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STRUCTURAL CHANGES IN PRIMARY ENERGY PRODUCTION AND THEIR IMPACT ON AIR POLLUTANT EMISSIONS IN POLAND IN THE LIGHT OF THE EU ENVIROMANTAL AND CLIMATE OBJECTIVES

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Purpose: The purpose of this article is to evaluate the dynamics of changes in the structure of gross available energy and to analyze the process of decarbonization and air protection in Poland against the background of the European Union over the 2014-2022 period.
Design/methodology/approach: The paper presents an analysis of the dynamics of structural changes in the production of gross available energy in Poland, compared to the other EU countries. To verify the hypothesis, synthetic measures of the similarity of structures and measures of the dynamics of the intensity of structural change were used. An analysis of the decarbonization process in the EU countries was conducted.
Findings: The structure of gross available energy in Poland and the other EU countries varied in the analyzed period. From 2014 to 2022, the intensity of the rate of change in the analyzed structures was relatively low. However, the acceleration of the energy transition process observed in 2022 resulted in an increase in the rate of decarbonization.
Practical implications: The results show that the rate of energy transition in Poland and the other EU countries varies. If the differences in the energy transition process and the degree of decarbonization of economies in different countries and regions of Europe are taken into account, the assumed EU-wide options for reducing the volume of emissions and the rate of decarbonization become feasible.
Originality/value: Achieving net zero emissions by 2050 requires rapid and profound changes in the decarbonization process. The most effective instruments in the decarbonization and air protection process are changes in the structure of electricity production. However, the rate of change in the field in Poland and the other EU countries varies. Failure to take these differences into account will make it virtually impossible to achieve the net zero emissions target.
Keywords: energy transition, decarbonization, synthetic measures of similarity of structures.
Category of the paper: Research paper.

1. Introduction

We are living at a time when global warming has reached 1.48°C above pre-industrial levels. Ocean temperatures and glacier melt are reaching record highs. The observed climate change is contributing to unprecedented forest fires, floods, severe droughts, and heat waves. Reducing emissions seems to be the only way to avoid the worst effects of climate change and to improve the quality of life, protect health and the proper functioning of ecosystems. The European Climate Law and the Fit for 55 legislative package, both effective from 2021, oblige all of the EU countries to reduce net greenhouse gas emissions by at least 55% by 2030, compared to 1990 levels. In December 2023, the European Commission proposed a new climate target for 2040. Reaching it will reduce dependence on imported fossil fuels, improve air quality, result in human welfare and benefit biodiversity. Efforts of countries in terms of energy transition focus mainly on the power sector, as it accounts for one of the largest shares of global greenhouse gas emissions. Global studies indicate that in the near future conventional energy sources based on fossil fuels will no longer be acceptable for both environmental and economic reasons.

The primary goal of this study is to analyze the dynamics of changes in the structure of gross available energy and to evaluate the process of decarbonization and air protection in Poland against the background of the European Union from 2014 to 2022, using data from the Eurostat database. The main research hypothesis is: "the rate of change in the structure of electricity production in the 2014-2022 period in Poland and in the EU countries varies, which translates into differences in decarbonization and air protection". To verify the hypothesis, synthetic measures of the similarity of structures and measures of the dynamics of the intensity of structural change were used.

The article is structured as follows. The next part of the article includes a review of literature on the impact of energy production structure analysis on the decarbonization process. The main part of the article is divided into three sections. The first one analyzes the decarbonization process in Poland and other EU countries. The second section describes the research methodology. Section three includes the results of the research. The closing section presents conclusions, recommendations, practical implications and limitations of the research.

2. Literature review

The subject literature lists various approaches and methods for analyzing the rate of change in the structure of energy production and its impact on the decarbonization process. Much of the research focuses on factors affecting the share of renewable energy in generation of electricity. He et al. (2018) used panel studies to examine the impact of technological innovation factors on individual renewable energy sources. Lau et al. (2018) used dynamic ARDL (Autoregressive Distributed Lag) models to examine long-term relationships between the level of renewable energy use, carbon emissions, the level of economic growth and the level of foreign investment in Malaysia. Hassan et al. (2022) analyzed the two main determinants of renewable energy development: the possibility of exploiting natural resources and the uncertainty of climate policy. In their research, they used Markov switching models. Sadorski (2009), in his research from 2009 on the G7 countries showed, using Pedroni cointegration tests, that the most important determinants of renewable energy use are carbon emissions and real GDP per capita. Different findings were obtained by Ahmadi & Firkha (2022) for the US for the 1960-2007 period. Using updated Granger causality test, they discovered a lack of causality between carbon emissions and renewable energy.

Studies on evaluation of the development of renewable energy in the EU were conducted by Rodriges et al. (2020), Adedoyi et al. (2020), Del Rio et al. (2017), Dascalu (2012). Interesting results were presented in the work by Cross et al. (2015). In their study, the authors demonstrated the problem of disproportion in using modern renewable energy generation technologies in the northern European countries. This phenomenon may have a significant influence on the decarbonization process and constitute a factor in achieving the EU climate goals. In the subject literature, there are also numerous review articles on barriers to renewable energy development. Works by Del Río et al. (2018), Eleftheriadis et al. (2015) are some of the most interesting ones.

Changes in economic structures play a very important role in pursuing environmental goals (Fernández González et al., 2014; Jeong, Kim, 2013; Xu et al., 2014). The subject literature includes numerous studies aimed at the evaluation of the quantification of the effects of the structure on the environment. Research in this area mainly focuses on changes in the sectoral structure of the economy (Ang, 2004; Enkhbat et al., 2020), on the structure of electricity production (Jesus et al., 2020) or product structure of typical consumer baskets (Kastner et al., 2012). Factors that influence the environment are often analyzed using the IDA index decomposition analysis (Ang, 2004; Plank, Eisenmenger, 2018). The most popular methods in this respect are: the Laspeyres index and the Divisia index (Granel, 2003). Since Laspeyres indices can make interpretation of the results difficult as they may leave potentially large residuals, various modifications of these indices were used, and Fischer ideal indices were modified (Ang et al., 2004). The literature shows that Divisia indices, which include the Arithmetic Mean Divisia Index (AMDI) and the Logarithmic Mean Divisia Index (LMDI), which provide an ideal distribution (i.e., leave no residual component), are frequently used in studies. The measure which is most widely used by researchers, institutions and statistical offices (including Eurostat) involved in public surveys and environmental impact assessments is the LMDI (Plank, Eisenmenger, 2018). Unfortunately, the IDA or LMDI methods are not without flaws (Roux, Plank, 2022).

Many research papers also devoted to topics connected with changes in carbon dioxide emissions caused by different energy sources.

Research on the EU focuses mainly on the energy transition in the context of achieving climate goals. Deka A. et al. (2022), using the GMM (generalized method of moments) methodology, showed that high economic growth coupled with high fossil fuel consumption has a direct impact on rising carbon dioxide emissions. The authors studied the impact of GDP level, population, effective capital and the structure of electricity production on carbon dioxide emissions in the EU from 1990 to 2019. Lau et al. (2018) also analyzed the impact of changes in the structure of energy production on greenhouse gas emissions, with a focus on the level of use of renewable and nuclear energy. To study similar topic, De Boer et al. (2020) used the Logarithmic Mean Divisia Index. The practical application of the LMDI methodology in China's energy and climate policy and carbon reduction recommendations was presented in the work by Ma et al. (2019). Changes in carbon dioxide emissions in 23 countries with the highest share of renewable energy consumption between 1985 and 2011 using LMDI were also studied by Moutinho et al. (2018). The application of LMDI in the study on the causes of global emissions growth between 1997 and 2015 can also be found in the work by Dong et al. (2020). In their study, the authors suggested that the carbon reduction process in highly industrialized countries should be higher than in developing countries, accompanied by support to developing countries in the transition to a low-carbon economy. Factors influencing the variation in carbon dioxide emission levels in 21 European countries before and after the Kyoto Protocol were studied by Moutinho et al. (2015). The authors proved that the consumption of renewable energy is also affected by country-specific factors, such as the size and structure of the economy. An interesting combination of the Index Decomposition Analysis (IDA) and the LMDI method to isolate the factors influencing changes in carbon emissions intensity in different regions of China over 14 years was used by Ma et al. (2022). Another interesting study was conducted by Dong & Pan (2020), in which the extended Kay identity equation and the LMDI approach were combined to examine factors, including changes in carbon emissions, affecting variations in renewable energy consumption in 23 BRI countries. The Logarithmic Mean Divisia Index (LMDI) is a widely used index decomposition method, but it has several significant limitations that must be taken into account when using it. Roux and Plank (2022) presented the limitations of the method in interpreting structural effects when changes in the structure of shares are characterized by similar intensity of change. Application problems with LMDI also concern data sets in which there are zero or near-zero share values. Also, when analyzing large data sets where there are zero or large changes in values over time, the accuracy of the LDMI method decreases significantly (Wood, Lenzen, 2006). In light of the above limitations, the article abandons the LDMI method in favor of alternative methods, as the data used contains multiple zero values.

An analysis of the literature enables the conclusion that there is no single universal method for studying the structure of electricity production and estimating the factors affecting the volume of renewable energy. The most commonly used methods are those based on the LMDI. There is also a lack of up-to-date research on the structure of gross available energy production and its relationship to the decarbonization processes in the EU. The paper comprehensively analyzes recent progress in the use of renewable energy in the generation of gross available electricity over the past decade in the context of achieving the EU climate goals.

3. Decarbonization process in Poland and the other EU countries in 2014-2022

Greenhouse gas emissions have a direct impact on climate change and represent one of the biggest challenges in the world today.

Under the Paris Agreement, which came into force in November 2016, nearly 190 countries around the world, including all EU countries, pledged to prevent an increase in global warming. Meeting this goal requires achieving a 45 percent reduction in greenhouse gas emissions by 2030 relative to 2010, and a total reduction by the middle of the century. Every five years, the countries participating in the Paris Agreement submit updated NDC emission tables to the UN system with the understanding that they should be more ambitious than the previous ones. Unfortunately, the analyses show that the majority of the national policies presented are insufficient to achieve the Paris Agreement. Crucial in this respect are the most prosperous countries. The affluent G20 countries with strong economic potential, including, among others, the United States, Australia, Brazil, India, and China, which are currently the largest emitters of greenhouse gases, and countries that rely on the extraction and sale of fossil fuels, such as Russia, Saudi Arabia and Iran, are reducing emissions insufficiently.

The 28th UN Climate Change Conference (COP 28) was held in Dubai in December 2023 to measure progress toward the climate goals detailed in the Paris Agreement. The need to reduce greenhouse gas emissions by 43 percent by 2030 and by 60 percent by 2035 compared to 2019 levels was emphasized. The COP 28 revealed that some of the countries are still a long way from achieving the goals of the Paris Agreement.

In Europe, climate policies and energy strategies are key to achieving sustainable development and meeting the goals of the European Green Deal. When analyzing the directions and dynamics of changes in greenhouse gas emissions in Poland, it is necessary to consider the impact of political, technological and social measures on reducing emissions in various sectors of the economy at the level of the European Union as a whole.

As required by the Paris Agreement, the European Union has submitted a long-term emissions reduction strategy and updated climate plans before the end of 2020. In the plans, the EU pledged to reduce emissions by at least 55 percent by 2030 compared to 1990, and to become climate neutral in 2050, which means achieving a balance between the amount of greenhouse gases emitted and absorbed. These are the key tenets of the European Green Deal and the Fit for 55 Package, which is part of it.

On 6 February 2024, the European Commission unveiled an ambitious new target to reduce net greenhouse gas emissions by 90 percent by 2040 compared to 1990 levels. It is an intermediate step toward achieving climate neutrality by 2050.

In recent decades, the European Union made significant progress in reducing greenhouse gas emissions. In 1990, the emission level of CO_2 equivalent was 4.9 gigatons. The recovery of the economy after the COVID-19 pandemic resulted in a short-lived increase in emissions, which came back to a downward trend in subsequent years. According to the European Commission, the EU greenhouse gas emissions in 2021 and 2022 were lower, respectively, by 28.5% and by around 31%, compared to 1990s levels. The volume of total net greenhouse gas emissions in the EU in 2022 was 3.24 billion metric tons of CO_2 equivalent ($GtCO_2e$). This represents an overall reduction of about 1.3% compared to 2021. In 2023, the emissions in Europe were 8% lower than in the previous year.

Interesting findings are offered by the analysis of per capita emission levels in individual EU countries. The per capita GGE levels in each of the EU countries in 2014 and 2022 are presented in Figure 1.

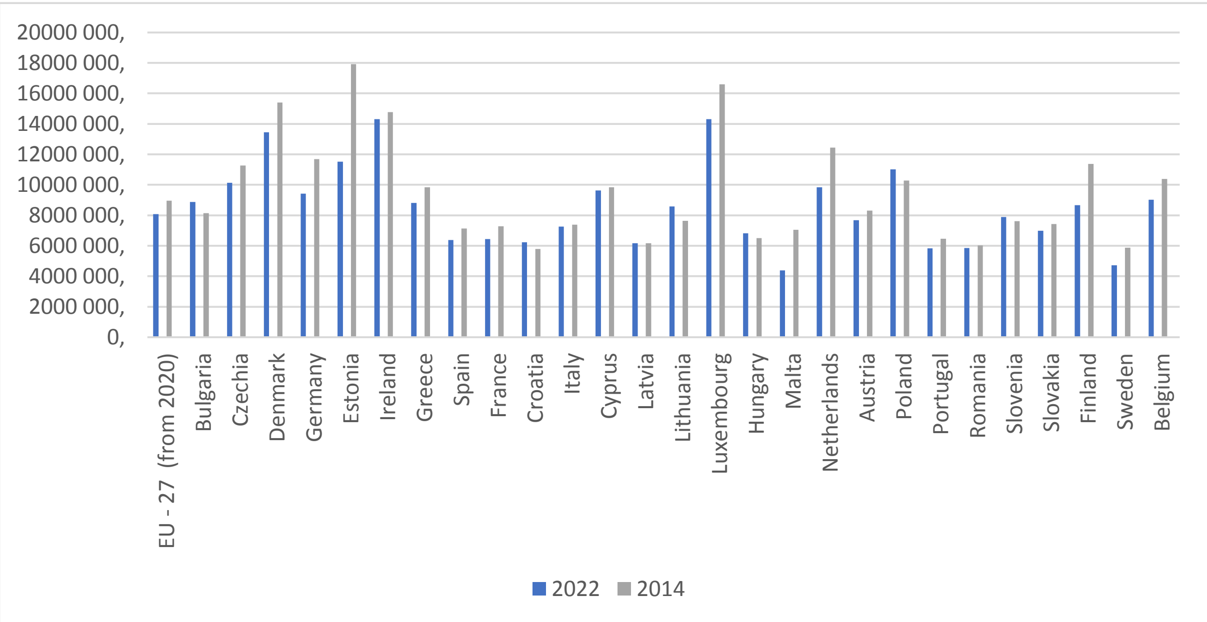

Figure 1. The per capita GGE levels in each of the EU countries in 2014 and 2022. (Grams per capita). Source: Own elaboration based on data published by Eurostat.

In 2014, the highest level of about 18 tons of CO_2 equivalent per person was recorded in Estonia. The second highest level of 16.5 tons of CO_2 equivalent per person was observed in Luxembourg. Poland, with a score of 10.2, was ranked 10th. The lowest level of about 5.7 was recorded in Croatia. The average level of GGE in the EU-27 was about 9 tons of CO_2 equivalent per person. In 2014, the highest level of about 14,31 tons of CO_2 equivalent per person was recorded in Luxembourg. A similar result of 14.3 tons of CO_2 was recorded in Ireland. Denmark was ranked third with a level of 13.45. In 2022, Estonia reached 11.5 tons of CO_2 equivalent per person. Poland, with a level of 11.01, was ranked 4th. The lowest level of about 4.3 was recorded in Malta. The average level of GGE in the EU-27 was about 8,08 tons of CO_2 equivalent per person.

Analysis of GDP emissions intensity (tons of gases emitted to generate €1000 of GDP) also confirms the presence of a downward trend in emissions. The EU average in 2022 was 259 kg of CO_2 equivalent. Analyzing the trends in the reductions of emission in different EU countries, one can observe differences in the path towards achieving the EU climate goals (EDGAR, 2024). Table1. presents a breakdown of the countries by similarity of emission paths (period of reaching maximum average emissions, stagnant emissions, reduction).

Table 1.
EU countries by emission reduction paths from 1990 to 2022

Groups	Country
I	Belgium, Czechia, Denmark, Germany, France, Luxemburg, Netherlands, Sweden
II	Bulgaria, Estonia, Croatia, Hungary, Lithuania, Latvia, Poland, Romania, Slovakia
II	Austria, Cyprus, Greece, Spain, Finland, Ireland, Italy, Malta, Portugal, Slovenia

Source: Own elaboration based on data published by Inforegio (EU, 2024).

Group I reached its highest emission levels in the early 1990s. Since 1996, the level of emissions has been gradually decreasing. Group II, which includes most of the central and eastern European countries, saw the largest declines in emissions levels in the early 1990s, which was a consequence of the decrease in GDP during the transition period. In subsequent years, starting in 2000, the group showed relatively stable emission levels, oscillating on average around 9 tons of CO_2 equivalent per person. Group III, which includes southern European countries plus Austria, Ireland and Finland, reached emission maxima around 2005. They showed a downward trend until 2020, which changed to slight increases in emissions after 2021. This was reflected in GDP growth after the end of the COVID-19 pandemic.

The analysis of changes in greenhouse gas emissions in the EU shows that the scale of emissions changes over the years, and the rate and direction of these changes varies among countries. This is due to significant economic, social, environmental and spatial differences between the countries.

In Poland, greenhouse gas emissions increased between 2014 and 2018 as a result of the economic boom and increased fuel consumption in the transportation sector. In 2019, a 6% decrease in domestic emissions was recorded, compared to 2018. In 2020, the COVID-19 pandemic resulted in another 4% decrease, compared to the previous year. The year 2021, however, brought an increase in emissions of about 8%, compared to 2021, which was due to an increased consumption in the fuel sector. In 2022, a decrease in emissions of almost 5% was observed, compared to 2021. A factor contributing to the reduction in total emissions was a decrease in emissions from fuel combustion of about 4.5% in the power and heat generation sector. In 2022, the energy sector had the largest share in the total greenhouse gas emissions (expressed in CO2 equivalent) reaching about 83.9%, and within this sector, fuel combustion processes (78.1%). Agriculture held a share of 8.8% in the total greenhouse gas emissions, while industrial processes accounted for 6.2%, and Waste for 1.0%. In many western European countries: Spain, France, Italy, Austria and Germany, the most important source of emissions in 2022 was transportation, especially in rural areas. In countries such as Denmark, Ireland, agriculture had the largest share in greenhouse gas emissions.

Identifying the potential determinants of changes in greenhouse gas emissions and taking into account the diversity of the EU regions in terms of both economics and emissions, is essential for planning effective measures to reduce greenhouse gas emissions, as well as to achieve the EU climate goals. Formulation of adequate regional policies for reduction of emissions will enable achievement of satisfactory results across the EU.

The prerequisite for reducing net greenhouse gas emissions is a rapid and significant reduction in carbon dioxide emissions, primarily through switching from fossil fuels to renewable energy sources. According to CREA database, although energy generation in 2023 was 25% less carbon-intensive than in the previous year, the energy supply sector remains the largest source of greenhouse gas emissions. Emissions projections show that the EU is not on track to meet its 2030 climate target. In order to achieve it, emissions in the subsequent years up to 2030 will have to show a higher rate of reduction than in the period up to 2022.

4. Research methodology

The concept of a structure is an ambiguous one. The chronological development of the concept of a structure is presented in the work by Strihafka (1986). In etymological terms, a structure can be treated as a system of proportions of the elements of a certain additive aggregate, hereinafter referred to as a feature. These proportions are expressed as shares of the partial values of the aggregate in the value of the whole. Proportions determined as the indicators of a structure, define the weight of an element in the aggregate as a whole. In another approach, used most often in taxonomic studies, a structure refers to comparisons of objects that are part of administrative space (states, provinces etc.) or socioeconomic space (businesses, consumers etc.). In this understanding, the concept of a structure is defined as a configuration of points in a multidimensional space of features, and it refers to a set of objects characterized by different features (Strahl, 1998).

This paper focuses on the analysis of the structure of gross energy production in the first sense of the term, that is, the analysis of changes in the structure on a sectoral basis.

The concept of an economic structure, as the totality of interrelated relations between the various elements of the economy, was defined in 1970 by Marciniak (1970). And the mathematically formalized concept of a structure, as a vector in a multidimensional space, was introduced in 2004 by Stawicki (2004), who distinguished between two definitional approaches. In the first one, a structure is identified as vectors of counts in a given community, while the other corresponds to the traditional understanding of structure vectors, in which individual indicators of a structure in a given community form a corresponding column vector.

Issues related to structure analysis, including comparisons of structures or determining the extent to which structures change over time, play an important role in many scientific fields. From the point of view of time, cross-sectional analyses can be distinguished, which primarily analyze the similarity of objects (structures), temporal analyses, which investigate changes in a structure over time, and temporal cross-section analyses that combine both approaches. The most commonly used measures are those that examine the similarity of structures (Kukuła, 1996). An overview of the basic measure types can be found in the works by Cormac (1971), Sireath (1973). In the subject literature, two groups of similarity measures can be distinguished. The first one relates to measures that are applicable to the study of the shape of structures (Borysiuk, 1973), the other one are distance measures that can be used to study both the similarity of size (scale) and the shape of structures (Canberra distance, Clark's divergence coefficient, Bray and Curtis measure). An overview of similarity measures, along with a discussion of their advantages and disadvantages, can be found in the works by Kukuła (1996), Strahl (1998), Malina (2004), Żwirbla (2006).

The paper will compare the structure of gross primary energy production in Poland and in the other EU countries.

Object similarity measure are used in analysis of this type (Malina, 2004). The measure is based on the value of the cosine of the α angle measured between the U_{t1} and U_{t2} vectors characterizing the state of the structure in respective periods $t1$ and $t2$. The formula was:

$$cos\alpha = \frac{\sum_{j=1}^{k} f_{j,t}^{1} \cdot f_{j,t}^{2}}{\sqrt{\sum_{j=1}^{k} \left(f_{j,t}^{1}\right)^{2} \cdot \sum_{j=1}^{k} \left(f_{j,t}^{2}\right)^{2}}} \quad (1)$$

where $f_{j,t}^{1}, f_{j,t}^{2}$ - components of the structure indexes vector respectively for Poland and the European Union.

The values of the measure are normalized, but to interpret the structures similarity assessment level, we consider the angle represented by the calculated cosine. A big α spread between the U_{t1} and U_{t2} vectors means significant structure changes in period t_2 in comparison to the structure in period t_1. A small spread of the angle indicates slight structure changes in the discussed periods. In an exceptional case, when the compared structures are identical, the angle between the structure vectors is 0. When the cosine value tends toward 0, which means the angle tends toward 90°, the vectors represent increasingly different structures. Arbitrary ranges determining small, medium or high structure similarity were set. The values of the cosine function for the division of a 90° angle into 3 equal parts were assumed as the ends of the ranges:

$\left[0, \frac{1}{2}\right]$ - big difference in structures,

$\left[\frac{1}{2}, \frac{\sqrt{3}}{2}\right]$ - moderate diversification of the structures,

$\left[\frac{\sqrt{3}}{2}, 1\right]$ - high similarity.

The function is not linear with respect to the angle, so we need to take caution expressing the size of structure changes in percentage.

According to Rutkowski (1981), a distinction should be made between measures for comparing structures in space (a statistical survey) and measures for inter-period comparisons that measure structural changes occurring in a dynamic manner. When it comes to measures of the dynamics of structural change, one of the concepts according to which the intensity of structural change is measured is that if the structure in two compared periods differs, then it is concluded that changes in the structure have occurred, and the greater the divergence of the structures in the two compared periods, the more intense the transformation was.

In order to analyze the intensity of changes in the sector structure of energy production, we use a measure determining structural changes proposed by Rutkowski. It is a variability coefficient of the indexes of the analyzed aggregation's growth, which at the same time measures the irregularity of the increase of the aggregate's components. The formula was:

$$V_{t,t+\tau}^{i} = \left[\sum_{j=1}^{k} f_{j,t+\tau}^{i} \cdot \left(\frac{f_{j,t+\tau}^{i}}{f_{j,t}^{i}} - 1\right)^{2}\right]^{\frac{1}{2}} \tag{2}$$

where:

$f_{j,t+\tau}^{i}, f_{j,t}^{i}$ – the structure index in moments t and t+τ,

j = 1, 2, …, k – components of the structure aggregate,

i – object number,

$V_{t,t+\tau}^{i}$ = 0 indicates the lack of change in the structure between periods. The higher the value of the measure, the more significant the structural changes.

5. Analysis of changes in the sectoral structure of gross available energy in Poland and other EU countries

Although energy demand in the EU has been declining since 2006, the increasing share of renewable sources, characterized by unpredictable and intermittent operation, in energy production is emphasizing the need to manage electricity production and demand.

In 2022, the primary energy production in the EU was 23,566 PJ (petajoules), down 5.9% compared to the previous year. In the 2012-2022 period, a noticeable downward trend was observed in primary energy production from solid fossil fuels, oil and natural gas by 38.7%, 38% and 64.9%, respectively. Also nuclear power generation saw a drop in that period. Renewable energy production, on the other hand, showed a clear upward trend over the past decade (32.6%). There was also an increase in energy production from non-renewable waste (22.3%). In 2022, compared to 2021, an unexpected increase in energy production from solid fossil fuels was observed, while production from crude oil and natural gas decreased. Unfortunately, in terms of renewable sources, 2022 saw a reversal of the upward trend resulting in a decrease in energy production.

One of the most important elements of any country's energy balance is the gross available energy rate. It determines the amount of energy required to meet the energy needs of the country or region. And the ratio of net imports to gross available energy describes energy dependence. This extremely important indicator is, therefore, essential for determining the extent to which a country or region is dependent on energy imports. It refers to all energy products, but its interpretation for primary products (from natural sources) and derivatives varies. For products drawn directly from nature, it shows the available supply. For secondary products, available energy includes international trade and inventory change. Its primary form of supply is considered in the form of relevant primary products.

In the last decade, the EU saw a decrease in gross available energy of about 6%. The first decrease came as a result of the financial and economic crisis in 2009. In 2010, however, there was an increase of about 4% in gross available energy. There were further drops in the years 2018-2019. However, the biggest decrease was observed in 2020, as a result of the Covid-19 pandemic. In 2021, the trend changed to a growth, which was then followed by a spectacular decrease in 2022, which was connected with the Russian aggression against Ukraine. In 2022, the volume of gross available energy in the EU was 58,461 PJ, and it was lower by 4.5% compared 2021.

A detailed structure of the volume of gross available energy by source in the EU from 1990 to 2022 is presented in Figure 2.

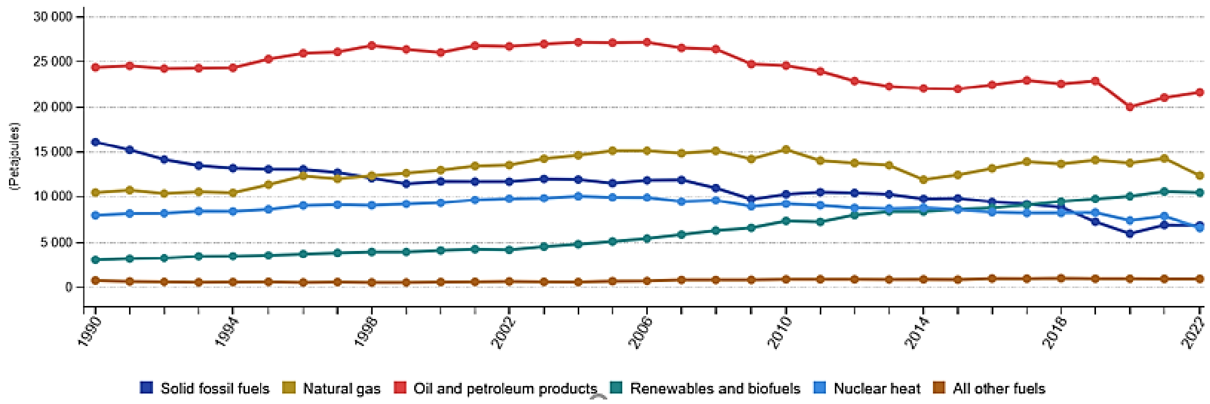

Figure 2. Gross available energy by fuel, EU, 1990-2022 (petajoule).

Source: Eurostat (nrg_bal_c).

Over the past decade, oil and petroleum products had the largest share of gross available energy in the EU, reaching 36,8% in 2022. Natural gas has become the second largest energy source, with a share of 21.1% in 2022, surpassing fossil fuels with a share of 11.6%. It should be noted that, compared to 2021, the volume of gross available energy from gas decreased by 13.3% as a result of sanctions introduced because of Russia's war against Ukraine. Renewable energy has seen a rapid growth over the past few years. In 2018, the share of gross available energy obtained from renewable sources surpassed the share of energy from solid fossil fuels, and in 2022 it reached 17,9%. Nuclear energy in 2022 accounted for 11.1% of gross available energy.

A detailed comparison of the structure of gross available energy in the EU-27 and Poland in 2014, 2018, 2022 is presented in Table 2.

Table 2.
Indicators of the structure of gross available energy in the EU-27 and Poland in 2018, 2014, and 2022

Year	The structure of gross available energy in the EU-27						
	solid fossil fuels	oil and petroleum products (excluding biofuel portion)	natural gas	nuclear heat	renewables and biofuels	non-renewable waste	other
2014	0,158495	0,357644	0,193056	0,14229	0,135431	0,008513	0,004572
2018	0,138736	0,35448	0,214381	0,12883	0,148951	0,009161	0,005461
2022	0,116051	0,36831	0,210798	0,111351	0,178803	0,010223	0,004464
	The structure of gross available energy in Poland						
2014	0,518825	0,240311	0,141144	0	0,091794	0,005419	0,002507
2018	0,446726	0,281776	0,146255	0	0,111432	0,009168	0,004642
2022	0,401648	0,316335	0,143369	0	0,130026	0,009783	0

Source: Author's calculations.

Comparing the sectoral structure of gross available energy in 2022 in the EU-27, compared to 2014, it can be concluded that the share of energy from renewable sources is increasing. In Poland, although fossil fuels held the largest share during the analyzed period, there is a clear downward trend. In 2014, fossil fuels represented 51,9% of energy sources, whereas in 2022 their share in gross available energy dropped to 40,16%. That is also accompanied by an upward trend in the share of renewable energy. In 2014 it was 9,18%, and in 2022 it grew to 13%. The next largest share in 2022, following fossil fuels, was held by petroleum products (31,6%). There are no nuclear power plants in Poland.

The next step of the research consisted in a detailed analysis of the changes taking place in the structure of gross available energy production in Poland and the other EU countries.

Data from Eurostat energy balances for 2014, 2018 and 2022 in annual terms in thousands of tons of oil equivalent (ktoe) were used to analyze changes in the structure of gross available energy in Poland and the EU countries.

To assess the similarity of the structure of primary energy production in Poland and in the other EU countries, the angular measure presented in chapter 4 was used. The similarity of structures in relation to Poland and to a structure representative of the EU average in 2014 and 2022 was analyzed according to the formula 1. The results of the analysis are presented in Table 3.

Table 3.
Values of similarity measures of gross available energy structures of the EU countries in relation to Poland and to a structure representative of the EU average in 2014 and 2022 and values of measures of the dynamics of the intensity of structural change $V_{2014/2022}$ in the EU countries in 2022 compared to 2014

Country	Poland		EU-27		V2014/2022
	2014	2022	2014	2022	
Austria	0,613846	0,352056	0,93788	0,498812	0,071985
Bulgaria	0,883559	0,424802	0,904292	0,448662	0,318441
Belgium	0,55258	0,319369	0,99345	0,498312	0,17985
Croatia	0,608752	0,344939	0,960556	0,508689	0,26529
Cyprus	0,412318	0,273049	0,799212	0,399126	1,300232
The Czech Republic	0,925681	0,415677	0,889558	0,430955	0,144692
Denmark	0,689123	0,358348	0,969402	0,51045	0,412049
Estonia	0,154155	0,088505	0,277756	0,149874	0,403207
Finland	0,546761	0,295821	0,905546	0,457138	0,26008
France	0,362658	0,237633	0,847261	0,420604	0,249906
Greece	0,792126	0,376138	0,948451	0,531483	0,512215
Spain	0,616847	0,347661	0,999	0,544384	0,001
The Netherlands	0,616868	0,354932	0,954692	0,506954	0,623433
Ireland	0,614499	0,346074	0,959834	0,506119	0,303754
Luxembourg	0,480947	0,299485	0,897807	0,447234	0,460754
Lithuania	0,516519	0,333622	0,907287	0,504235	0,50132
Latvia	0,478759	0,3008	0,881132	0,475198	0,204048
Malta	0,404503	0,266537	0,785438	0,396653	0,232857
Germany	0,677604	0,289695	0,644671	0,3254	0,264882
Poland	1	1	0,763512	0,4081	0,284749
Portugal	0,64211	0,331876	0,96241	0,518886	1,662214
Romania	0,749012	0,381133	0,984916	0,530704	0,435971
Slovakia	0,722854	0,317673	0,928413	0,441916	2,639345
Slovenia	0,668038	0,351178	0999	0,495705	0,136733
Sweden	0,364147	0,23924	0,792093	0,413272	0,00012
Hungary	0,614649	0,332961	0,979358	0,517502	0,165288
Italy	0,61639	0,334858	0,957741	0,499221	0,124222

Source: Author's calculations.

The analysis showed high similarity in the structure of gross available energy in 2014 in relation to Poland in the following countries: the Czech Republic, Bulgaria, moderate similarity: Austria, Belgium, Croatia, Denmark, Greece, Hungary, Ireland, Italy, Lithuania, Portugal, Romania, Slovakia, Slovenia, and Spain. In 2022, all of the analyzed countries showed a large difference in structures in relation to Poland, with the highest similarity observed in the structures of Bulgaria and the Czech Republic. Compared to the structure representative of the EU average, Austria, Bulgaria, Belgium, Croatia, the Czech Republic, Denmark, Finland, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Portugal, Romania, Slovakia, Slovenia, and Spain show high similarity in 2014. A large disparity in the structure of energy production compared to the EU-28 average was shown by Estonia in 2014 and in 2022. In 2022, Austria, Bulgaria, Belgium, Cyprus, the Czech Republic, Finland, France, Germany, Italy, Latvia, Luxembourg, Malta, Poland, Slovenia, Slovakia, and Sweden also showed a large disparity compared to the structure representative of the EU average. The structures of the other countries analyzed bear moderate similarity in 2022. In the case of Poland and the EU-27 average, the angle between the structure vectors oscillates around the value of 40° in 2014, and around the value of 66° in 2022, indicating a moderate similarity of structures in 2014 and large differences between structures in 2022.

The next step in the analysis was to determine the intensity of structural change during the discussed period according to formula (2). The values of the measure of the intensity of structural change in 2022 compared to 2014 for the EU countries are shown in Table 3.

Not taking the path of change into consideration and focusing on the extreme periods, it can be concluded that in 2022, compared to 2014, most of the results of the measure have similar, relatively low values, which means low intensity of the rate of change in the analyzed structures. The most intense dynamics of change were observed for Slovakia, Portugal and Cyprus. The dynamics of change were also more intense than in the analyzed countries in the case of the Netherlands, Greece, and Lithuania. The rate of change was also low across the whole EU at 0.185604 in 2022, compared to 2014.

6. Grouping countries based on similarity in the structure of gross available energy production

To group the analyzed countries in terms of the similarity of the structure of gross available energy production by sources, the Ward method, which belongs to the agglomeration grouping methods, was used. The description of the method can be found in many works in the field of numerical taxonomy (Malina, 2004). Figures 3 and 4 present the country groupings for 2014 and 2022.

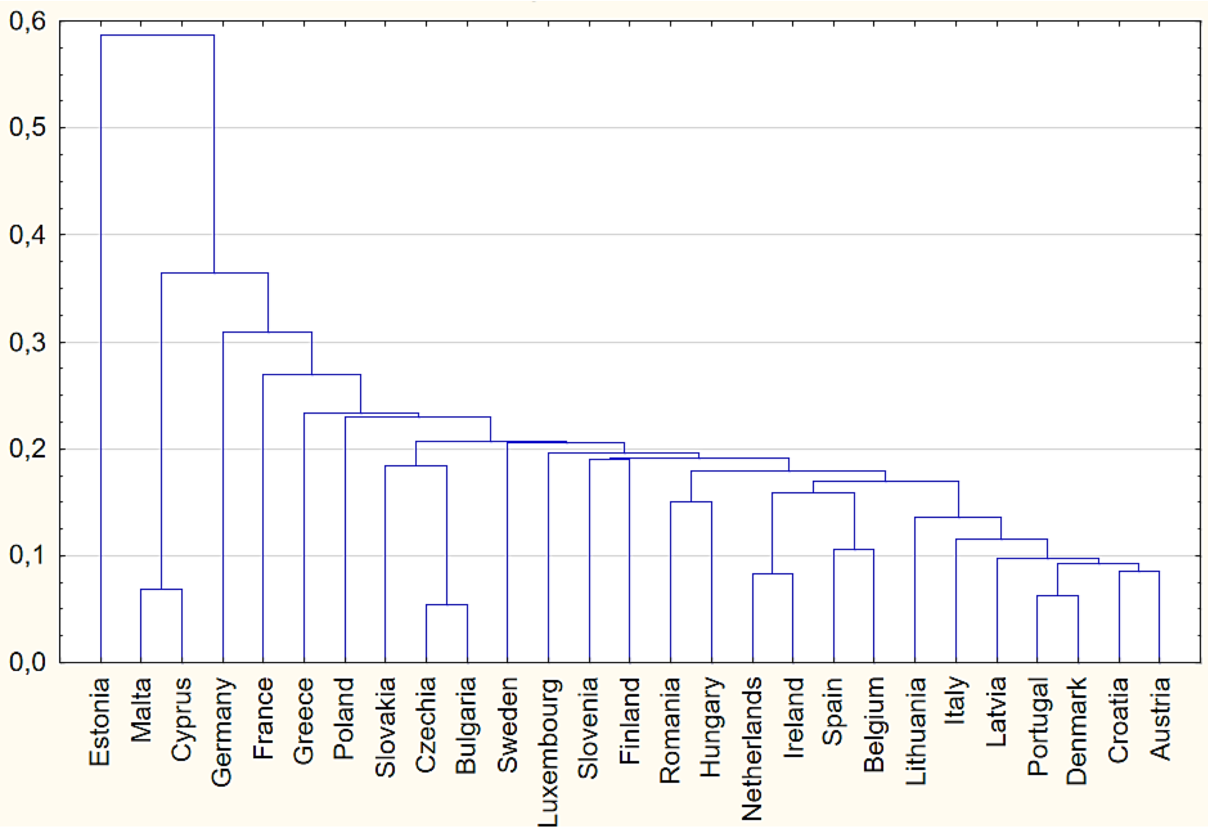

Figure 3. Grouping of the EU-27 countries based on similarity in the structure of gross available energy production in 2014 (Ward method).

Source: Author's calculations.

Countries showing the highest similarity in terms of the structure of gross available energy production in 2014 were Bulgaria and the Czech Republic, at a binding level of 0.0546686, Denmark and Portugal, at a level of 0.0627652, and Cyprus and Malta, at a level of 0.0683892. Moderate similarity to Poland was observed for: the Czech Republic, Bulgaria, Slovakia, Sweden, Luxembourg, Slovenia, Finland, Romania, Hungary, the Netherlands, Ireland, Spain, Belgium, Lithuania, Italy, Latvia, Portugal, Germany, Croatia, Austria, Greece. Estonia showed a very low level of similarity in reference to Poland and the other EU countries.

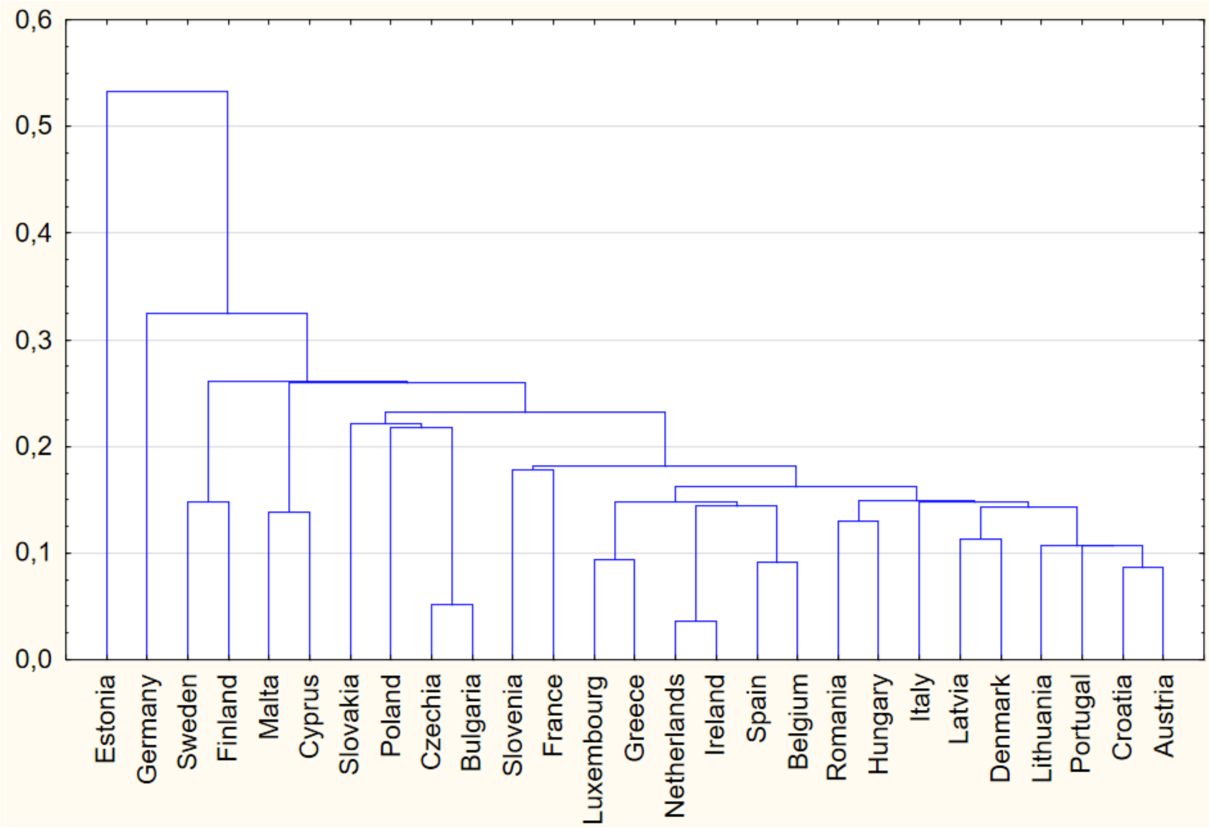

Figure 4. Grouping of the EU-27 countries based on similarity in the structure of gross available energy production in 2022 (Ward method).

Source: Author's calculations.

In 2022, the most similar structure of available primary energy production, at a binding level of 0.0363029, was observed for Ireland and the Netherlands. At a binding level of 0.0519367, Bulgaria and the Czech Republic showed the highest similarity.

Moderate similarity to Poland was observed for: the Czech Republic, Bulgaria, and Slovakia. Estonia and Germany showed a very low level of similarity in reference to Poland and the other EU countries.

Analyzing the agglomeration graph for 2014, it can be concluded that the point of division of the dendrogram should be placed after step 26. In the case of the agglomeration graph for 2022, the division point should be placed after step 18. The Ward method was used to distinguish two groups of objects for 2014: Estonia and the other EU countries. For 2022, however, it is possible to distinguish 6 groups of objects with countries similar in terms of the structure of gross available energy production. They are presented in table 4.

Table 4.
Results of grouping of the EU-27 countries based on similarity in the structure of gross available energy production in 2022

Groups	Country
I	Austria, Croatia, Portugal, Lithuania, Denmark, Latvia , Denmark, Hungary, Romania, Belgium, Spain, Ireland, The Netherlands, Greece, Luxembourg, France, Slovenia
II	Bulgaria, The Czech Republic, Poland, Slovakia
III	Malta, Cyprus
IV	Finland, Sweden
V	Germany
VI	Estonia

Source: Author's own elaboration.

The analysis of the division for 2022 showed that countries belonging to group 1, which is the most heterogeneous one, are characterized by a high share of energy from petroleum products and gas, as well as a high share of renewable sources. Group 2 is dominated by countries, including Poland, with the highest share of energy from solid fuels, group 3 includes countries with a low level of energy from fossil fuels and a relatively high level of energy from petroleum products. In group 4 there are mainly countries with the highest renewable energy share. Germany is in group 5, with a high share of energy from gas. Group 6 is Estonia, which in both 2014 and 2022 shows the highest shares in the so-called other sources of gross available energy.

Conclusions

The research confirmed the hypothesis that the rate of change in the structure of electricity production in the 2014-2022 period in Poland and in the EU countries varies, which translates into differences in decarbonization and air protection. The analysis of data for 2014 and 2022 showed that the structure of gross available energy in Poland and other EU countries varied in the analyzed period. Dividing the EU countries into separate groups, based on their gross available energy structure, provides valuable information on their energy landscape and impact on greenhouse gas emissions. However, the division of countries into groups according to greenhouse gas emission pathways differs from the division according to the structure of energy production. Also the intensity of the rate of change in the analyzed structures in the 2014-2022 period was examined. Considering the extreme periods, it was relatively low. However, the acceleration of the energy transition process observed in 2022 resulted in an increase in the rate of decarbonization.

The contribution of the paper is twofold: first, it offers a detailed understanding of the changing pattern of gross available energy production in Europe, highlighting the transition from fossil fuels to more sustainable energy sources. It identifies the implications of these patterns for EU decarbonization goals. Secondly, it shows that the rate of energy transition in

Poland and other EU countries varies. Taking into account the differences in the energy transition process, and the degree of decarbonization of economies in different countries and regions of Europe makes the assumed EU-wide options for reducing the volume of emissions and the rate of decarbonization feasible.

The novelty of the study lies in the use of synthetic measures of structural similarity and measures of the dynamics of the intensity of structural change for data on gross available energy in the EU.

The article has the following practical implications for decision makers. Achieving net zero emissions by 2050 requires rapid and profound changes in the decarbonization process. The most effective instruments of the decarbonization and air protection process are changes in the structure of electricity production. However, the rate of change in the structure of electricity production in Poland and other EU countries varies. Failure to take these differences into account will make it virtually impossible to achieve the net zero emissions target.

Given current technological and geopolitical constraints, such as the lack of nuclear infrastructure and heavy dependence on coal, the evolution of Poland's energy structure will be gradual and complex. Although Poland's energy policy until 2040 assumes the development of nuclear energy and a reduction in the share of coal to 28%, the first nuclear power plants may not start operating until the second half of the 2030s. This is due to both the lengthy investment procedures and the capital-intensive nature of such investments. The development of renewable energy sources is also hampered by an outdated, inflexible power system, a lack of adequate network infrastructure and energy storage facilities, as well as complicated connection procedures and high operating costs. As a result, surpluses of energy from renewable sources are often wasted, and the system is unable to fully exploit the potential of these sources. Gas-fired power plants are an alternative and can play a significant role as a transitional fuel in the process of moving away from coal. Gas allows for greater system flexibility and easier integration of renewable energy sources, although it remains a fossil fuel and is subject to geopolitical risks. As recent years have shown, the energy transition is not only a matter of technology, but also of geopolitics. Poland, like other countries, has to deal with restrictions on access to critical raw materials (lithium, cobalt, nickel), which are essential for the development of RES and energy storage. The concentration of extraction of these raw materials in a few countries may lead to the risk of export restrictions and increased costs. As a result, Poland will gradually reduce its share of coal, develop renewable energy sources to around 50-60% of the energy mix by 2040, and nuclear energy will only begin to play a role in the longer term. However, without significant investments in grid modernization, energy storage, and simplification of procedures, the transition will be slow and fraught with the risk of shortages and rising energy costs. Geopolitical conditions regarding critical raw materials further complicate this path, requiring strategic management and diversification of supplies.

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