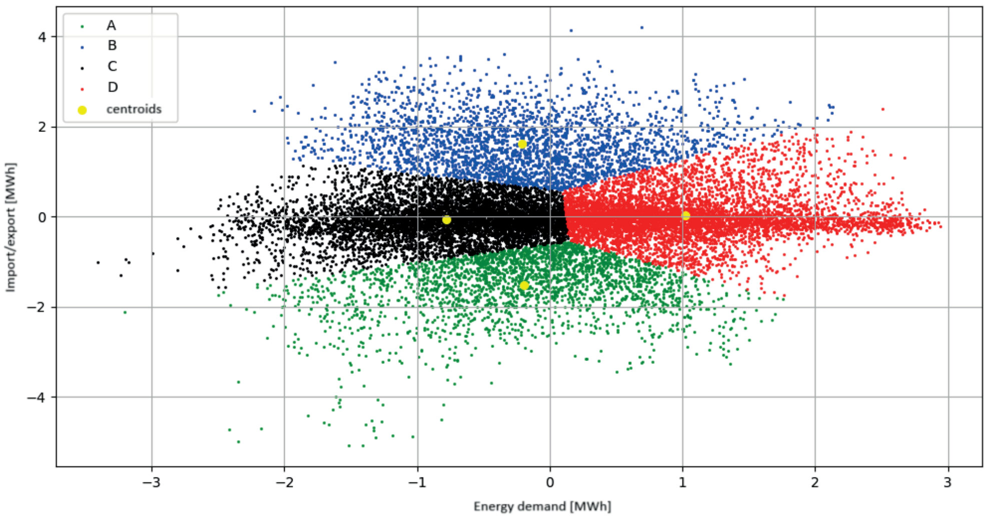

Fig. 8. Clustering of cross-border exchange data in relation to the demand for black energy in the period 2022-2023 (own study)

Figure 9 presents the result of clustering in a three-dimensional system, sets characterized by energy prices, the level of cross-border exchange and the level of demand for black energy.

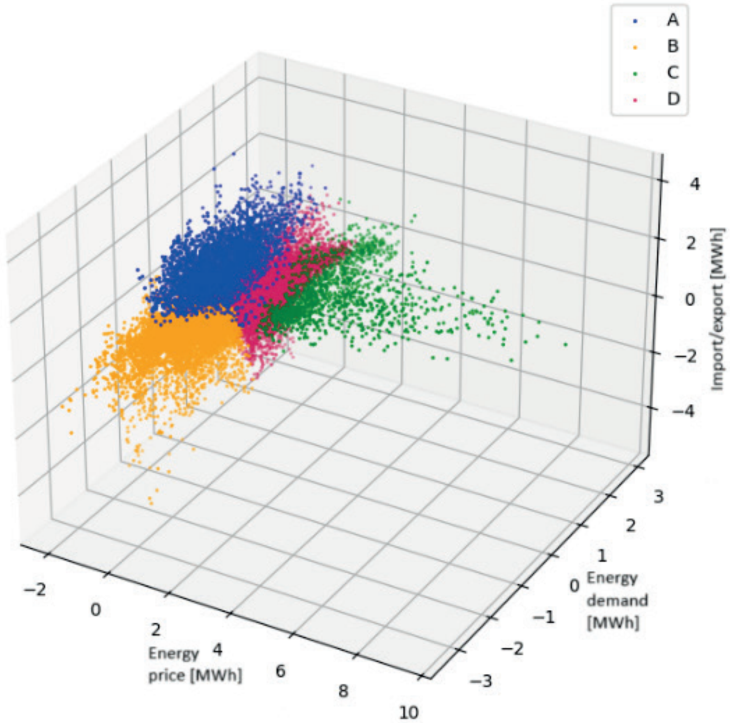

Fig. 9. 3D clustering of cross-border exchange data in relation to the demand for black energy in the period 2022-2023 (own study)

Charts 10 to 13 present the results of similar analyzes as above, but for the period from January 1 to December 31, 2022.

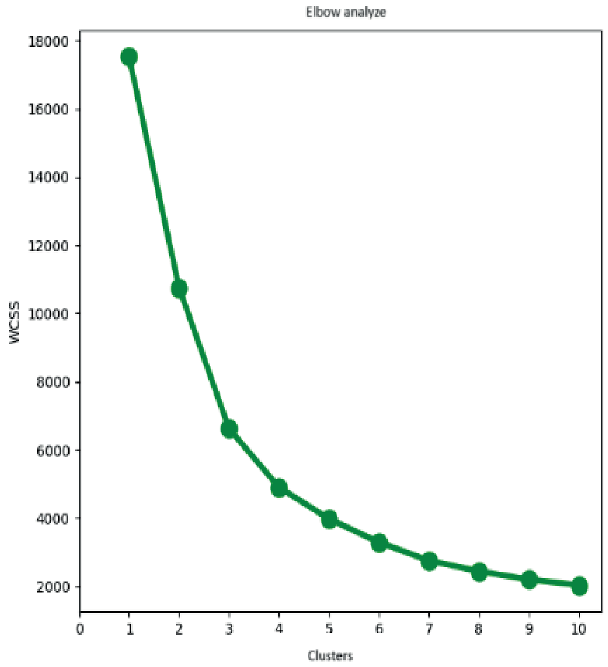

Fig. 10. Graphical presentation of the elbow analysis for data from 2022 (own study)

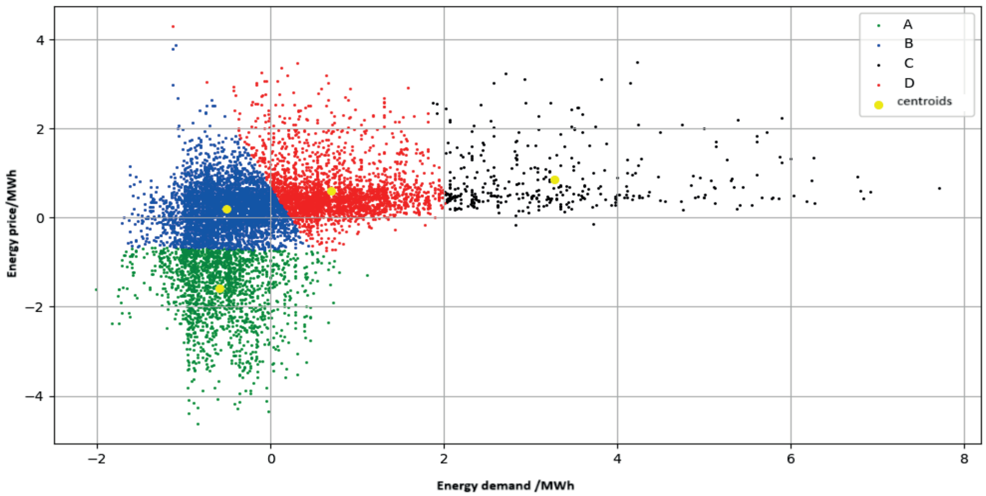

Fig. 11. Clustering of energy price data in relation to the demand for black energy in 2022 (own study)

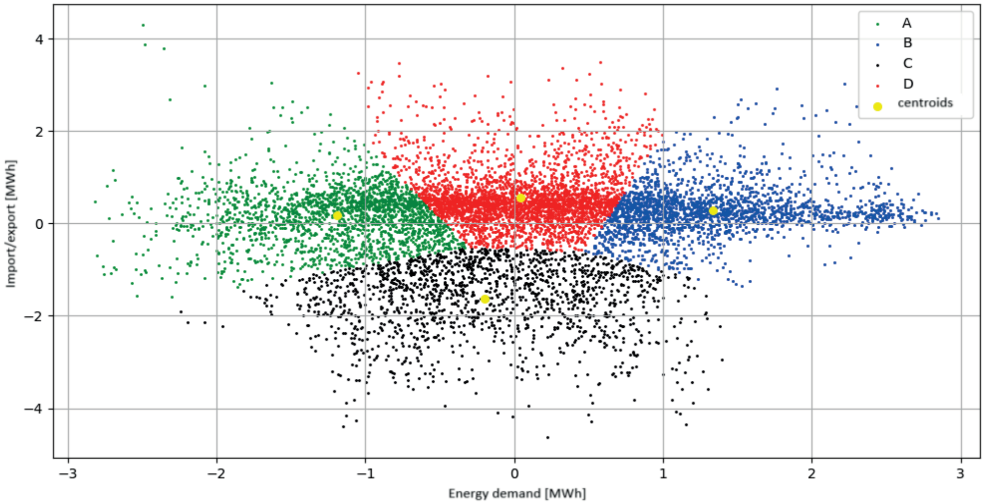

Fig. 12. Clustering of cross-border exchange data in relation to the demand for black energy in 2022 (own study)

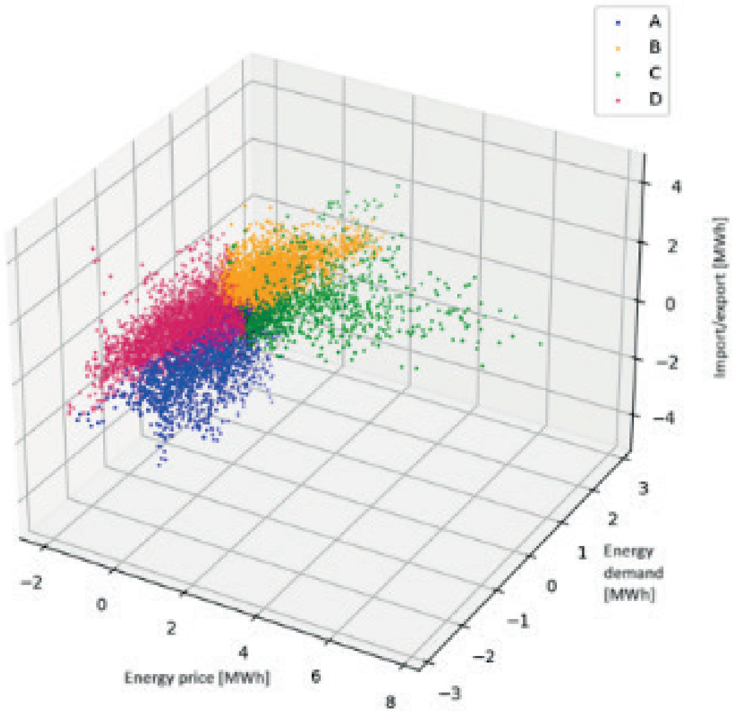

Fig. 13. 3D clustering of cross-border exchange data in relation to the demand for black energy in 2022 (own study)

Figures 14-17 present the results of similar analyzes as above, but for the period from January 1 to December 31, 2023.

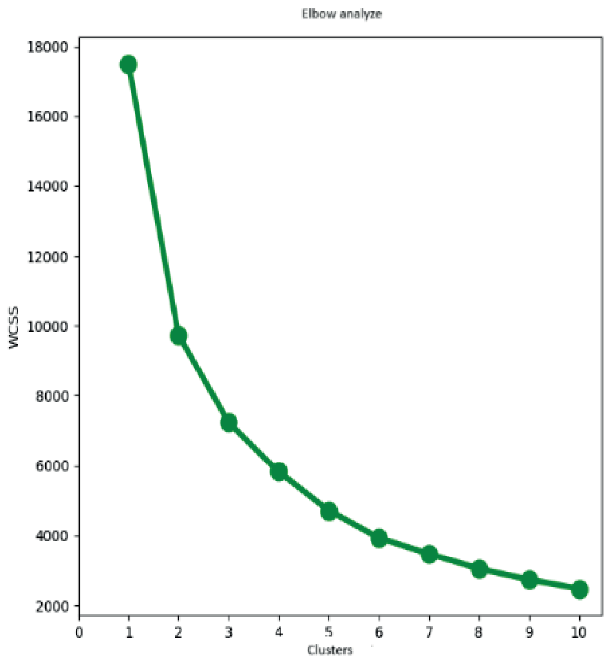

Fig. 14. Graphical presentation of the elbow analysis for data from 2023 (own study)

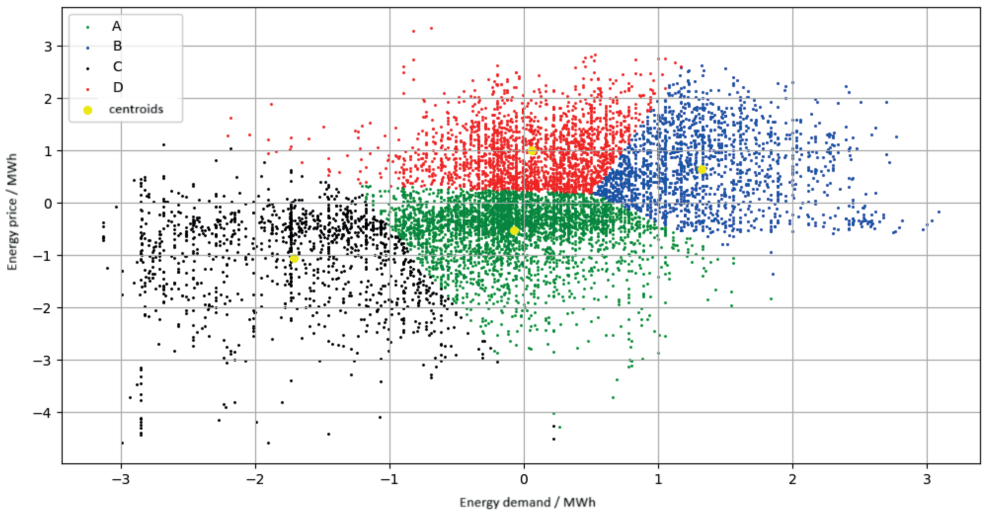

Fig. 15. Clustering of energy price data in relation to the demand for black energy in 2023 (own study)

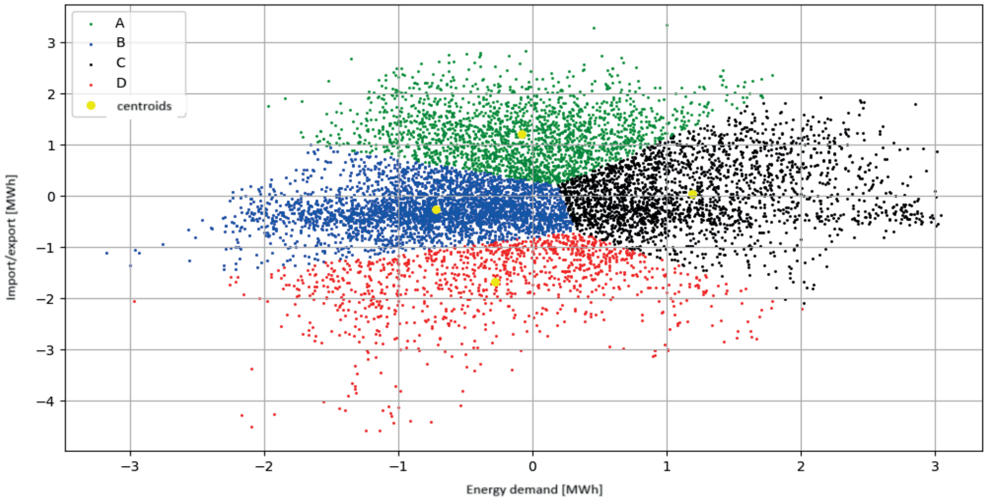

Fig. 16. Clustering of cross-border exchange data in relation to the demand for black energy in 2023 (own study)

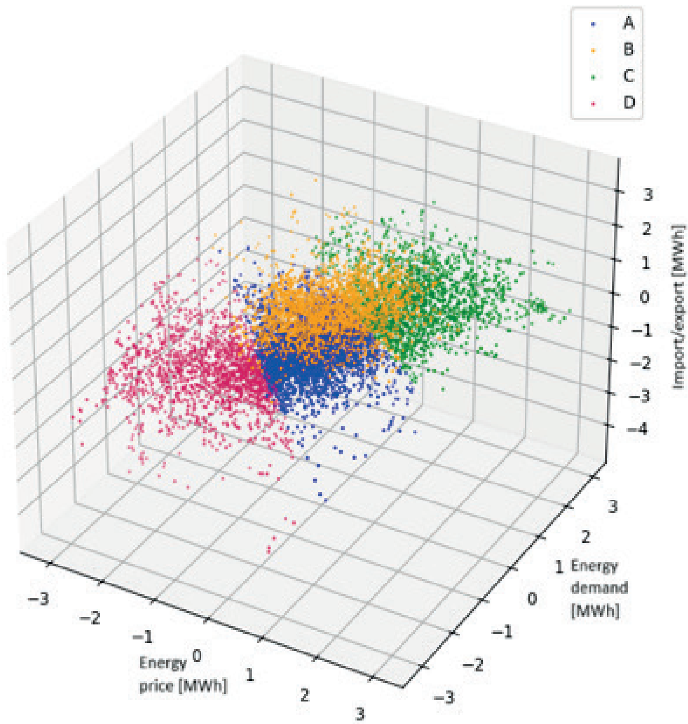

Fig. 17. 3D clustering of cross-border exchange data in relation to the demand for black energy in 2023 (own study)

3. DISCUSSION ON THE OBTAINED RESULTS

In accordance with the objective of the article, the results of using the clustering technique to assess energy price quotations on the Day-Ahead Power Exchange are presented. The analysis covers two contrasting years: a year of stable quotations (2023) and a year of anomalies (2022), characterized by significant market turbulence due to Russia's armed aggression against Ukraine.

Based on the analysis, it can be concluded that in each analyzed case the optimal number of clusters is 4.

Table 3. Results of statistical analysis of the analyzed sets

	Energy price		
	2022	2023	2022-2023
Average	787,97 PLN	510,90 PLN	649,41 PLN
Median	699,50 PLN	512,00 PLN	580,00 PLN
Standard deviation	392,30 PLN	179,25 PLN	334,97 PLN
quartile 25%	521,00 PLN	421,00 PLN	464,00 PLN
quartile 75%	950,00 PLN	620,00 PLN	752,00 PLN
Maximum	3 812,00 PLN	1 064,00 PLN	3 812,00 PLN
Minimum	–PLN	–50,00 PLN	–50,00 PLN
	Conventional energy demand		
	2022	2023	2022-2023
Average	16 576	14 453	15 514
Median	16 463	14 173	15 344
Standard deviation	3 389	3 576	3 642
quartile 25%	14 172	11 875	12 938
quartile 75%	18 877	16 723	17 985
Maximum	26 222	25 319	26 222
Minimum	7 034	3 114	3 114

	Import/export		
	2022	2023	2022-2023
Average	–105	477	186
Median	46	373	140
Standard deviation	694	1 189	1 016
quartile 25%	–382	–142	–264
quartile 75%	258	1 262	625
Maximum	2 886	4 458	4 458
Minimum	–3 321	–4 973	–4 973

Source: own study.

Comparing 2022 and 2023 based on energy price samples, it is evident that in 2022 there were many samples that could be classified as anomalies, which significantly differed in price level, in relation to the population. The cross-section for 2022 is also confirmed by the large difference between the arithmetic mean price and the median. Also noteworthy is the range between the 25% quartile and the 75% quartile, which for 2022 is more than twice as large as for 2023. In the case of energy demand, it can be said that the dynamics of the data is the same, but the level of demand differs. In 2022, the demand for black energy[6] was on average 2 GWh more.

In terms of cross-border exch. In 2022, the difference between the median and the average was close to zero, indicating that cross-border exchange did not have a significant impact on energy provision. However, in 2023, both the average and median values indicate significant imports, averaging 477 MWh, which can be read as a change in market dynamics. Identifying four clusters aligns with the daily energy demand pattern, encompassing the lowest demand during nighttime hours, a rise in demand at dawn, peak consumption during daytime, and a gradual decline in the late evening hours.

[6] In the literature, this term refers to electricity generated from conventional fossil fuel-based sources, mainly hard coal, lignite, and natural gas. It contrasts with "green energy", which comes from renewable sources such as wind, solar, biomass, and hydropower (Kusz, 2017; Wójcicki, 2015).

4. SUMMARY

Based on the research conducted, it can be confidently stated that the k-means clustering analysis is effectively used in the analysis of the energy market in Poland. From a scientific perspective, the application of clustering methods allows for a better understanding of the dynamics of the energy market. The use of this method enables the identification of price groups depending on market factors, which can help forecast future price fluctuations, analysis of the impact of market anomalies (e.g., the Russia-Ukraine war) on energy price structure and volatility, and verification of energy price formation patterns, determining whether they follow consistent trends or are largely irregular and difficult to predict. The article provides a new perspective on energy price analysis by using clustering methods to identify structural differences in price formation mechanisms between periods of stability and crisis. As a result of the analysis conducted for the period from January 1, 2022 to December 31, 2023, the optimal number of clusters can be defined at four. Their division is related to the level of demand for energy produced from conventional energy sources. This result is justified by the price formation mechanism on the Polish Power Exchange, known as the Merit Order principle, and the Merit Order effect. The latter is driven by the increasing penetration of renewable energy sources in the market, which displaces energy from the most expensive generation units. Based on the obtained results, further analysis of the use of the clustering method in the energy market should focus on searching for additional factors that may influence energy price characterization. These factors could include CO_2 emission allowance quotations, raw material price fluctuations, and weather conditions.

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ANALIZA KLASTERYZACJI NOTOWAŃ CEN ENERGII Z RYNKU DNIA NASTĘPNEGO (RDN) (DAY-AHEAD-TRADING) TOWAROWEJ GIEŁDY ENERGII (TGE) W POLSCE W LATACH 2022-2023 Z ZASTOSOWANIEM METODY K-ŚREDNICH

Streszczenie

Energia elektryczna na TGE podlega obrotowi w ramach Rynku Dnia Następnego (RDN) oraz rynku terminowego. W przypadku RDN sprzedawcy i nabywcy składają oferty dostawy i nabycia energii na dzień następny. Rynek europejski ma szeroką ofertę dostawców, ceny energii uzależnione są od jej cen obowiązujących w innych krajach. Na tym rynku dziś składane oferty dotyczą dostaw energii dopiero za rok, a to oznacza, że producenci muszą niejako przewidzieć koszty wytworzenia energii, jakie poniosą za wiele miesięcy. Podejście zmienia sposób postrzegania energii elektrycznej na rynku jako towar. Istnieje wiele czynników wpływających na kształtowanie cen energii na Towarowej Giełdzie Energii. Do najważniejszych zaliczyć można: ceny paliw, ceny emisji ETS, uwarunkowania pogodowe itd. Celem niniejszego artykułu jest przedstawienie wyników zastosowania techniki klasteryzacji do oceny notowań cen energii na Towarowej Giełdzie Energii Rynku Dnia Następnego z perspektywy roku stabilnych notowań (2023), jak i roku anomalii (2022, spowodowanych agresją zbrojną Rosji wobec Ukrainy). Na podstawie badań można stwierdzić, że analiza klasteryzacji k-średnich jest stosowana w analizie rynku energii w Polsce. W okresie od 1.01.2022 r. do 31.12.2023 r. optymalna liczba klastrów została określona na cztery, co jest związane z zapotrzebowaniem na energię z konwencjonalnych źródeł. Wynik ten jest uzasadniony mechanizmem kształtowania cen na Polskiej Giełdzie Energii tzw. zasadą Merit Order, która uwzględnia wpływ energii z odnawialnych źródeł wypierającej energię z najdroższych jednostek. Dalsza analiza powinna skupić się na innych czynnikach wpływających na ceny energii, takich jak notowania uprawnień do emisji CO_2, ceny surowców i warunki pogodowe.

Słowa kluczowe: Towarowa Giełda Energii, metoda k-średniej, klasteryzacja