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Interconnection between the Dynamic of Growing Renewable Energy Production and the Level of CO_2 Emissions: A Multistage Approach for Modeling

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Abstract: The global reduction of carbon dioxide emissions is one of the critical priorities for implementing the Sustainable Development Goals by 2030 and the Paris Agreement 2015. Therefore, it stimulates and increases the ability of countries to implement green imperatives in policies to force the anthropogenic environment, reduce use of fossil fuels, and simultaneously develop alternative energy. Thus, it is crucial to understand the impact of renewable energy development on the dynamic of CO_2 pollution. Countries can increase or decrease the development of renewable energy depending on the effectiveness of its impact on the level of CO_2 pollution. This paper aims to analyze the influence of the growth dynamics of renewable energy production in countries on CO_2 emissions. The article uses Ward's method to test the research hypothesis. Empirical results allowed us to conclude the interdependence of renewable energy production and CO_2 emissions. The results indicate a strong relationship between the level of renewable energy production and carbon emissions in countries. For the global development of renewable energy technologies, governments must understand their impact on changing the scale of environmental pollution and expand the awareness of state leadership, the business sector, and society.

Keywords: energy efficiency; clean energy technology; renewable energy; energy consumption; CO_2 emissions

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1. Introduction

Combating global climate change has long since become mainstream in most developed countries. The problem of global warming caused by carbon dioxide (CO_2) emissions was reflected in 2015 when 196 countries joined the consensus document "Paris Agreement", which implements various measures to reduce CO_2 emissions from 2020 [1,2]. Global warming is primarily associated with increased concentration of CO_2 in the environment due to burning fossil natural resources (oil, coal, and gas). In recent decades, the scientific community has been actively developing new and improving current practices for implementing the 2030 Agenda for Sustainable Development. Previous studies have shown that using a wide range of approaches and tools stimulates the implementation of sustainable management practices. In particular, it is adequate to work in the following fields and areas: study of the impact of regulatory and direct restrictions on the pollution dynamics [3]; assessment of the influence of indicators of the national economy on the environmental protection processes [4,5]; study of prerequisites for improving the energy security of countries [6,7]; introduction of green financial instruments [8]; application of specific restrictions on the development of economic sectors of countries [9]; development of new and improvement of existing energy technologies, use of intelligent networks [10–12]; analysis of green taxation [13,14]; research of social, economic, technological, ecological, and social scenarios of the sustainable growth [15,16]; implementation of environmental management [17,18]; research on the development of alternative energy [19–21]; analysis of green competitiveness at the level of countries and individual companies [22,23]; study of the features of the functioning of the circular economy [24,25]; assessment of energy gaps and efficiency of the energy sector [26,27].

The acceleration of relevant processes is followed in the global business environment. According to Bloomberg [28], in 2020, USD 501.5 billion was invested in the transition technologies of the energy decarbonization of the economy in the United States, which is a record amount compared to the previous 10-year period when funding was USD 303.5 billion in renewable sources energy In addition, the dynamics of the implementation of decarbonization market instruments by countries and the increase in the share of renewable energy production worldwide indicate a steady trend of their spread. Thus, the percentage of RES in the energy balance in 2021 is Sweden—69%, Denmark—78%, Latvia—63%, Slovenia—33%, Estonia—47%, and Germany—41% [29–31]. Implementing alternative energy has several indisputable advantages: inexhaustibility of resources, safety for the environment, economic benefit, autonomy, a long period of operation, formation of a positive image, stability, and the possibility of earning. However, not all countries have actively joined the implementation of alternative energy. Thus, it is quite essential to determine how introducing renewable energy sources affects the reduction of CO_2 emissions, which in the future can become an appropriate stimulus for activating the decarbonization processes of countries.

Thus, it is relevant from this perspective to assess the effectiveness of the implementation of renewable energy projects from the point of view of their impact on the decarbonization of national economies and ensuring the sustainable development of countries. The object of the study is 112 countries. Despite the strong background in analyzing the theoretical framework of decarbonization processes and assessment of renewable energy development [32–38], the conclusions need to consider the influence of renewable energy production on the reduction of CO_2 emission.

The paper contains a literature review, which analyzes the development of renewable energy and its link with CO_2 emission dynamics; materials and methods, which explains the methodology used in the paper; results, giving the representation of the findings; a discussion part with an analysis of the obtained findings and previous research; and a conclusion, clarifying the critical paper's outcomes, regulatory recommendations, limitations, and future directions for study.

2. Literature Review

The literature review results allow us to emphasize the significant alternative energy impact on climate change mitigation, particularly the impact on the CO_2 emission dynamic. The authors [39] used the Fuzzy DEMATEL model for the assessment of CO_2 emission and for outlining the significance of global economy decarbonization for seven emerging countries. They concluded that carbon emissions are a distressing global environmental problem and result from accelerating fossil fuel use. At the same time, renewable energy implementation can be an important method for the decarbonization of energy sectors and economies. At the same time, the scholars [40] justified the implementation of recent fiscal instruments, such as green bonds, for supporting investment processes in renewable energy development. The calculations for China's economy significantly facilitate green investment and reduce CO_2 pollution. They also accented the necessity of renewable expansion for China's economy and the global economic sector for stimulating SDG 2030 implementation. Barbar et al. [41] underscored that the success of decarbonization efforts depends directly on alternative technology development. Based on the scenario approach, they assessed electric vehicles and a power systems implementation. Adebayo et al. [42] empirically justified the interconnection between CO_2 emissions and implementing fiscal tools for investing in sustainable energy technologies. They noticed that green investments could reduce CO_2 emissions while the acceleration of economic development intensifies it. In the frame of implementation of SDG 2030, the scholars in [43] provided a systematic analysis of the nexus between clean energy spreading, environmental sustainability actions, and ecological quality. The study realized that the E-7 economies point to the interdependence of financial and renewables development and environmental pollution. Tang et al. [44] showed that an effective regulatory system and well-developed state institutions reduce the negative environmental impacts. Using the CS-ARDL approach, they described the moderate economic development in Asia with regard to carbon dioxide reduction. Rogala et al. [45] chose Polish biogas potential as a system that can stabilize alternative energy. They also emphasized its core significance in decreasing CO_2 emissions. The results of calculations for Malaysia proved that promoting renewable energy initiatives can reduce absolute carbon emissions by 20 per cent. The authors emphasized the necessity to implement several state incentives for the green energy sector, particularly the decarbonization of electricity production. Scientists in [46] studied the impact of renewable energy production on developing the circular economy for 193 countries. Using panel data with various effects, they proved that alternative electricity production provides so-called adjusted savings in the form of reduced forest depletion. At the same time, the study [47] examined the interconnection between 25 EU Member States' economic growth, carbon emissions, total energy consumption, and investments indicators. They proved such interdependences' causality and outlined the positive correlation between GDP growth, pollution, and energy consumption increase. The authors [48] examined the United States' second-largest CO_2-emitting economy as it plans to reduce its environmental challenges and contribute to achieving the Sustainable Development Goals 2030. They explored the transition to renewable energy and environmental innovations that will accelerate the decarbonization of the US economy. Using the ARDL approach, the authors illustrated the co-integration of the investigated variables in the long-term and short-term perspective and also emphasized that the transition to renewable energy reduces carbon emissions. Zhang [49] investigated the interconnection between energy transition processes and implementing environmental innovations with environmental sustainability. The article examined the ten most populous Asian countries in the context of the impact of renewable energy production and consumption, the development of ecological innovations, and the development of scientific research on the scale of CO_2 pollution. The results showed that industrialization processes significantly increase CO_2 emissions. Interesting is the study of the authors in [50], who the development of the stock market as a driver of the promotion of renewable energy on CO_2 emissions. Empirical findings indicate that foreign direct investment is an essential financial instrument stimulating energy conservation. The authors [51] examined the asymmetric and long-term effects of the UK energy sector's impact on environmental degradation. Using the nonlinear autoregressive distribution model, they evaluated energy efficiency change scenarios. The study results indicated that the increase in productivity in the energy sector and introducing renewable energy sources contributed to reducing carbon emissions, but there is a gap in the scientific approaches to investigate the interconnection between the development of renewable energy production in countries and the level of carbon emissions.

The analysis of the existing practice of studying the impact of renewable energy is nonsystematic. In general, scientists evaluate the impact of green innovations and the implementation of separate environmental projects on changes in the quality of the environment and, in particular, CO_2 emissions. Such studies are conducted for some countries, groups, or regions. Thus, it is relevant to assess the impact of renewable energy development on the decarbonization of national economies. The paper aims to substantiate and empirically confirm the connection between the sustainable increase of renewable energy production in countries and the level of CO_2 emissions.

3. Materials and Methods

Evaluation of the efficiency of using renewable energy indicators in 112 countries is proposed to be carried out within five stages.

3.1. Formation of a Sample of Indicators

The first stage is devoted to forming the input sample of renewable energy indicators and indicators that determine this economic sector's regulatory and legal field of operation.

To evaluate the effectiveness of renewable energy indicators, renewable energy consumption indicators for 112 countries were used, recorded by the World Bank's sustainable energy database based on the data of the SE4ALL global tracking system and the International Energy Agency [52]. The regulatory and legal indicators were formed based on the reports of the RISE International Agency, which is engaged in the formation of a database and research of regulatory sustainable energy indicators in the countries of the world [53]. This makes it possible to compare the national policies and legal frameworks of sustainable energy in different countries [54,55].

Therefore, the input sample of the study is statistical data, namely [52–56]:

K1—consumption of renewable energy;

K2—production of solar energy;

K3—an indicator of the total output of renewable energy;

M4—legislation background for renewable energy promotion;

M5—the potential for the expansion of renewable energy;

M6—incentive mechanisms and organizational support for renewable energy;

M7—financial instruments and regulatory incentives.

Each of the indicators M4–M7 is already aggregated and is measured on a 100-point scale (0 is the worst and 100 is the best value of the indicator). Information about the input data is given in Table 1.

Table 1. Information about the input data.

Indicator/Characteristics	Data Sources	Explanation	Measurement Units	Expected Linkages
K1	World bank [52]	Renewable energy consumption	% of total final energy consumption	The indicator has a direct relationship with K2 and K3
K2	Our world in data [31]	Share of electricity production from solar	% share of total	The indicator affects K3
K3	Our world in data [56]	Share of electricity production from renewable	% share of total	Ostentatious is a generalization of the total RES production and affects K1
M4	Regulatory indicators for sustainable energy [53]	Legal framework for renewable energy	100-point scale	The indicator demonstrates the country's position relative to the field of renewable energy, affects K2 and K3
M5	Regulatory indicators for sustainable energy [53]	Planning for renewable energy expansion	100-point scale	The indicator reflecting the ability to develop affects K2 and K3
M6	Regulatory indicators for sustainable energy [53]	Incentives and regulatory support for renewable energy	100-point scale	Assesses the level of legal protection related to energy, affects K2 and K3
M7	Regulatory indicators for sustainable energy [53]	Attributes of financial and regulatory incentives	100-point scale	Assesses the transparency of the development of renewable energy affects K2 and K3

Source: the authors.

3.2. Checking the Density and Directions of Relationships between the Studied Indicators

Descriptive analysis using the tools of descriptive statistics was used to form a statistically significant characteristic space of indicators of renewable energy consumption, solar energy production, total renewable energy production, a legal framework for renewable energy, planning for the expansion of renewable energy, incentive mechanisms and organizational support for renewable energy, financial instruments, and regulatory incentives [57].

Spearman's coefficient is used to assess the density and directions of relationships between the studied indicators [58]:

$$\rho = 1 - \frac{6}{n(n-1)(n+1)} \sum_{i=1}^{n} (R_i - S_i)^2, \quad (1)$$

where n is the number of data points; R_i is the rank being observed for the one indicator from researching data K1–K3, M4–M7; S_i—the rank of another indicator from analyzing data, $\rho \in [-1; 1]$.

3.3. Justification of the Expediency of Using Clustering Methods

To identify the degree of influence on the results of the clustering and distribution of countries into classes based on similar "behavior" in terms of the use of renewable energy indicators (renewable energy consumption, solar energy production, total renewable energy production) and regulatory and legal indicators (a legal framework for renewable energy, planning for the expansion of renewable energy, incentive mechanisms and organizational support for renewable energy, financial instruments, and regulatory incentives) it is advisable to implement the fourth stage with the use of discriminant analysis. To obtain the optimal value of the number of clusters, the Sturges formula was applied [59]:

$$k = 1 + [3.322\lg N] \approx 7.8 \quad (2)$$

where N—number of study countries.

Cluster analysis was carried out using three methods:

(1) Ward's method [60] (hierarchical type of clustering, two clusters will be closest if, in the case of their merging, the increase in the total variance is minimized) (Formula (2));
(2) The *k*-means method [61];
(3) The "farthest neighbor" method [59–62] (performs clustering based on the maximum distance between objects, considers diverse pairs, and avoids chain problems) using Statgraphics 19 software.

$$V_I = \sum_i \sum_j (x_{ij} - \overline{x}_{jI})^2,$$

where I—the number of clusters, i—country's number $(i = \overline{1, \ldots, n_I})$, n_I—the number of countries in I cluster, j—the number of the indicator $(j = \overline{1, \ldots, l})$, and l—the number of indicators included in each country.

Applying this approach will make it possible to compare the clustering results with each other and choose the optimal method for further evaluation of the efficiency of renewable energy indicators in each class.

3.4. Checking the Distribution Quality into Clusters (Classes) of Countries Using Canonical Discriminant Functions

The theory and essence of the algorithm for constructing canonical discriminant functions are similar to the methods and goals of the main components in factor analysis: the development of canonical discriminant procedures and their subsequent implementation are carried out by creating functions ordered by significance, similar to the main components of factor analysis [63]. The average discriminant function values for different clusters, which differ most significantly from each other, determine the choice of the first discriminant function. The second discriminant function is chosen similarly, but so that there is no correlation with the first. The third feature should be different from the first two. Thus, the first three to five discriminant functions (main) contain all the information about the difference between clusters (classes) [64]. Methods of variance analysis estimate differences between types based on the quantitative values of a particular indicator. According to their content, the discriminant functions are some aggregated (generalizing) variables, consisting of linear combinations of initial features, in the space where the differences between the classes are most clearly visible. The coefficients of linear combinations are determined from the condition of the maxima of a specific function, which characterizes the differences between categories [65].

In the general case, it is possible to consider y as some variable, for example, one of the m initial features of x_j. It is necessary to determine its overall average value μ and middle group up-average values in each class. To detect differences between classes, it is required to calculate the sums of square deviations of variances (3) and (4) (total SS_y, intergroup SS_e and intragroup SS_u) and determine the values of numerical characteristics (5):

$$SS_y = SS_e + SS_u \tag{3}$$

$$\sum_{p=1}^{k}\sum_{q=1}^{h_p}\left(y_{pq}-\mu\right)^2 = \sum_{p=1}^{k}\sum_{q=1}^{h_p}\left(y_{pq}-u_p\right)^2 + \sum_{p=1}^{k}\sum_{q=1}^{h_p}\left(u_p-\mu\right)^2 \tag{4}$$

Depending on the values of the numerical characteristics (5), conclusions are made about the discriminant analysis results: the larger the importance of these statistics, the more influential the discriminator is in the feature (index) y [66]:

$$\eta^2 = \frac{SS_u}{SS_y}, \lambda = \frac{SS_u}{SS_e}, F = \lambda\frac{n-k}{k-1} \tag{5}$$

where η^2—correlation relation; F—Fisher's variance ratio; n—total number of observations.

To determine Fisher's dispersion ratio, there are special tables where quantiles $F_{0.05}$ and $F_{0.01}$ are given for each pair of degrees of freedom, then the indicator y is a bad discriminator (it is impossible to draw reliable conclusions about the differences between classes based on its value). A good discriminator indicates which condition is fulfilled: $F < F_{0.01}(k-1, n-k)$.

The correlation ratio $\eta^2 = \frac{\lambda}{1+\lambda}$ varies from 0 to 1. The value 0 indicates that the feature y is not a discriminator. Value 1—feature y is an ideal (most powerful) discriminator.

3.5. Determination of the Efficiency of Renewable Energy Generation Sources

Using discriminant analysis will reveal the degree of influence of the signs of renewable energy on the results of the clustering of the countries. Data coverage analysis will be conducted using Frontier Analyst 4.1 software. The evaluation will be carried out using the data envelopment analysis (DEA) analysis methodology of the input-oriented CCR model (named after scientists Charnes, Cooper, and Rhodes), which allows seeking optimal meaning for inputs) [67,68].

Efficiency is determined from the point of view of minimizing CO_2 emission values. The main models of DAE analysis are the direct and dual CCR model focused on input data (6) (Charnes, Cooper, Rhodes model), the direct and dual input-oriented VCC model (7), and the binary aggregate Var-Multi model (8) (Table 2).

Table 2. General models of DAE analysis.

Functional Presentation of the Model	
$\sum_{j=1}^{s} u_j y_{j0} \rightarrow max$ if $\sum_{i=1}^{r} v_i x_i = 1, u_j, v_i \geq 0$	(6)
$\sum_{j=1}^{s} u_j y_{j0} + a_0 \rightarrow max$ if $\sum_{i=1}^{r} v_i x_i = 1, u_j, v_i \geq 0$	(7)
$\sum_{j=1}^{s} u_j \log(y_{j0}) - \sum_{i=1}^{r} v_i \log(x_{i0}) \rightarrow max$ if $\sum_{i=1}^{r} v_i x_i = 1, u_j, v_i \geq 0$	(8)

Source: constructed by the authors using [66,67].

Let us consider the Formulas (6)–(8), where x_i are entrance indicators, the overall amount of which is r; y_j—initial data points, the total amount of which is equal to s; v_i, u_j—input and output weighted coefficients, respectively, and a_0—constant term (constant value, constant meaning).

Therefore, the CCR model was used to assess the effectiveness of countries' activities in the use of renewable energy sources [68]:

$$e_0 = \frac{\sum_{i=1}^{r} v_i x_{i0}}{\sum_{j=1}^{r} u_j y_{j0}} \to min \tag{9}$$

When the minimization conditions are met (10):

$$\frac{\sum_{i=1}^{r} v_i x_{im}}{\sum_{j=1}^{s} u_j y_{jm}} \geq 1; m = 1, 2, \ldots, n; u_j \geq 0; j = 1, 2, \ldots, s; v_i \geq 0;\ i = 1, 2, \ldots, r \tag{10}$$

where e_0—the value of the efficiency of the evaluated indicator; n—the number of items to be compared; r—the number of input characters; s—the number of initial parameters; x_{i0}—an expression of the i-th input characteristic of the item under examination; y_{j0}—meaning of the j-th output parameter of the studied element; x_{im}—the term of the i-th input parameter of the m-th component from i = 1, . . . , r and m = 1, . . . , n; y_{jm}—the expression of the j-th output parameter of the m-th element from i = 1, . . . , r and m = 1, . . . , n; v_i—the weight for input parameter i from i = 1, . . . , r; u_j—the weight of the output variable j with j = 1, . . . , s.

The following indicators were selected as key indicators for analyzing the efficiency of the development of renewable energy sources: the volume of electricity production from renewable sources, the volume of solar electricity production, and CO_2 carbon dioxide emissions [68–70]. The data were generated from analytical reports of the World Bank.

4. Results

To determine the quality and statistical significance of the input space of renewable energy indicators within the first stage of the study, a descriptive multivariate analysis procedure was applied using Statgraphics 19 software. The results of numerical characteristics are shown in Table 3.

The value of the coefficient of variation exceeds 5%, which indicates the statistical significance of the indicators of renewable energy, which form the input sample of data on political instability. The reader should also pay attention to the indicators for which the values of the standardized coefficients of asymmetry and kurtosis are outside the range (−2; 2), because depending on the purpose of their use, for example, the development of econometric models and the application of specific methods of multivariate statistical analysis of the interpretation of the obtained results, they may not satisfy the relevant tests. Thus, if the values of the standardized skewness and kurtosis coefficients are outside the range (−2; 2), then a transformation such as LOG(Y), SQRT(Y), or 1/Y is recommended to make the variables more normal; however, it is also possible to use the built-in function for standardization in the appropriate software. The authors used a built-in function for standardization in Software Statgraphics 19 for cluster analysis.

Conducting a correlation analysis to investigate the denseness and focus of relationships between the studied pairs of indicators is advisable.

The results of Spearman's pairwise rank correlations are represented in Table 4, which, unlike Pearson's pairwise correlations, are more sustainable and less sensitive to outliers.

The results presented in Table 4 indicate that indicators M5 (renewable energy expansion potential) and M6 (incentives and regulatory support for renewable energy) have a high directly proportional density of interconnection, which is 70.17%. For other pairs of variables, as directly proportional, there is an inversely proportional connection at an average level, which increases within (45–60%), and the density of interconnection at a low level (9–15%) or levels below the average (20–40%).

Table 3. Descriptive statistics of renewable energy indicators.

Descriptive Characteristic	Meaning of Descriptive Parameters						
	K1	**K2**	**K3**	**M4**	**M5**	**M6**	**M7**
Count	112	112	112	112	112	112	112
Average	35.676	2.050	36.557	79.464	63.335	50.438	45.667
Median	26.375	1.075	28.540	80.000	67.5	48	50
5% Trimmed mean	34.640	1.731	35.075	81.825	64.514	50.4861	45.2824
5% Winsorized mean	35.445	1.943	36.473	79.643	63.813	50.438	45.354
Variance	831.276	6.725	977.858	500.611	583.734	783.511	830.023
Standard deviation	28.832	2.593	31.271	22.374	24.161	27.991	28.810
Coefficient of variation, %	80.82%	126.52%	85.54%	28.16%	0.381	0.555	0.631
Gini coefficient	0.456	0.620	0.482	0.142	0.215	0.320	0.363
Standard error	2.724	0.245	2.955	2.114	2.283	2.645	2.722
5% Winsorized sigma	31.177	2.456	34.160	23.956	25.023	30.070	31.038
Mean absolute deviation	24.882	1.928	26.665	15.475	19.540	23.671	24.661
MAD	18.74	1.05	23.28	20	14.335	23.500	25.000
Sbi	30.862	1.812	32.591	21.268	24.510	29.000	30.137
Minimum	0	0	0	0	0	0	0
Maximum	95.03	14.29	100	100	100	100	100
Range	95.03	14.29	100	100	100	100	100
Lower quartile	10.715	0.165	10.115	80	48	30	25
Upper quartile	60.425	2.99	61.1	100	80	75	67
Interquartile range	49.71	2.825	50.985	20	32	45	42
1/6 sextile	8.17	0.04	4.44	60	36	19	17
5/6 sextile	76.4	3.94	70.63	100	89	82	75
Intersextile range	68.23	3.9	66.19	40	53	63	58
Skewness	0.564	1.994	0.623	−1.362	−0.5968	0.065206	0.195505
Stnd. skewness	2.436	8.616	2.692	−5.883	−2.5785	0.281723	0.84468
Kurtosis	−1.050	4.890	−0.865	1.702	−0.2077	−0.9992	−1.01138
Stnd. kurtosis	−2.268	10.563	−1.868	3.677	−0.4488	−2.15852	−2.18483
Sum	3995.72	229.56	4094.39	8900	7093.51	5649	5114.67
Sum of squares	234,823	1216.99	258,221	762,800	514,061	371,891	325,703

Source: built using Statgraphics 19.

Table 4. Spearman's rank correlations.

	K1	**K2**	**K3**	**M4**	**M5**	**M6**	**M7**
K1		−0.0942	0.5282	−0.2375	−0.1001	−0.0901	−0.1422
		0.3208	0.0000	0.0123	0.2915	0.3424	0.1340
K2	−0.0942		0.1087	0.2097	0.3291	0.3786	0.3438
	0.3208		0.2523	0.0271	0.0005	0.0001	0.0003
K3	0.5282	0.1087		−0.0061	0.1349	0.0979	0.0404
	0.0000	0.2523		0.9490	0.1552	0.3022	0.6702
M4	−0.2375	0.2097	−0.0061		0.5452	0.4744	0.4154
	0.0123	0.0271	0.9490		0.0000	0.0000	0.0000
M5	−0.1001	0.3291	0.1349	0.5452		0.7017	0.4967
	0.2915	0.0005	0.1552	0.0000		0.0000	0.0000
M6	−0.0901	0.3786	0.0979	0.4744	0.7017		0.6389
	0.3424	0.0001	0.3022	0.0000	0.0000		0.0000
M7	−0.1422	0.3438	0.0404	0.4154	0.4967	0.6389	
	0.1340	0.0003	0.6702	0.0000	0.0000	0.0000	

Source: built using Statgraphics 19.

Thus, for example, between indicator K1 (consumption of renewable energy) and indicator K3 (total production of renewable energy), the density correlation is at the level of 52%, which corresponds to the average level; between indicator K1 (consumption of renewable energy) and M4 (the legal basis for renewable energy), correlation is 23%; between indicator K2 (solar energy production) and M4 (legislation background for renewable energy promotion)—20%; between indicator K2 (solar energy production) and M5 (renewable energy expansion potential)—32%; between indicator K2 (solar energy production) and M6 (incentives and regulatory support for renewable energy)—37%; between indicator K2 (solar energy production) and M7 (financial instruments and regulatory incentives)—34%; between indicator M4 (legal framework for renewable energy) and M5 (renewable expansion potential energy)—54%; between indicator M4 (legislation background for renewable energy promotion) and M6 (incentive mechanisms and organizational support for renewable energy)—47%; between indicator M4 (legislation background for renewable energy promotion) and M7 (attributes of financial and regulatory incentives)—41%; between indicator M5 (renewable energy expansion planning) and M7 (financial instruments and regulatory incentives)—49%; M6 (incentive mechanisms and organizational support for renewable energy) and M7 (attributes of financial and regulatory incentives)—63%. The indicated correlation pairs of variables have a significance level (p-value) below 0.05, which indicates the statistical significance of a nonzero correlation at a confidence level of 95.0%.

The results of the study of the division of countries into clusters (classes) as a basis for evaluating the efficiency of the use of renewable energy sources, carried out using three methods, are presented in Table 5.

Table 5. Clustering of countries according to Ward's method.

Cluster	The Number of Countries in the Cluster	Percentage
1	10	8.93
2	28	25.00
3	18	16.07
4	23	20.54
5	8	7.14
6	11	9.82
7	11	9.82
8	3	2.68

Source: built using Statgraphics 18.

In addition, the optimal number of clusters was proven using the agglomeration protocol (Figure 1). The absence of specific jumps between the diagram points allows us to state that the selected number of clusters for the set of observations is correct.

The first cluster includes ten countries: Afghanistan, Albania, the Central African Republic, Guatemala, Madagascar, Nepal, Paraguay, Sierra Leone, Sudan, and Tajikistan. The second cluster includes 28 countries—Algeria, Argentina, Azerbaijan, Bahrain, Bangladesh, Belarus, Bosnia and Herzegovina, Dominican Republic, Indonesia, Jamaica, Kazakhstan, Kosovo, Malaysia, Maldives, Mongolia, North Macedonia, Oman, Pakistan, Philippines, Poland, Qatar, Saudi Arabia, Singapore, Thailand, Ukraine, United States, Uzbekistan, and Vietnam. Cluster 3 includes 18 countries: Angola, Benin, Colombia, Costa Rica, Croatia, Liberia, Mali, Montenegro, New Zealand, Nicaragua, Niger, Nigeria, Panama, Peru, Romania, Sri Lanka, Togo, and Zimbabwe. Cluster 4 consists of 23 countries, namely: Armenia, Belgium, Bulgaria, Denmark, Finland, France, Germany, India, Israel, Lebanon, Mexico, Morocco, Netherlands, Portugal, Rwanda, Serbia, Slovak Republic, South Africa, Switzerland, Tunisia, Turkey, United Arab Emirates, and United Kingdom. Cluster 5 unites eight countries: Australia, Chile, El Salvador, Greece, Hungary, Italy, Jordan, and Spain. Cluster 6 comprises 11 countries: Brazil, Canada, Chad, Ethiopia, Kenya, Malawi, Sweden, Tanzania, Uganda, Uruguay, and Zambia. Cluster 7 includes 11 countries: Burkina Faso, Burundi, Cambodia, Eritrea, Haiti, Mozambique, Myanmar, Papua New Guinea, Somalia, South Sudan, and Turkmenistan. The last, eighth cluster contains three countries: Mauritania, Senegal, and Vanuatu.

For example, the geographical distribution of countries for cluster 2 according to Ward's method is shown in Figure 2.

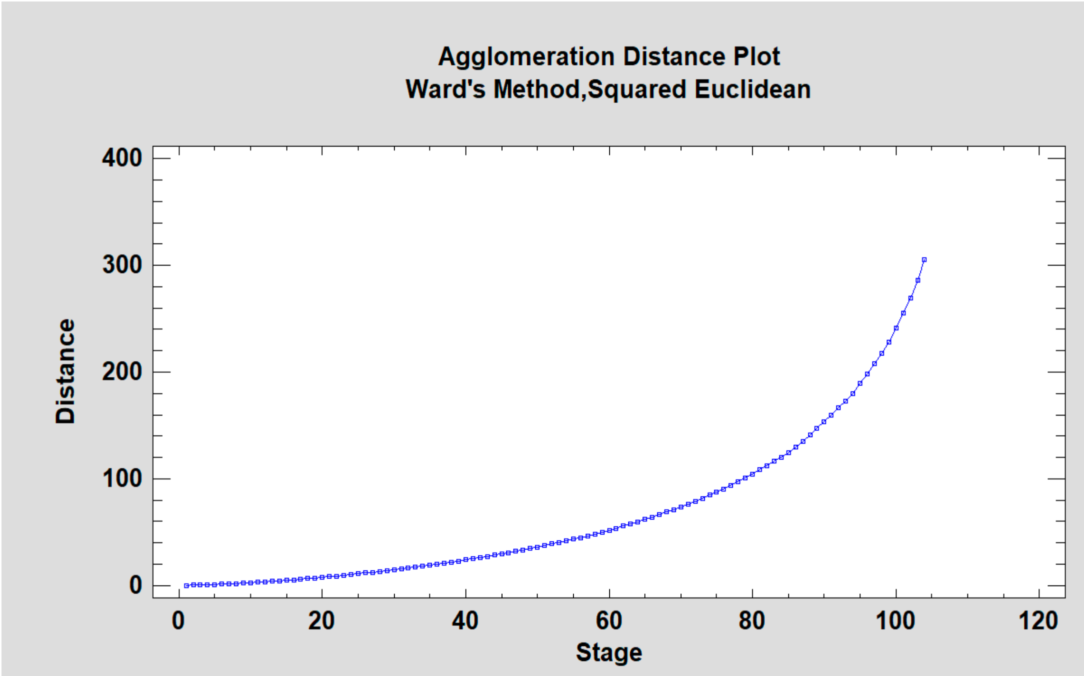

Figure 1. Results of the evaluation of agglomeration intervals: confirmation of the optimal number of clusters by Ward's method. Source: built using Statgraphics 19.

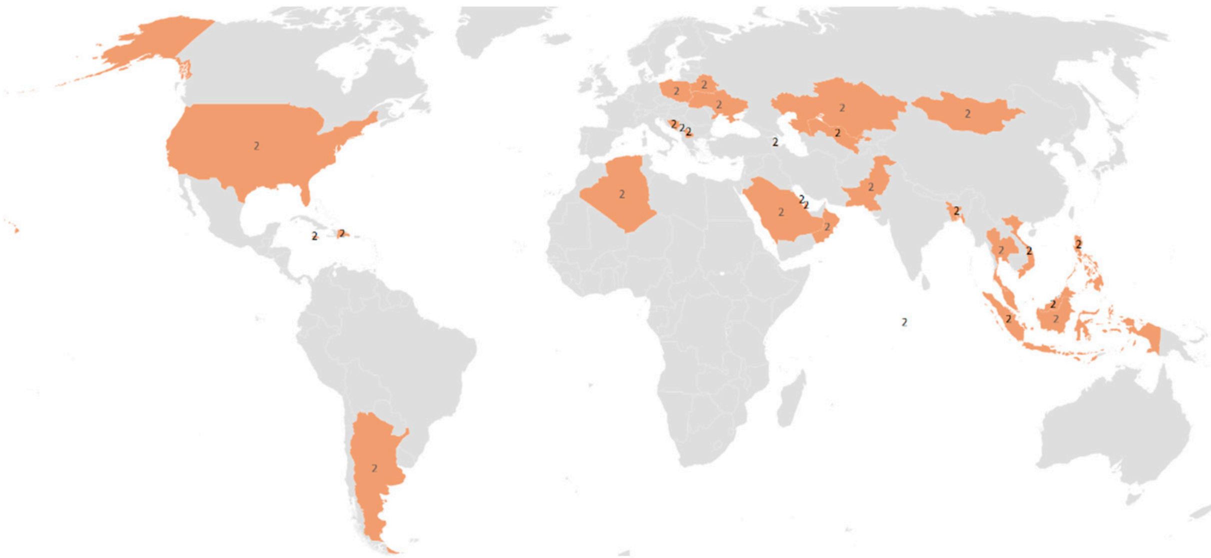

Figure 2. Map of the cluster distribution of countries for cluster 2 according to Ward's method. Source: constructed by the authors using Excel.

According to the clustering by the k-means method using the Euclidean squared distance metric, the results are given in Table 6.

It should be noted that the results of the distribution by the k-means method significantly depend on the initial element and the final element, and step k; in addition, the lack of the possibility to construct a graph of the agglomeration scheme forces us to abandon the use of the obtained results in further research.

Table 7 shows the cluster analysis by the "farthest neighbor" method (full binding) using the Euclidean squared distance metric.

Table 6. Cluster distribution of countries by the k-means method.

Cluster	The Number of Countries in the Cluster	Percentage
1	6	5.36
2	6	5.36
3	25	22.32
4	14	12.50
5	18	16.07
6	18	16.07
7	13	11.61
8	12	10.71

Source: built using Statgraphics 19.

Table 7. Cluster distribution of countries by the "farthest neighbor" method.

Cluster	The Number of Countries in the Cluster	Percentage
1	14	12.50
2	12	10.71
3	33	29.46
4	24	21.43
5	6	5.36
6	10	8.93
7	12	10.71
8	1	0.89

Source: built using Statgraphics 19.

When examining the agglomeration protocol (Figure 3) using the "farthest neighbor" method, the visible gaps indicate the irrelevance of the chosen strategy.

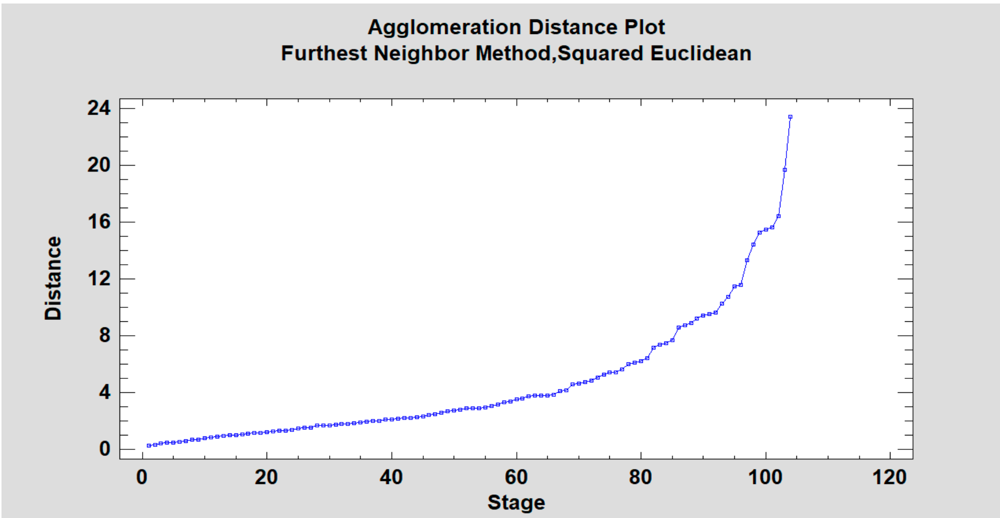

Figure 3. Scheme of agglomeration according to the "farthest neighbor" method. Source: built using Statgraphics 19.

Thus, Ward's method aims to minimize the total within-cluster variance when merging clusters, and it is beneficial when the goal is to create compact, homogeneous clusters with low within-cluster variability, which is proposed in the article. In addition, Ward's method is based on the concept of variance analysis, where the objective is to maintain the structure of the original data as much as possible. It tends to produce clusters with relatively balanced sizes and can handle different cluster shapes. Of course, this method also has a drawback: sensitivity to outliers. Ward's approach is sensitive to outliers or noise in the data, aiming to minimize the within-cluster variance. Outliers can significantly affect the clustering results and potentially lead to suboptimal cluster assignments, but the previously conducted descriptive analysis using the construction of box and whisker plots showed no outliers for the included sample of data (Figure 4), except for two indicators—production of solar energy and legislation background for renewable energy promotion. However, these values indicating the emissions are logically argued, based on the geographical location of the countries and the features of the regulatory and legal framework regarding its frequency of change in terms of the features of the use of renewable energy.

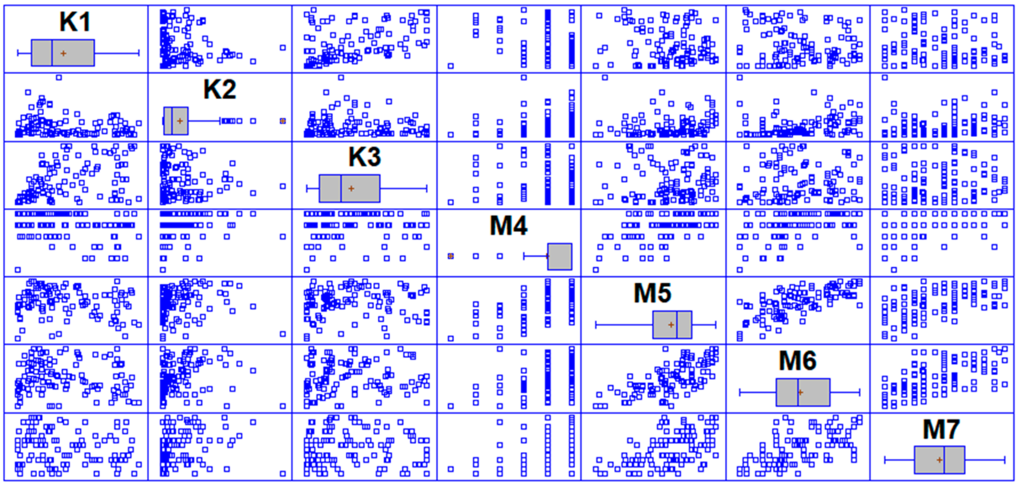

Figure 4. Box and whisker plots of the research indicators. Source: built using Statgraphics 19.

To evaluate the performance of countries in terms of the efficiency of renewable energy use, it is proposed to use the clustering results obtained by Ward's method.

The methodology of discriminant analysis, which makes it possible to evaluate the quality of the clustering performed, is given and implemented with the Statgraphics 19 toolkit.

The results of the obtained discriminant functions are shown in Table 8.

Table 8. Standardized coefficients of discriminant functions.

	F1	F2	F3	F4	F5	F6	F7	Sum of F1–F5
K1	−0.447294	0.327673	0.384274	0.297589	0.377388	−0.115231	0.568488	0.93963
K2	0.177813	−0.792476	0.622515	0.123638	0.0422518	0.0494716	0.0282298	0.173742
K3	−0.290784	0.393824	0.594677	−0.371049	−0.261015	0.186145	−0.494086	0.065653
M4	0.535412	0.120929	0.204042	−0.687822	−0.0796015	−0.139243	0.464574	0.092959
M5	0.3987	−0.0281953	−0.160521	0.161783	0.859733	0.45279	−0.291758	1.2315
M6	0.418919	0.312553	0.157806	0.255723	−0.266788	−0.857358	−0.150898	0.878213
M7	0.261849	0.387078	−0.0458057	0.394562	−0.456168	0.658733	0.235165	0.541515

Source: built using Statgraphics 19. Note: F1–F7 are discriminant functions.

Thus, Table 8 shows the values of the coefficients of the discriminant functions that form eight linear combinations from the input feature space.

Based on the calculation of the sum of the standardized coefficients of the discriminant functions, the value of the influence of each variable on the formation of clusters was obtained: K1 has a power of impact on the construction of groups of 0.93963; in turn, K2—0.173742; K3—0.065653; M4—0.092959; M5—1.2315; M6—0.878213; M7 is 0.541515. From the obtained estimates, it is clearly seen that K1 indicators of renewable energy consumption and M4 indicators of legislation background for renewable energy promotion for renewable energy have the most significant influence on the formation of clusters. Other indicators have a much smaller impact on the construction of groups. Therefore, countries were divided into clusters according to the characteristics of renewable energy consumption indicators.

For example, the model of the first discriminant function appears as follows:

$$F1 = -0.447294 \cdot K1 + 0.177813 \cdot K2 - 0.290784 \cdot K3 + 0.535412 \cdot M4 + 0.3987 \cdot M5 + 0.418919 \cdot M6 + 0.261849 \cdot M7 \quad (11)$$

However, it is sufficient to use the first five discriminant functions to identify the degree of influence of the given indicators of the input feature space (Table 9).

Table 9. Statistical characteristics of discriminant functions.

Discriminant Function	Eigenvalue	Relative Percentage	Canonical Correlation	Wilks' Lambda	Xi Square	DF	*p*-Value
F1	5.72053	54.15	0.92261	0.00813059	498.0547	49	0.0000
F2	2.26766	21.47	0.83305	0.0546418	300.8699	36	0.0000
F3	1.68443	15.95	0.79214	0.178551	178.3183	25	0.0000
F4	0.599608	5.68	0.61225	0.479307	76.1154	16	0.0000
F5	0.237287	2.25	0.43793	0.766703	27.4954	9	0.0012
F6	0.050911	0.48	0.22010	0.948631	5.4581	4	0.2434
F7	0.00308259	0.03	0.05544	0.996927	0.3186	1	0.5725

Source: built using Statgraphics 19.

The absolute value of the coefficient reflects the importance of each indicator. A more excellent value will significantly impact this indicator in forming clusters.

Thus, renewable energy indicators were used across 112 countries to construct discriminant functions. They were divided into eight clusters. Five of the seven discriminant parts have an effective rate (*p*-value is lower than 0.05%, indicating statistically significant discriminant functions at the 95.0% confidence level). The value of the lambda Wilks statistic in functions 1–2 (Table 9) is the closest to zero, and the closer the value is to zero, the better the quality of the discriminative functions.

Therefore, it is advisable to use the results of linear combinations of the first five discriminant functions for further deeper and more detailed analysis of the prospects for the development of renewable energy, as they allow us to determine which indicators of the character input space are the most important for dividing countries into clusters. Thus, by using the absolute value of the coefficients in Table 9, one can determine how the independent variables are used to differentiate between groups; the greater its value, the more outstanding the indicator's contribution to the classification results.

The study of the effectiveness of the functioning of renewable energy at the level of national economies based on data envelopment analysis (DEA) is based on methods of multiple-criteria optimization modeling [71,72]. The following 11 countries were chosen to analyze the sixth cluster at the authors' discretion: Brazil, Canada, Chad, Ethiopia, Kenya, Malawi, Sweden, Tanzania, Uganda, Uruguay, and Zambia. Indicators for data envelopment analysis were chosen as the following indicators: volumes of electricity production from renewable sources (TWh·h) (output indicator), volumes of solar electricity production (TWh·h) (output indicator), and emissions of carbon dioxide CO_2 (kt) for 2019 (input indicator).

Table 10 presents the initial data for evaluating the effectiveness of the use of renewable energy sources.

The results of data coverage analysis using the Frontier Analyst Application for CO_2 emissions, renewable electricity generation, and solar electricity generation revealed that the reference countries are Sweden and Uruguay (they have 100% efficiency compared to other countries). Other countries received the following indicators of the efficiency of the use of renewable energy: Brazil—45.58%, Canada—27.2%, Chad—0.16%, Ethiopia—27.3%, Kenya—16.24%, Malawi—53.28%, Tanzania—11.17%, Uganda—34.7%, and Zambia—54.94%

Table 10. Initial data for the analysis of the efficiency of energy use from renewable sources.

Country	CO_2 Emissions (kt)	Electricity from Renewable Sources (TWh)	Electricity from the Sun (TWh)
Brazil	434,300	515.4381	6.654579
Canada	580,210	429.033	4.079798
Chad	2250	0.01	0
Ethiopia	18,360	14.14	0.02
Kenya	22,280	9.89	0.09
Malawi	1450	1.37	0.05
Sweden	35,000	98.75301	0.663
Tanzania	12,450	2.97	0.09
Uganda	5860	5.27	0.07
Uruguay	6490	13.9	0.42
Zambia	6800	9.81	0.12

Source: built on the basis of [55–68].

The marginal efficiency graph (Figure 5) shows the gap between countries.

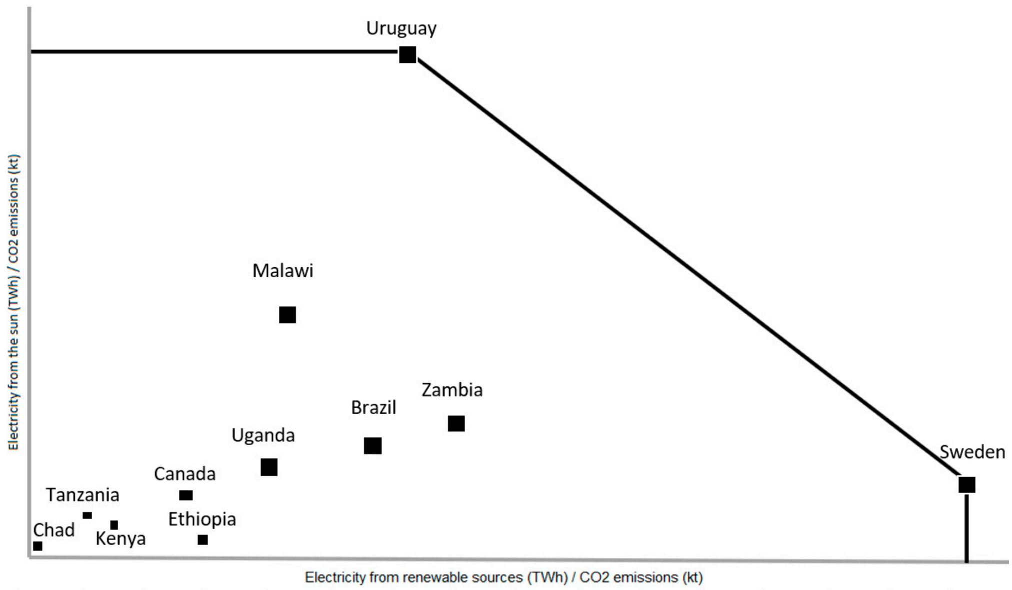

Figure 5. Graph of the marginal efficiency. Source: built using Frontier Analyst Application.

The analysis results indicate that only two of the twelve countries studied are efficient; that is, the production of renewable energy and their CO_2 emissions are in relative balance. However, the rest of the countries participating in the study cannot ensure such efficiency; for this, they need to increase the production of renewable energy or reduce CO_2 emissions.

Thus, according to the results of the analysis, Chad should reduce CO_2 emissions to 99.84%, that is, from 2250 to 3.7; for Tanzania, it is advisable to reduce CO_2 emissions by 88.83%, that is, from 12,450 to 1390.71; for Kenya, the CO_2 reduction potential is 83.76%, that is, from 22,280 to 3618.17; for Canada reduction of CO_2 emissions is 72.8%, that is, from 580,210.02 to 157,789.28; for Ethiopia, reducing CO_2 emissions is 72.7%, that is, from 18,360 to 5011.49; for Uganda, the reduction of CO_2 emissions is 65.3%, that is, from 5860 to 2033.48; the potential for Brazil to reduce CO_2 emissions is 54.42%, that is, from 434,299.99 to 197,968.98; Malawi must work to reduce CO_2 emissions by 46.72%, that is, from 1450 to 772.62; reduction of CO_2 emissions for Zambia to optimally reduce is by 45.06%, that is, from 6800 to 3735.98.

5. Discussion

The paper's analysis and calculations confirmed the hypothesis that there is a connection between the growth of renewable energy production and the reduction of CO_2 at the level of national economies. The evaluation results indicate a strong interconnection between the level of renewable energy production and countries' carbon emissions. This is different to the existing studies in evaluating the results of the implementation of renewable energy on the national economic level. Thus, a study [73] assessed the role that renewable energy assumes in the context of global and national "sustainable" energy strategies, i.e., strategies aimed at solving climate change demands and guaranteeing energy security. The authors of [74,75] identified key challenges facing renewable energy and suggested ways to overcome these barriers. The authors of [76,77] mapped the potential of national economies for adaptation to global goals of sustainable development and carbon emission reduction by applying an assessment system based on indicators of economic status, dependence on coal, and contribution to climate change. The studies [78,79] demonstrated an inverse relationship between CO_2 emissions and national financial performance and positioned green growth as a determinant for further economic development. In addition, the authors analyzed the effect of bioeconomy sectors on the indicators of the national economy, particularly the GDP [80]. They concluded that in the long term, all bioeconomy sectors contribute equally and significantly to the national economy.

6. Conclusions

Evaluation of the effectiveness of the development of clean energy technology was conducted within the framework of a multistage approach, which included the following stages: formation of a sample of indicators; checking the density and directions of relationships between the studied indicators; substantiation of the expediency of using clustering methods; checking the quality of distribution into clusters of countries using canonical discriminant functions; evaluation of the efficiency of the use of renewable energy sources. The evaluation results indicate that only two countries out of the twelve studied are efficient; their renewable energy production and CO_2 emissions are in relative balance. The approach applied in the paper made it possible to compare the clustering results with each other and choose the optimal method for further evaluation of the efficiency of renewable energy indicators in each class.

Deep decarbonization of the energy sector requires a lot of policy measures and efforts to accelerate the deployment of renewable energy sources. Decarbonization of the economy should be one of the priorities for sustainable development. No one-size-fits-all approach can achieve CO_2 reduction goals. For the decarbonization of the energy sector, a combination of energy efficiency measures and renewable energy policy is inevitable. Renewable energy offers a powerful energy resource for the economy but requires a comprehensive and innovative approach, a combination of regulatory guidelines and socioeconomic measures.

Considering the paper's results, the following suggestions can be provided to facilitate the decarbonization of the energy sector and promote renewable energy implementation:

- Regulation of the "green tariff" system. To a large extent, introducing green tariffs encourages society to develop renewable energy sources.
- Determining and providing more ambitious goals in the field of alternative energy. Global crises and military actions push the world economy to abandon fossil fuels faster. Countries should review draft national action plans to develop renewable energy and improve their goals.
- Formation of the legislative framework for stimulating the development of small renewable energy generation. Supporting small renewable energy producers will help communities become more energy-independent, but for this to become possible, an adequate legislative framework is necessary. It is also essential to define specific deadlines for adopting the legislative framework and develop documents based on the fundamental principles and provisions under the 4th Energy Package.

- Reducing risks for investors. "Green tariff" is not the only way to support small producers. For example, the "green auctions" mechanism guarantees investors that the state will buy electricity produced by their stations, even before the stations' construction, while guarantees under the "green tariff" could be obtained only after construction. Therefore, when planning the project, the investor will be sure that he will be able to sell the energy after completing the work. In addition, this mechanism does not offer a fixed price for electricity, as was the case with the tariff. On the contrary, the cost of electricity will be determined by auction, so the state will also benefit by buying energy from those who offer it more favorably. Such a mechanism will attract more foreign investors and give them confidence.
- Involvement of communities in the process of forming goals and making decisions. Communities should actively participate in developing strategic documents in the energy sector. The needs of communities should be the foundation for defining national goals because they will be realized in the future. The effectiveness of achieving the plans depends on the request and powers of the municipalities. The energy security of communities and individual energy independence should be a priority on the energy agenda. This can be achieved by developing a decentralized small generation, where citizens are the leading direct energy producers and beneficiaries of the energy transition.
- Implementation of the system of guarantees of the origin of electricity. Countries must achieve the planned indicators of decarbonization of electric energy released into the network. Guarantees of Origin is an electronic document that provides consumers with information about the source of electricity and is also a support tool for renewable energy producers. They will help consumers monitor exactly what electricity they consume. Ideally, consumers should be interested in the sources of the electricity they use.

The shortcoming of the proposed approach is the conditional countries' division into groups, which is why it was proposed to compare the outcomes of the cluster analysis comprehensively.

Recent studies [42,46,47] emphasized that countries' decarbonization is a complicated process, which is determined by a set of factors (green culture and awareness, green financing, green management, etc.), and which can accelerate the process of the green transition and, as a result, CO_2 reduction. Thus, it should be considered in future research. In addition, follow-up studies will be topical in investigating the influence of implementing separate renewable technologies (wind, hydro, tidal, geothermal energy, biomass, etc.) on developing the carbon-free energy sector.

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