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Quality of Consumed Energy as a Key Element in the Development of Processes of Energy Transformation in the European Union Countries

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Abstract: The process of energy transformation is one of the crucial elements of the process of improvement of the quality of consumed energy. The aim of the research is to assess the European Union countries in terms of the quality of their consumed energy and the speed of adaptation of this aspect of the energy transformation process. We assess the quality of consumed energy by means of the synthetic measure obtained by means of the dynamic version of the COmplex PRoportional ASsessment (COPRAS) method. We compare the countries with the dynamics of the energy transformation process by means of the dynamic time warping method and the hierarchical clustering. Obtained results indicate the best countries with respect to the quality of consumed energy were Malta, Austria, and Germany, and the worst ones—Poland, Czechia, and Slovakia. The process of energy transformation was evolving in the right direction—the quality of consumed energy increased. This increase was the fastest in Malta, Luxembourg, and Poland. The direction for future research is extending the set of variables to also consider other aspects of the energy transformation.

Keywords: quality of consumed energy; energy transformation; EU countries; COPRAS method; dynamic time warping; hierarchical clustering

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1. Introduction

The energy sector plays a vital role in the sustainable economic growth of both developed and developing economies. Energy represents an important input to production processes. The manufacturing sector is highly dependent on the availability of electricity. Energy consumption is responsible for environmental degradation as a result of carbon dioxide (CO_2) emissions from the burning of fossil fuels in industrial production. Concerns about climate change have led many countries to switch to renewable energy to improve environmental quality [1]. Current energy portfolios should be diversified by improving or incorporating renewable energy technologies as a necessary part of environmental policy progress [2]. Unfortunately, European Union countries are still highly dependent on fossil fuels [3].

The energy transformation is a key element of current economic development. It is therefore an issue that requires in-depth research and economic analysis. It consists of multiple, constantly evolving processes and is a multidimensional phenomenon linked to technological, social, and systemic changes [4]. The ongoing energy transformation

processes most strongly affect the development of energy markets, the largest of which are the electricity primary fuel markets [5]. Along with economic growth and the development of innovation, the energy transformation is expanding into new processes. It drives the socio-economic transformation of economies. The question arises as to which element of the economy causes these processes to occur faster and influences the transformation more strongly. A second important problem is to assess which economies are more strongly transformed in terms of energy transformation processes. The economic element that influences the speed of uptake of these energy transformation processes is the process of energy production and consumption within a country. Consequently, the quality of consumed energy in the economy becomes an important issue. An increase in this aspect of energy transformation is associated with an increase in the share of energy obtained from renewable sources, a decrease in the share of fossil fuels, a decrease in greenhouse gas emissions, an increase in energy efficiency, or a decrease in dependence on energy imports. Within a few decades, energy transformation processes can be expected to unify economies in terms of the quality of consumed energy. Legal and institutional regulations mean that these processes are taking place globally. On the other hand, countries are diverse in terms of geography, natural resources, and socio-economic situation. It may happen that the energy transformation will cause a partial change in the socio-economic-institutional aspect but will not be able to influence the unification of economies in terms of the quality of consumed energy. Economies will remain unique in this aspect.

The aim of the study is to assess the EU countries in terms of the quality of consumed energy and the speed of adaptation of this aspect of the energy transformation process. The EU member states are a community highly committed to the energy transformation. Jointly set goals must be pursued by all EU member states. This is a very complex task. The EU countries are not a homogeneous group due to their different levels of socio-economic development. The common objectives of the EU are therefore pursued on the basis of politically independent states. The problem of diversity in the level and rate of change in the quality of consumed energy by the member states is therefore an interesting one. Many studies on the energy transformation of EU countries in various aspects are being conducted. However, there is a research gap in assessing the quality of consumed energy in these countries.

Due to the different levels of development of EU member states, there is a need to monitor the pace and direction of change in selected aspects of the energy transformation. One reason for this is the need to achieve the Sustainable Development Goals.

We propose the following research hypothesis:

H1: energy transformation processes occur more easily and quickly in countries with a higher quality of consumed energy.

The added value of the study is a multifaceted assessment of EU economies in terms of the quality of consumed energy and an evaluation of the dynamics of change in this aspect of energy transformation.

The rest of the article is structured as follows: The second chapter contains the literature review. The third chapter presents the data and research methodology. The fourth one presents the results of empirical research and their discussion. The article ends with the conclusions.

2. Literature Review

Energy efficiency and renewable energy technologies are central to the energy transformation. Renewable energy has the potential to meet two-thirds of the world's total energy demand and contribute to significant reductions in greenhouse gas emissions. The share of renewable energy could increase from 15% in 2015 to 63% of total primary energy supply in

2050 [6]. The CO_2 reduction targets set by European countries outside the EU are lower than in the EU. This affects the dynamics of the energy transformation, which has implications for the amount and allocation of funding for renewable energy development [7]. Energy transformation is one element of the green economy concept, the domain of which is the mitigation of climate change and the rational management of natural resources [8–11].

The article of Pietrzak et al. [12] presents a discussion focusing on the implementation of the energy transformation in the European Union. The subject of the analysis consisted of 24 countries in 2019. The article assesses the countries' readiness for energy transformation in the long term in general. The analysis showed that Estonia, Denmark, Finland, and Sweden were the countries where the energy transformation should proceed smoothly and at the same time affect further economic growth. Bulgaria, Croatia, Greece, Latvia, Lithuania, Romania, and Portugal were the countries with a high risk of failure to meet the conditions of existing EU legislation. The authors pointed out that there were regions in the EU where the energy transformation was too costly from an economic point of view and a significant proportion of households were condemned to energy poverty. In these regions, public opposition to the green transition is slowly emerging, making it likely that energy transformation processes may be slowed down or even stopped from below.

Studies indicate that climate-neutral energy independence based solely on renewable energy sources (RES) can be achieved at the regional level [13].

Planning for energy transformation should be linked to assessing the reliability, failure costs, and maintenance costs of renewable energy sources [14].

Renewable energy is a tool for a circular economy. Jakubelskas and Skvarciany [15] attempted to determine the effectiveness of European Union countries implementing closed-loop economy practices through the use of renewable energy in achieving sustainability goals. Based on the results of the study, Sweden, Luxembourg, Ireland, Latvia, Estonia, Malta, the Netherlands, and Bulgaria could be considered the most efficient countries, while Austria was considered the least efficient. However, the development of investments in renewable energy sources carries certain risks. Firstly, the marginal cost of renewable energy is close to zero, imposing a significant strain on electricity prices, which can be extremely low during sunny hours. Secondly, the intermittency of renewable energy supply has increased the volatility of electricity prices. These factors make investment in domestic energy capacity unattractive. Countries have an incentive to forego these strategically important investments instead of importing electricity from abroad [16].

The goal of the energy transformation is also to ensure energy security. An undoubted task of state energy policy is to develop appropriate regulations to facilitate the development of domestic energy production [17]. An analysis conducted for 26 EU countries in 2007 and 2016 indicated that they imported 53% of the energy consumed [18]. Domestic production did not sufficiently cover internal demand. These countries are closely dependent on stable access to energy sources and energy imports. There is also a large variation between EU member states. The energy dependency rate varies from over 95% for Malta, Luxembourg, and Cyprus to less than 15% in Estonia and Denmark. The situation has changed little in the following years. An analysis of European countries between 2015 and 2020 shows that only 11 out of 32 countries were able to cover their electricity demand by more than 50% [19]. The highest level of sufficiency (more than 80%) was achieved by Denmark, Norway, the UK, Czechia, Romania, and Finland. These countries should therefore be considered energy secure. In contrast, the lowest values (below 15%) were achieved by Cyprus, Hungary, Iceland, Lithuania, and Luxembourg, which should be considered as highly dependent on external suppliers of energy resources. These are countries that rely mainly on non-renewable raw materials for their energy production while at the same time lacking the possibility to obtain them themselves. Increasing the share of renewable energy

sources in the energy market, in addition to ensuring energy security, has an environmental dimension, including the reduction in CO_2 emissions [20,21].

Streimikiene et al. [22] analyzed the energy security of selected EU countries (Czechia, Belgium, Greece, and Sweden) from 2015 to 2020. Their study showed that Czechia was the best-performing country according to energy security and diversification levels, followed by Belgium. The worst-performing country was Greece, followed by Sweden. The primary rationale for the ranking was Sweden's high dependence on energy imports from natural gas, oil, and coal; an exceptionally low score for the N-1 rule for gas infrastructure; and a high rate of market concentration in the gas sector, although the country had a low overall dependence on energy imports and a fairly high capacity of electricity connections. The N-1 rule for the gas infrastructure indicator is the percentage of total demand that can be satisfied if the largest item of gas supply infrastructure is disrupted.

The study by Brożyna et al. [23] provided new insights into the energy mix of the Visegrad countries and their progress towards the EU climate goals. The data covered the period 1990–2021. In the V4 group, Poland had the most problematic and polluting mix, while Slovakia had the best, dominated by nuclear energy (58.3%). Slovakia also stands out because 33.8% of its primary energy is generated from renewable sources.

One alternative to fossil fuels is 'green' hydrogen, provided that the electricity used to power the process comes entirely from renewable sources [24]. A hydrogen economy has long been promoted as a ground-breaking aspect of low-carbon future energy production. However, the high cost of transporting green hydrogen hinders international trade and the wider use of hydrogen to meet global carbon targets [25]. Renewable energy sources, such as wind and solar power, are intermittent in nature. This can lead to mismatches in the power grid. Hydrogen production and storage will increase the flexibility of the energy system [26]. However, the storage of 'green' hydrogen faces many barriers [27,28]. The European hydrogen roadmap appears difficult to implement, because although the technologies have reached maturity, large-scale deployment has been hampered by technical and infrastructural barriers [29].

Energy efficiency policies can help reduce energy consumption and mitigate the effects of climate change. Tsirimokos [30] examined and compared the role of the energy pull and push effect of the productive sectors in the US and Chinese economies in 2014. According to the results of this study, energy efficiency-oriented policies in the US economy should target the service sectors. In the case of the Chinese economy, energy efficiency policies should mainly focus on the industrial sectors.

Voigt et al. [31] analyzed energy intensity developments in 40 major economies. This analysis covered 34 sectors between 1995 and 2007. This research covered the beginning of the period of our analysis, which was conducted for the years 2004–2021. The 40 countries included all countries of the then–European Union. All but one of the countries analyzed (Brazil) experienced an overall improvement in energy efficiency. This improvement was due to a decrease in energy intensity in large sectors of the respective economies. At the global level, much of the decline in energy intensity was driven by technology, suggesting a general movement towards more efficient means of production. The study showed high heterogeneity between countries. As a result, a common pattern could not be easily extracted.

3. Materials and Methods

The process of energy transformation in terms of the quality of consumed energy is a multidimensional phenomenon. The analysis of the studies by Tutak et al. [32], Cheba and Bąk [33], and Manowska et al. [34] allowed a preliminary selection of seven variables describing the issue we are investigating. Although the studies cited above are not directly

related to our topic, they address similar issues. Some of the variables used there could also be applied in our analysis.

The analysis is based on data from Eurostat and covers the period 2004-2021. EU countries are described by the following variables:

x_1 —share of solid fossil fuels in the final energy consumption (in%);
x_2 —share of renewable sources and biofuels in the final energy consumption (in%);
x_3 —share of energy from renewable sources in the final energy consumption (in%);
x_4 —area of solar collectors per km^2 of the country's area per average direct normal irradiance (DNI);
x_5 —net greenhouse gas emissions in tons per capita;
x_6 —energy efficiency in million tons of oil equivalent per GDP in constant prices (as of 2021);
x_7 —energy import dependency (in%).

Of the above variables, x_1, x_6, and x_7 are the destimulants (the lowest possible value is the most desirable). The remaining variables are the stimulants (the highest possible values are the most desirable).

The quality of consumed energy can be expressed by multiple aspects. These aspects can be analyzed by means of the multivariate statistical analysis methods. It is important that such analysis covers many aspects characterizing the analyzed phenomenon. In our case, the quality of consumed energy can be expressed by its efficiency, cleanness (share of energy obtained from renewable sources, greenhouse gas emissions), infrastructure (area of solar collectors), independence (energy import dependency), and, as a part of energy transformation, the decreasing share of solid fossil fuels. By combining these indicators into one composite measure, we can assess the quality of consumed energy. Of course, the choice of indicators in many types of multivariate analyzes is always debatable and subjective, as there are no universally accepted sets of such indicators.

It is worth noting that the normalization of the area of solar collectors per country's area by the solar irradiance helps to even the odds for countries with this respect. For example, as countries like Cyprus and Malta are located at the very south of the EU, they receive much more solar irradiance than, for example, Ireland or the Nordic countries. Therefore, in order to achieve the same level of this indicator by the latter countries as for the former ones, much smaller areas of the solar collectors with respect to these countries' areas are required.

We obtained the data referring to the solar irradiance from the Global Solar Atlas webpage [35].

The research is conducted by using the multivariate statistical analysis, namely the linear ordering. It is conducted in several steps. The first step of any multivariate analysis is the observation matrix **X**.

It is prepared for every period t:

$$\mathbf{X}_{(t)} = [x_{ijt}] \begin{bmatrix} x_{11t} & x_{12t} & \cdots & x_{1mt} \\ x_{21t} & x_{22t} & \cdots & x_{2mt} \\ \vdots & \vdots & \ddots & \vdots \\ x_{n1t} & x_{n2t} & \cdots & x_{nmt}, \end{bmatrix} \quad (1)$$

where the following is true:
x_{ijt} – value of j-th variable in i-th object for t-th year ($i = 1, \ldots, n, j = 1, \ldots, m, t = 1, \ldots, T$);
m—number of variables;
n—number of objects;
T—number of years.

As the variables are measured in different units and orders of magnitude, they need to be normalized. Normalization of the observation matrix is the second step of the analysis. As all variables are measured on the ratio scale, one of the quotient inversions is used:

$$z_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{n} x_{ij}^2}} \tag{2}$$

where z_{ij} – normalized value of j-th variable in i-th object$(i = 1, \ldots, n, j = 1, \ldots, m)$.

As we have the data for multiple periods, for comparison purposes we use two normalization procedures: static normalization (for every year separately) and dynamic one (for all years together). The static normalization is useful when we wish to have a clear comparison of objects in one period only, while the dynamic one allows us to compare the results in multiple periods. The static version of the Equation (2) is calculated by means of the following formula:

$$z_{ijt}^{(s)} = \frac{x_{ijt}}{\sqrt{\sum_{i=1}^{n} x_{ijt}^2}} \tag{3}$$

where z_{ijt} – normalized value of j-th variable in i-th object for t-th year.

The dynamic version of the Equation (2) is given by means of the following formula:

$$z_{ijt}^{(d)} = \frac{x_{ijt}}{\sqrt{\sum_{i=1}^{n} \sum_{t=1}^{T} x_{ijt}^2}} \tag{4}$$

The third step of the analysis consists in assigning weights to the variables. We denote weights by w_j $(j = 1, \ldots, m)$, $\sum_{j=1}^{m} w_j = 1$. In our analysis we selected the Entropy Weights Method (EWS) to calculate the variables' weights [36,37]. The method is based on the Shannon's measure of entropy [38]:

$$s(p_1, \ldots, p_n) = -k \sum_{i=1}^{n} p_i \ln p_i \tag{5}$$

where k is a positive constant.

The information entropy of every variable in our research in a given year is obtained by means of the following equation [37]:

$$E_{jt} = -\frac{1}{\ln n} \sum_{i=1}^{n} p_{ijt} \ln p_{ijt}, j = 1, \ldots, m, t = 1, \ldots, T \tag{6}$$

where

$$p_{ijt} = \frac{x_{ijt}}{\sum_{i=1}^{n} x_{ijt}}, j = 1, \ldots, m, t = 1, \ldots, T \tag{7}$$

We calculate weights for j-th variable in each year separately by means of the following equation [37]:

$$w_{jt} = \frac{1 - E_{jt}}{m - \sum_{j=1}^{m} E_{jt}}, j = 1, \ldots, m, t = 1, \ldots, T \tag{8}$$

Eventually, we calculate the weights for j-th variable regardless of the analyzed year, as the average for the values in every year:

$$w_j = \frac{\sum_{t=1}^{T} w_{jt}}{T}, j = 1, \ldots, m \tag{9}$$

In the fourth step of the analysis, we calculate the weighted normalized observation matrix for every analyzed year. The weighted normalized observation matrix for the static normalization is calculated as follows:

$$v_{ijt}^{(s)} = w_j z_{ijt}^{(s)} \tag{10}$$

The weighted normalized observation matrix for the dynamic normalization is calculated as follows:

$$v_{ijt}^{(d)} = w_j z_{ijt}^{(d)} \tag{11}$$

In the next step of the linear ordering, we calculate the composite variable. There are many linear ordering methods that can be used. Some of them use the reference point(s) (the pattern or anti-pattern), while some of them do not use them. The former are called the pattern methods and the latter—the patternless ones. One of the oldest ones, developed for the needs of the linear ordering of economic objects, is the Hellwig's Taxonomic Measure of Development [39]. It is based on the weighted distance of every object from the pattern, i.e., the theoretical object created from the best values of normalized variables. In its classical form, the Hellwig measure is not normalized. However, we can normalize it in the interval $[0, 1]$. The closer the value to 1 is, the better the analyzed object is. The maximal value of the Hellwig's measure indicates the best object, and the minimal value—the worst one. Another example of the pattern method is the TOPSIS (Technique for Ordering Preferences by Similarity to Ideal Solution). It was proposed by Hwang and Yoon [36] for the needs of multi-criteria decision-making. It is based on the distances of weighted normalized values of every object from two reference points: the pattern and the anti-pattern, i.e., the theoretical object created from the worst values of normalized values. The TOPSIS measure is normalized in the interval $[0, 1]$. The maximal value of the TOPSIS measure indicates the best object, and the minimal value—the worst one. There are also numerous patternless linear ordering methods. The Simple Additive Weighting (SAW) is the easiest one. It is based on the sums of normalized values of variables [40]. The SAW measure is not normalized. Its main drawback is that all variables must be of the same type (stimulants). The maximal value of the SAW measure indicates the best object, and the minimal value—the worst one. One of the most popular patternless linear ordering methods is the COPRAS (COmplex PRoportional ASsessment). It was proposed for the needs of the decision sciences by Zavadskas et al. [41]. It is based on the assumption that an object is directly proportional to a weighted sum of normalized stimulant variables and inversely proportional to a weighted sum of normalized destimulant variables. It is usually normalized in the interval $[0, 1]$. The maximal value of the COPRAS measure indicates the best object, and the minimal value—the worst one.

In the research, we use the COPRAS method. For the static normalization, the weighted sums of normalized stimulant variables $\left(S_{it}^{(s)+}\right)$ and the destimulant ones $\left(S_{it}^{(s)-}\right)$ are obtained by means of the following formulas:

$$S_{it}^{(s)+} = \sum_{j \in J^+} v_{ijt}^{(s)}, i = 1, \ldots, n, t = 1, \ldots, T \tag{12}$$

$$S_{it}^{(s)-} = \sum_{j \in J^-} v_{ijt}^{(s)}, i = 1, \ldots, n, t = 1, \ldots, T \tag{13}$$

where the following is true:
$J^+, j = 1, \ldots, m$—stimulant variables;
$J^-, j = 1, \ldots, m$—destimulant variables.

For the dynamic normalization the weighted sums of normalized stimulant variables $\left(S_{it}^{(d)+}\right)$ and the destimulant ones $\left(S_{it}^{(d)-}\right)$ are obtained by means of the following formulas:

$$S_{it}^{(d)+} = \sum_{j \in J^+} v_{ijt}^{(d)}, i = 1, \ldots, n, t = 1, \ldots, T \tag{14}$$

$$S_{it}^{(d)-} = \sum_{j \in J^-} v_{ijt}^{(d)}, i = 1, \ldots, n, t = 1, \ldots, T \tag{15}$$

Finally, the composite COPRAS measure for the static normalization is obtained by means of the following formula:

$$q_{it}^{(s)} = S_{it}^{(s)+} + \frac{\sum_{i=1}^{n} S_{it}^{(s)-}}{S_{it}^{(s)-} \sum_{i=1}^{n} \frac{1}{S_{it}^{(s)-}}}, \quad i = 1, \ldots, n, t = 1, \ldots T \tag{16}$$

The higher the value of the composite COPRAS measure obtained for the static normalization in given period is, the better is the situation of analyzed object in analyzed period.

The COPRAS measures obtained by means of the static normalization present the rankings of the EU countries in selected years: 2004, 2009, 2015, and 2021. The choice of these years was dictated by two reasons. The first one was that the time span between presented years should be more or less similar (5–6 years), and it should present some important events in the global economy. The first and last years were selected to show the situation in the first and last periods of the observed period. Year 2009 was selected as the peak of the financial 2007–2009 crisis. Year 2015 was selected because it was in the middle between years 2009 and 2021.

For the dynamic normalization, the COPRAS measure is calculated as follows:

$$q_{it}^{(d)} = S_{it}^{(d)+} + \frac{\sum_{i=1}^{n} \sum_{t=1}^{T} S_{it}^{(d)-}}{S_{it}^{(d)-} \sum_{i=1}^{n} \sum_{t=1}^{T} \frac{1}{S_{it}^{(d)-}}}, \quad i = 1, \ldots, n, t = 1, \ldots T \tag{17}$$

The rankings obtained by means of the dynamic normalization of variables serve as the assessment of dynamics of the quality of consumed energy, rather than the each year's rankings of countries.

Thanks to the dynamic normalization (when the normalization basis is the same for all analyzed years), if the values of the composite COPRAS measure for selected country in subsequent periods are higher, the situation of this country is improving. It would be impossible to measure the improvements of the situation in subsequent years by means of the static normalization, because in such a case we analyze each year separately, thus we cannot compare the values between various years.

The composite COPRAS measures obtained on the basis of the dynamic normalization are the basis of the final step of the analysis—the comparison of dynamics of the quality of consumed energy in the EU countries. We conduct this comparison by means of the dynamic time warping (DTW) method. It was proposed by Bellman and Kalaba [42]. Its first field of application was speech recognition [43]. It found its application in many fields of technical sciences [44]. The DTW algorithm was also applied in comparisons of time series of energy commodities [45] or in the field of sustainable energy [46].

If we have the two time series, denoted by $X = (x_1, \ldots, x_N)$ and $Y = (y_1, \ldots, y_M)$, we find the match between them by minimizing the total cost function $c_p(X, Y)$, calculated as follows:

$$c_p(X, Y) = \sum_{l=1}^{L} c\left(x_{n_l}, y_{m_l}\right) = \sum_{l=1}^{L} \left| x_{n_l} - y_{m_l} \right| \tag{18}$$

where $p = (p_1, \ldots, p_L)$ is the time warping path with $p_l = (n_l, m_l) \in \{1, \ldots, N\} \times \{1, \ldots, M\}$ for $l \in \{1, \ldots, L\}$ $(L \in \max(N, M), \ldots, N + M - 1)$. The time warping path must satisfy the three conditions:

- Boundary, meaning that the first (last) element of the first time series must be matched with the first (last) element of the second one;
- Monotonicity, meaning that the warping path can move only right or up or right–up of its current position;
- Step size, meaning that every index from time series X must be matched with at least one index from the time series Y.

We obtain the optimal match between the two analyzed time series by means of the following formula:

$$DTW(X, Y) = c_{p^*}(X, Y) = \min\{c_p(X, Y) \mid p \in P\} \quad (19)$$

where P is the set of all possible warping paths.

The optimal path is obtained by the application of dynamic programming. The $DTW(X, Y)$ is the minimal distance between the two compared time series, which will be further called the DTW distance.

We use the DTW distance measures calculated between all compared time series as the dissimilarity matrix in the hierarchical clustering. By its means, we distinguish the homogeneous clusters of EU countries with respect to the dynamics of the quality of consumed energy. We use Ward's method to build the tree [47].

4. Results and Discussion

We used the following software to perform calculations:

- We applied Microsoft™ Excel® to calculate the COPRAS measure, obtain rankings, and analyze the dynamics of the COPRAS composite variable.
- We used the R [48] language (v4.4.2) with the use of the following functions: `data.Normalization` function in the `clusterSim` (v0.51-5) package [49], the `dtw` function in the `dtw` (v1.23-1) package [50], the `NbClust` function in the `NbClust` (v3.0.1) package [51], and the `fviz_dend` function in the `factoextra` (v1.0.7) package [52] to obtain the DTW distance matrix between the time series of the COPRAS measure obtained for the dynamic normalization and to perform the hierarchical clustering of countries with respect to the similarity of these time series.

Before starting any further analysis, we checked the level of dispersion of all variables and correlations between them. We used the coefficients of variation for analysis of dispersion and Pearson product–moment correlation coefficients to assess the correlation between variables. Because the analysis was conducted for multiple periods, we calculated the average values of these measures. The dispersion of variables in multivariate statistical analysis should be high enough (the coefficients of variation should exceed 10% [53]), and the correlation between them should not be too strong (the value of the correlation coefficient should not exceed the value of 0.9 [54]). We present the coefficients of variation (C_V) in Table 1.

Table 1. Average values of coefficients of variation (C_V). Source: own elaboration on the basis of the Eurostat data.

Variables	x_1	x_2	x_3	x_4	x_5	x_6	x_7
C_V	139.20%	56.95%	62.82%	161.08%	48.20%	38.43%	42.61%

As seen in Table 1, the level of dispersion for all variables is high enough. From this point of view, all variables are well suited to be included in multivariate statistical analysis.

In the second step of preliminary analysis, we present the average values of correlation coefficients in Table 2.

Table 2. Matrix of average Pearson product–moment correlation coefficients. Source: own elaboration on the basis of the Eurostat data.

Variables	x_1	x_2	x_3	x_4	x_5	x_6
x_2	−0.065					
x_3	−0.189	0.890				
x_4	−0.188	−0.322	−0.229			
x_5	0.062	−0.561	−0.537	0.167		
x_6	0.398	0.435	0.151	−0.395	−0.234	
x_7	−0.284	−0.449	−0.440	0.411	0.208	−0.314

We found that there was a very strong correlation between variables x_2 (share of renewable sources and biofuels in the final energy consumption) and x_3 (share of energy from renewable sources in the final energy consumption). The values of the Pearson product–moment correlation coefficients between these two variables ranged from 0.855 in 2010 to 0.914 in 2015, with the average value of 0.890. As the correlations between the variable x_3 and the remaining ones were generally smaller, we decided to remove the variable x_2 from further analysis, as the combined impact of these two variables could dominate the value of the composite measure. Although the average correlation strength was slightly below the threshold level, in many periods this value exceeded 0.9, so we kept our decision of excluding the variable x_2. The average values of correlation coefficients between other variables did not exceed 0.561. The remaining variables were re-numbered—original variable x_3 became x_2, etc.

Having selected the variables, we can assign their weights by means of the EWS method. Weights of variables are presented in Table 3. Variable x_3 (area of solar collectors per square kilometer of a country per average direct normal irradiance) had the most differing values amongst the EU countries in all years; thus, it had the highest entropy. Therefore, it has the highest weight, constituting over 45% of all weights. The second highest entropy characterized the variable x_1 (share of solid fossil fuels in the final energy consumption), thus it represented over 30% of all weights. The entropy of the remaining variables was much smaller, and their weights did not exceed 0.1.

Table 3. Weights of the analyzed variables. Source: own elaboration on the basis of the Eurostat data.

Variables	x_1	x_2	x_3	x_4	x_5	x_6
weights	0.305	0.096	0.454	0.056	0.035	0.054

On the basis of calculated weights, we present the rankings of the EU countries obtained on the basis of the static normalization in the years 2004, 2009, 2015, and 2021 in Table 4.

Table 4. Rankings of the EU countries in years 2004, 2009, 2015, and 2021. Source: own elaboration on the basis of the Eurostat data.

Country	2004	2009	2015	2021
Belgium	19	11	11	12
Bulgaria	25	24	24	27
Czechia	26	25	25	24
Denmark	7	6	5	4
Germany	4	3	4	3
Estonia	15	21	17	9
Ireland	24	23	22	21
Greece	5	5	9	11
Spain	14	13	16	15
France	12	15	15	18
Croatia	17	18	18	20
Italy	16	10	10	13
Cyprus	2	2	3	5
Latvia	10	17	19	16
Lithuania	20	22	23	25
Luxembourg	22	15	14	8
Hungary	21	20	20	19
Malta	13	16	1	1
Netherlands	3	4	8	7
Austria	1	1	2	2
Poland	27	27	27	26
Portugal	9	8	6	6
Romania	18	19	21	22
Slovenia	8	9	12	14
Slovakia	23	26	26	23
Finland	11	12	13	17
Sweden	6	7	7	10

The best EU countries with respect to the quality of consumed energy throughout the whole analyzed period were Cyprus, Austria, Germany, Denmark, Portugal, the Netherlands, and Sweden. Malta is an interesting case, as up to the year 2009 it had been in the middle, while after 2009 it reached the first place. It was mainly due to the large area of solar collectors that had been built after 2009. Throughout the entire period, the positions of Finland, Latvia, and Lithuania deteriorated to the highest degree. It was caused by the fact that other countries had made greater progress towards the improvement in the quality of consumed energy. The worst countries with this respect throughout the whole period were Poland, Czechia, Slovakia, Ireland, Bulgaria, and Lithuania. The last place of Poland during the most part of the analyzed period was caused by the largest share of fossil fuels in the final energy consumption, a relatively small area of solar collectors, and big greenhouse gas emissions. Czechia also had a big share of fossil fuels in the final energy consumption, a relatively small area of solar collectors, and big greenhouse gas emissions. The quality of consumed energy in Ireland and Luxembourg was mainly influenced by big greenhouse gas emissions, high energy dependency, and a small share of energy from renewable sources in the final energy consumption. Slovakia's and Lithuania's positions were low mostly due to the small area of the solar energy collectors.

The dynamics of the quality of consumed energy in the EU countries (for the values of the COPRAS measure obtained on the basis of the dynamic normalization) in selected years is presented in Table 5.

Table 5. Dynamics of the quality of consumed energy in the EU countries in years 2004, 2009, 2015, and 2021. Source: own elaboration on the basis of the Eurostat data.

Country	$q_{i2004}^{(d)}$	$q_{i2009}^{(d)}$	2009/2004 Percentage Change	$q_{i2015}^{(d)}$	2015/2009 Percentage Change	$q_{i2021}^{(d)}$	2021/2015 Percentage Change	2021/2004 Mean Rate of Change
Belgium	0.012	0.021	70.24%	0.031	49.14%	0.037	17.29%	6.63%
Bulgaria	0.006	0.011	77.53%	0.014	30.39%	0.015	5.46%	5.39%
Czechia	0.005	0.007	57.33%	0.013	67.20%	0.015	17.94%	6.89%
Denmark	0.022	0.032	47.95%	0.047	46.35%	0.066	39.54%	6.72%
Germany	0.025	0.042	67.70%	0.053	27.70%	0.065	22.09%	5.82%
Estonia	0.017	0.017	−4.64%	0.025	49.95%	0.039	54.46%	4.77%
Ireland	0.007	0.011	54.39%	0.015	37.02%	0.018	22.46%	5.76%
Greece	0.022	0.032	43.29%	0.033	1.88%	0.038	17.37%	3.22%
Spain	0.018	0.022	21.17%	0.026	19.16%	0.030	18.14%	3.19%
France	0.018	0.020	11.44%	0.026	28.95%	0.030	13.72%	2.84%
Croatia	0.015	0.019	23.83%	0.023	25.60%	0.023	−0.03%	2.63%
Italy	0.017	0.024	44.29%	0.030	23.75%	0.035	16.33%	4.39%
Cyprus	0.039	0.051	31.07%	0.061	20.62%	0.061	−0.47%	2.70%
Latvia	0.020	0.019	−2.71%	0.023	20.29%	0.031	34.31%	2.70%
Lithuania	0.012	0.014	9.75%	0.014	2.32%	0.015	10.60%	1.28%
Luxembourg	0.009	0.016	73.74%	0.029	82.73%	0.039	33.45%	8.86%
Hungary	0.011	0.017	59.39%	0.021	23.03%	0.024	17.17%	5.02%
Malta	0.020	0.021	5.20%	0.120	479.90%	0.099	−17.25%	9.99%
Netherlands	0.030	0.035	14.24%	0.035	0.36%	0.038	9.92%	1.37%
Austria	0.043	0.060	40.41%	0.070	17.82%	0.068	−3.44%	2.79%
Poland	0.004	0.005	42.04%	0.010	86.05%	0.015	52.68%	8.55%
Portugal	0.022	0.029	31.03%	0.035	21.33%	0.042	19.99%	3.87%
Romania	0.015	0.018	21.41%	0.015	−16.22%	0.016	9.40%	0.63%
Slovenia	0.021	0.026	26.36%	0.029	13.40%	0.036	20.84%	3.28%
Slovakia	0.006	0.007	9.85%	0.012	73.23%	0.016	27.82%	5.37%
Finland	0.020	0.024	25.95%	0.028	17.31%	0.029	4.67%	2.60%
Sweden	0.026	0.032	20.10%	0.033	4.35%	0.041	22.59%	2.66%

The dynamics of the quality of consumed energy can be equated with the energy transformation. In all EU countries the quality of consumed energy has increased, which is a very positive sign. It means that the overall quality of consumed energy increases; therefore, the energy transformation goes in the appropriate direction. However, the rates of change between analyzed countries differ to a high degree. The most notable example is Malta, where between the first compared periods (years 2004 and 2009), the indicator measuring the overall quality of consumed energy increased by just 5.2%. However, in 2015, with respect to 2009, the increase was almost 480%. It was caused by the installation of a large area of solar panels, which were absent in Malta before 2010. On one hand, we may wonder if the applied composite indicator (the COPRAS measure) is the appropriate one. However, when we look closer at the values of variables and assigned weights, we can see that Malta became the leader in the solar collectors installation. Considering the fact that Malta is a very small country with a very small economy, such a large increase in values of any variable or indicator can have a much larger relative impact on the whole economy than in the case of bigger countries. Therefore, for such a small country, no composite measure would be free from indicating that dramatic change in value. So, considering that all applied variables used to construct the composite measure are the relative ones (presented as percentages, with respect to the country's GDP or per capita), it is advisable to present changes as they are. However, when we interpret the results, we must consider the fact that the size of the economy can influence the larger or smaller impact of even one

indicator on the analyzed phenomenon. In the last year (2021), with respect to the year 2015, the overall quality of consumed energy in Malta decreased by just over 17%. The biggest overall (besides Malta) and most steady increase of the quality of consumed energy has been observed in Poland and Luxembourg. However, despite these improvements, Poland still has the second lowest (as of 2021) overall quality of consumed energy, mainly due to the largest share of energy obtained from fossil fuels. Countries where the overall change in the quality of consumed energy was the lowest were Lithuania, the Netherlands, and Romania. On the other hand, the countries with the largest total increase in the quality of consumed energy (besides Malta, Luxembourg, and Poland) were Czechia, Denmark, and Belgium.

The dynamic values of the composite COPRAS measure were the basis for finding the homogeneous clusters of the EU countries with respect to the dynamics of the quality of consumed energy (energy transformation). In order to ensure the comparability of comparisons of time series of the composite COPRAS measures, time series for all countries have been *z*-normalized. Next, the normalized time series have been pairwise compared by means of the DTW method, and the DTW distance matrix has been obtained. We have then used this matrix as the dissimilarity matrix for the hierarchical clustering. We have used the Caliński–Harabasz index to obtain the optimal number of clusters [55]. By its means the optimal number of clusters was 5. Figure 1 presents the dendrogram of the EU countries with respect to the similarity of the dynamics of the quality of consumed energy.

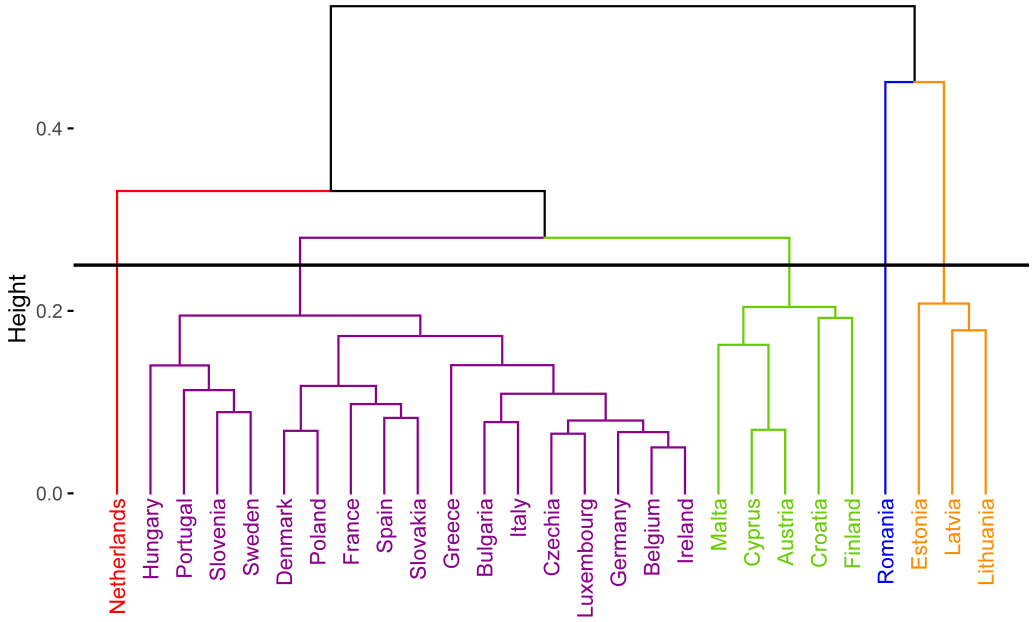


Figure 1. Homogeneous clusters of countries with respect to the dynamics of the quality of consumed energy in years 2004–2021 (dendrogram). Source: own elaboration on the basis of the Eurostat data.

In order to make the geographic representation clearer, we also presented the results of the cluster analysis on the map (Figure 2).

The two out of five clusters consisted of just one country. One of these two clusters was created by Romania. It was the country with the lowest overall increase in the quality of consumed energy. The second single-member cluster contained the Netherlands. The dynamics of the quality of consumed energy in the Netherlands even though increased, but the period 2015–2018 was characterized by the decrease of this indicator. The third cluster consisted of the Baltic States (Estonia, Latvia, and Lithuania). These countries were characterized (except Lithuania) by a big increase in the overall quality of consumed energy in the last analyzed years. The fourth cluster consisted of six countries: Austria, Croatia,

Cyprus, Finland, and, quite surprisingly, Malta. Countries in this cluster were characterized by stabilization of the COPRAS measure in the second part of the analyzed period and a decline in the overall quality of consumed energy in the last year. The fifth, largest cluster consisted of the remaining 17 EU countries. It was characterized by more or less steady increase throughout the whole analyzed period.

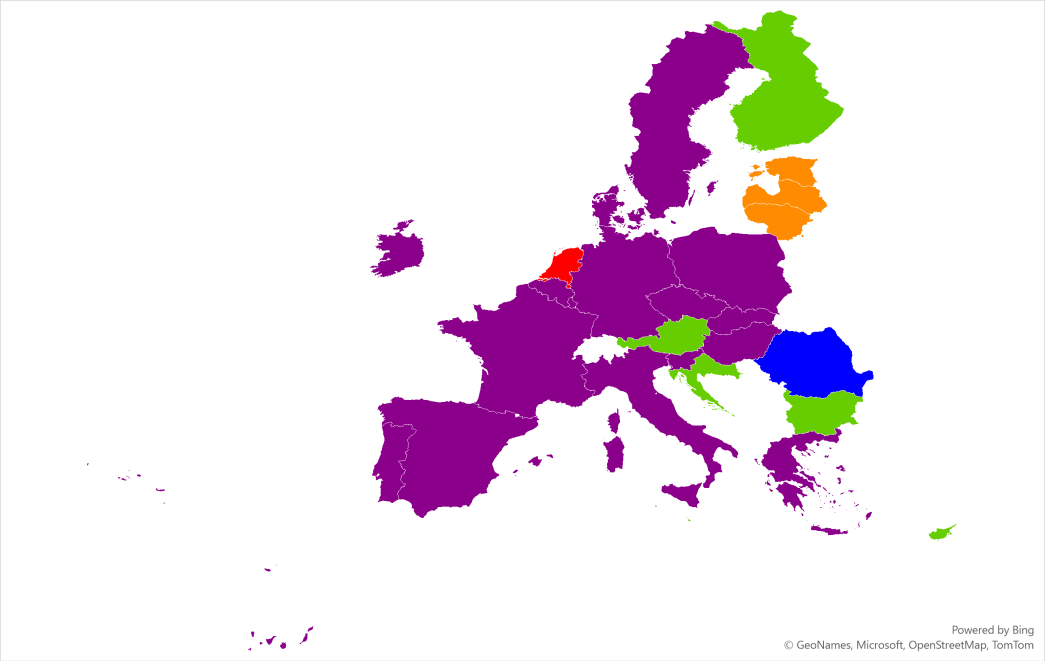


Figure 2. Homogeneous clusters of countries with respect to the dynamics of the quality of consumed energy in years 2004–2021 (map). Source: own elaboration on the basis of the Eurostat data.

Therefore, we can draw the conclusion that these 17 countries had the best situation with respect to the dynamics of the quality of consumed energy—steady, undisturbed growth. Although it consists of countries with various levels of this quality (with the worst country in this respect—Poland, and some of the best ones, such as Denmark or Germany). The policy of Romania and the Netherlands with this respect needs improvement (although the Netherlands belongs to the group of the best countries with this respect). Although the situation of the Baltic states and the countries in the fourth cluster (Austria, Bulgaria, Croatia, Cyprus, Finland, and Malta) generally develops in the appropriate direction, the policy with this respect should concentrate on making the increase in the quality of consumed energy more steady.

In order to compare the quality of consumed energy with the dynamics of the process of energy transformation, we draw the map of the median position of every EU country in rankings with respect to the dynamics measured by the mean rate of change throughout the whole analyzed period (2004–2021). We present the map in Figure 3. The X-axis is presented in the reverse order, as lower values denote higher positions in rankings. Two crossing lines denote median rank for the countries (14, as we have 27 of them) and median value of mean rate of change for all EU countries.

The chart in Figure 3 is divided into four quadrants. The first one contains the EU countries with high positions in rankings (thus relatively high quality of consumed energy) and a high rate of change in the quality of consumed energy, which can be interpreted as a high rate of change in the energy transformation. The second quadrant contains countries with a relatively high rate of change in the energy transformation but low positions in rankings (thus relatively low quality of consumed energy). The third quadrant contains countries with a relatively low quality of consumed energy and a low rate of change in the

energy transformation. The fourth quadrant contains countries with relatively high quality of consumed energy and a low rate of change in the energy transformation.

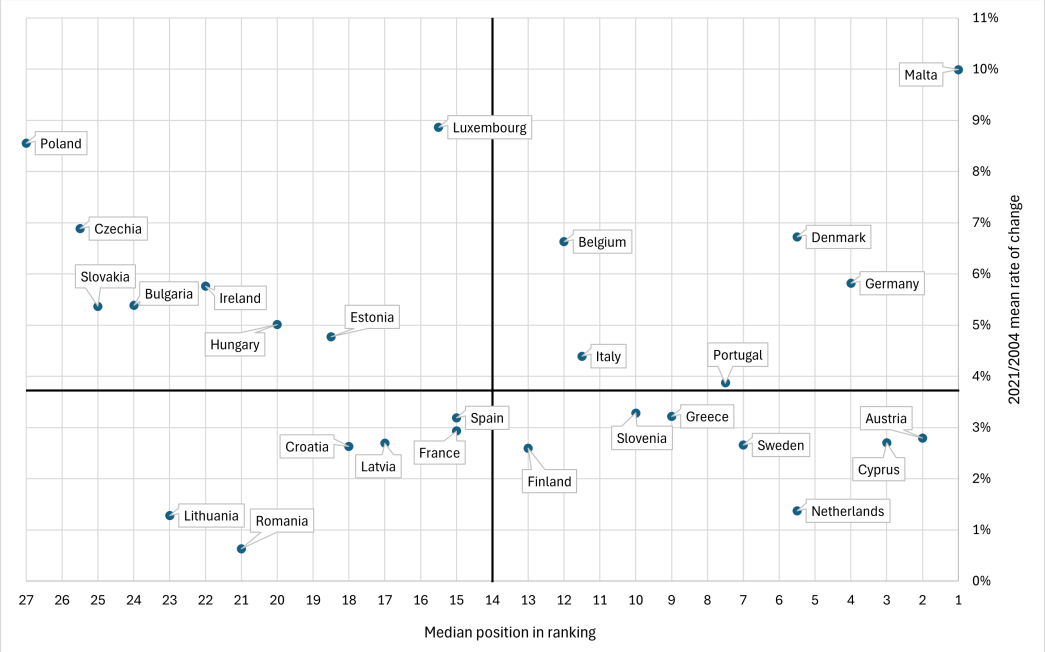


Figure 3. Median position in rankings vs. 2021/2004 mean rate of change. Source: own elaboration on the basis of the Eurostat data.

Countries in the first and third quadrants confirm the research hypothesis—that the processes of energy transformation occur more easily and quickly in countries with a higher quality of consumed energy. Therefore, the hypothesis is confirmed for 12 out of 27 EU countries: Romania, Lithuania, Croatia, Latvia, France, and Spain (with relatively low quality of consumed energy and low rate of change in the energy transformation—third quadrant of the coordinate system); Belgium, Italy, Portugal, Denmark, Germany, and Malta (with relatively high quality of consumed energy and high rate of change in the energy transformation—first quadrant of the coordinate system).

The relation between the quality of consumed energy and the mean rate of change in the energy transformation between the remaining 15 countries did not confirm the research hypothesis. Poland, Czechia, Slovakia, Bulgaria, Ireland, Luxembourg, Hungary, and Estonia had relative quality of consumed energy below the EU-27 median but were characterized by a growth rate of the quality of consumed energy that was above the EU-27 median, which was a good thing (second quadrant of the coordinate system). The remaining countries (Austria, Cyprus, Greece, Latvia, the Netherlands, Slovenia, and Sweden) belonged to the fourth quadrant, which meant the quality of consumed energy was above the EU-27 median but had a low rate of change in the energy transformation. It can be concluded that the hypothesis was confirmed for 12 countries: Romania, Lithuania, Latvia, Croatia, Spain, France, Belgium, Portugal, Italy, Denmark, Germany, and Malta. For the first six countries, low levels of quality of consumed energy corresponded with low dynamics of this aspect of energy transformation, while for the remaining six of them, high levels of quality of consumed energy corresponded with high dynamics of energy transformation.

The results of the presented study are in many respects in line with those considering energy dependency and self-sufficiency [15,19], although it happens that countries that are mostly energy self-sufficient (Poland, Czechia, or Bulgaria) occupy low positions in the rankings (Table 4). On the other hand, some countries with a high dependence on energy

imports (Malta or Cyprus) ranked high in the rankings. This is because dependence on energy imports was only one of the factors taken into account when analyzing the quality of consumed energy.

The study by Tutak et al. [32] made it possible to divide EU countries into groups similar in terms of their level of energy-climate sustainability. Among other things, the study used the entropy-COPRAS method. Based on the analysis over the period 2009–2018, a high level of energy-climate sustainability was found for four countries: Sweden, Denmark, France, and Austria, and low for Poland, Cyprus, and Bulgaria. The high positions of Sweden, Denmark, and Austria were due to the fact that these countries had already embarked on the path of energy transformation protection in the 1970s and 1980s.

The common goal of the European Union countries is to reduce CO_2 emissions, increase energy efficiency, and increase the share of renewable energy in the energy mix. Due to the political independence of the member states, different instruments are used to achieve these goals. As Borozan [56] points out, only a configuration of specific policy instruments targeting energy efficiency and renewable energy can influence the sustainable success of the energy transformation. Our results show that the EU countries are reducing the share of fossil fuels and increasing the share of renewable energy in the energy mix, as reflected in the growth of the synthetic variable in dynamic terms for all EU countries (Figure 3).

The implementation of energy policies related to the decarbonization of the energy mix of developing countries does not generate immediate effects. As the study by Galeazzi et al. [57] indicates, the period after which they are visible varies from 5 to 7 years.

The added value of this study lies in the proposal for a multivariate assessment of the quality of consumed energy and in the analysis of the dynamics of the synthetic variable determined by a dynamic version of the selected linear ordering method (COPRAS). By using this method, this aspect of the energy transformation between 2004 and 2021 was investigated, and homogeneous clusters of EU countries were identified.

5. Conclusions

The EU countries differ both with respect to the quality of consumed energy and the dynamics of energy transformation in the years 2004-2021. Conducted analysis allowed for ranking the EU countries with respect to the quality of consumed energy—the best ones were Malta, Cyprus, Germany, and Austria. The highest positions of these countries in the rankings were caused mostly by the large area of solar collectors and low share of energy obtained from fossil fuels. The worst countries with respect to the quality of consumed energy were Poland, Czechia, and Slovakia. Their low positions in rankings were caused mostly by the highest share of energy from fossil fuels and a relatively low share of energy from renewable sources. All countries showed an overall increase in the quality of consumed energy throughout the whole analyzed period. Most EU countries created one homogeneous cluster with respect to the dynamics of the energy transformation. The Netherlands and Romania created separate clusters with this respect.

The research hypothesis was only partially confirmed for 12 countries: Belgium, Romania, Latvia, Lithuania, Croatia, Spain, Portugal, France, Italy, Denmark, Germany, and Malta.

Policy recommendations—if economies are unique, changing certain processes by force may introduce more harm than benefit. Transformation needs to be introduced sensibly and gradually, as this may inhibit these processes and return the economy to its initial state. A barrier may be the lack of social acceptance.

At the European level, there are a number of regulations that pave the path of necessary actions for the energy transformation process. These include the industrial emissions directive, the energy union, the Green Deal, and its Fit for 55 package [58], among many others. However, the energy transformation requires public acceptance. Certain restrictions that are associated with the implementation of the Green Deal have caused a wave of protests in the EU countries. In order to mitigate the effects of the new EU policy, appropriate public support should be implemented in addition to an information campaign. Subsidies for the installation of renewable energy sources have had the expected effect of increasing the share of renewable energy sources (RES) in domestic energy production (e.g., in Poland, Germany, Spain, or the Netherlands).

There are programs in the EU countries aimed at encouraging the energy transformation in society. Among these there are those aimed at counteracting energy poverty. Their effectiveness results from the fact that some of them directly target households. According to the report [59], projects aimed at mitigating energy poverty that include renewable energy communities have been highly effective. In Portugal, this is the Porto Energy ElevatoR European project, within the scope of Horizon 2020, which aims at counteracting energy poverty, promoting energy efficiency, and encouraging people to participate in renewable energy communities. In the Netherlands, municipalities work with local communities to alleviate energy poverty. This is usually done in conjunction with one of the subsidy programs. In Spain, the CE IMPLEMENTA program is an initiative implemented as a part of the Spanish Recovery Plan. The aim of this program is to promote social innovation and citizen participation in renewable energy sources. In Greece, smart metering systems are being used to supply part of the electricity generated from RES to energy-poor households and vulnerable consumers. In Poland, the programs Mój Prąd, Moje Ciepło, Czyste Powietrze, and Ciepłe Mieszkanie, which aim to subsidize investments in energy-efficient and environmentally friendly energy sources, are very popular. They are addressed to households, companies, and local government units.

Our research has its certain limitations. The first one is that we have a limited number of variables describing the EU countries with respect to the quality of consumed energy. However, this limitation results from the lack of available data. The second limitation refers to the subjectivity of the choice of variables.

From the second limitation there results the direction for future research. It will consist of more variables depicting more aspects of energy transformation.

Due to the diversity of projects implemented in the field of energy transformation in different EU countries, it is important to monitor the effects of their implementation. As there are different grant rules in different countries, it is not possible to benchmark individual projects between countries. Within the EU, the disbursement of total funds is assessed. However, the rules for their distribution in a given country depend on the level of socio-economic development and current needs. Future research can focus on evaluating the implementation of projects in selected countries as case studies.

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