Ranking of Energy Structures in EU27 Countries Focusing on the V4 Countries

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Abstract: While EU countries are acting as one and making commitments to achieve global climate targets, there are significant differences in the performance of individual countries and thus their contribution to the targets. The present study aims to establish a ranking based on objective weighting, using relevant environmental and economic indicators, with the main objective of identifying the position of the V4 countries (Czech Republic, Poland, Hungary, Slovakia). The ranking is carried out using the DEA (Data Envelopment Analysis) methodology with 5 different approaches (stepwise envelopment analysis, three different models of the common weights approach, stepwise Pareto efficiency approach). Despite the different weighting schemes of the different models, the country positions are well defined, on the basis of which the Member States can be grouped into five groups. The V4 countries tend to show signs of the least efficient structures, but the weight vectors in each model allow the reasons for this to be identified.

Keywords: energetic structure; ranking; V4 countries; renewable energy; data envelopment analysis

1 Introduction

The signing of the Single European Act in 1987 declared the unity of the European Union Member States in the global fight against climate change [1]. The EU, the third largest carbon emitter after China and the United States, is striving to contribute to global goals with ambitious targets both in terms of greenhouse gas emissions (GHG emissions), which play a significant role in climate change, and in terms of sustainable development efforts (energy transition, energy efficiency) [2].

Although EEA experts see a clear shift towards sustainable development solutions at EU level [3], despite the unity of action and targets, there are in some cases significant difference in the performance of Member States' indicators against the various commitment targets.

Within the EU, Germany is the largest GHG emitter (21.8% of EU GHG emissions in 2022), while five countries (Germany, France, Italy, Poland and Spain) account for 65.2% of total EU emissions. However, if we take into account the size of these countries, for example in terms of population, the order changes significantly: the largest emitter Germany joins the middle, France, Italy, and Spain the top, while the 26th smallest absolute emitter Luxembourg is at the other end of the scale as the largest specific emitter in terms of GHG emissions per population [4-5].

These discrepancies are not only visible in terms of GHG emissions. While the share of renewables in the Nordic countries' EU accession countries (Sweden, Finland, Denmark) averaged close to 52% in 2022, the V4 average was just under 17%, less than a third of that in 2022. [6] Beyond these isolated differences, the overall picture is that the dynamics of the shift from fossil fuels to renewables are much more dynamic in the western and northern countries of Europe than in the central and eastern/southern regions. This is largely in line with the evolution of GDP per capita, which is also higher in the western and northern countries compared to other regions [7], whose environmental investment-inducing effect is now well established [8-9], and is also related to the finding of Kiss et. al. (2024) that the sense of threat associated with climate change and environmental vulnerability weakens from west to east in Europe, and is lowest in post-socialist countries [10].

Despite sometimes significant differences in regional performance, common objectives, and common guiding policies necessarily force member countries' behavior and attitudes towards sustainable development and the climate crisis in the same direction. This is well supported by a study by Erőss et al (2025), which uses cluster analysis to demonstrate similarities and an increase in homogeneity between member countries from 2012 to 2022, partly through the analysis of environmental/energy data and partly through the analysis of variables related to economic performance [11].

However, keeping in mind the increasingly ambitious global climate and environmental aspirations, explicitly called for by the 29th UN Climate Change Conference (COP29) [12], it may become important to identify which within similar structures are better than others and what makes them better perceived. Answering these questions can inform the design of EU energy policies and help identify countries that need more attention to achieve the energy transition. At the same time, the identification of "good practice" could further help other Member States to better shape their energy structures.

Based on this, the objective of this study is to rank the 27 countries of the European Union, and within this, to understand the position of the V4 countries by analysing their energy structure, identifying best practices and areas for improvement, and mapping the direct links between the member countries.

This study is innovative in terms of both the selected research methods and the data set used for analysis, but even more significant is the fact that the data is up-to-date and comes from a reliable source (the Eurostat database), providing a fresh picture of the energy structures of the EU27 countries and highlighting both good practices that help improve efficiency and opportunities for development. The area studied and its results are of paramount importance both in terms of the community's climate commitments and the climate and energy policy aspirations of individual nations.

First, Chapter 2 presents the relevant literature background regarding the applied approach and its application in the relevant research area, followed by a description of the data used and the methodology (Chapter 3). Chapter 4 presents the results (Subchapter 4.1: TDEA, Subsection 4.2: DEA/CWA models, Subsection 4.3: Pareto optimality), and finally, Chapter 5 summarizes the findings based on the studies.

2 Literature Review

If the efficiency of a socio-economic activity is determined by a single input and a single output, the result can be defined as the ratio of output to input. However, in the case of multiple inputs or outputs, both the outputs and the weighted sum of the inputs can be used to determine the result. While the determination of weights is not self-evident, this methodological factor plays a prominent role in the final result. DEA (Data Envelopment Analysis) analysis, which can be approached according to this interpretation, consists of generating a multidimensional surface of efficient points from the available data using a linear programming technique, and then relating and determining the efficiency index of a given point to this surface [13].

DEA, or Data Envelopment Analysis, is an objective approach for comparing the efficiency of Decision Making Units (DMUs) with the same multiple inputs and/or outputs, first developed (CCR model) in 1978 by Charnes, Cooper and Rhodes. A major feature of the DEA procedure is that the methodology used provides the possibility to compare indicators available in different measures [14]. The traditional DEA methodology divides DMUs into two groups - efficient and inefficient (for the present study, these are the European Union countries), while in practice, a full ranking would be required in most cases, and it does not provide the possibility to rank efficient DMUs [15]. Onion peeling, based on a sequential algorithm developed by Barr et al. (2000) [16], separates efficient DMUs (with the same DEA efficiency) from other DMUs as onion peels. After the first 'peel', the remaining units are re-determined and then separated from the efficient elements - repeating the analysis until it finally 'peels the onion' [17]. The approach is referred to throughout this paper by the acronym TDEA, which is developed from its English name (Tiered Data Envelopment Analysis).

To date, several improved and extended versions of the DEA-based model are known, one of which is the Common Weights Analysis (CWA) approach, the first use of which (Maximin DEA model) was by Podinovski and Athanassopulos [18]. The procedure involves determining the DMU with the lowest efficiency value for a given vector weight and then selecting the weight vector that maximizes this lowest value. Other models use distance functions (e.g., Euclidean or Chebyshev distance function) to provide objective weighting in addition to the optimization technique achieved by compromise programming [19].

As a result of, DEA-based efficiency analysis, beyond the concrete and quantifiable results, there is a potential to understand and, above all, improve the processes under study. However, it is important to emphasise in the evaluation of the results that DMUs holding different positions in the rankings produced by the DEA approach can only be considered efficient or inefficient in relation to each other [14].

In addition to DEA-based models, other decision-theoretic approaches support the search for efficient, optimal solutions. One optimisation approach in multi-criteria decision theories is the identification of Pareto-optimal (also known as non-dominated) solutions, which are optimal in the sense that no other solution in the design space is better than or dominated by them, given all the objectives under consideration [20]. Stepwise Pareto ranking thus provides a sequential filtering of dominant objects (in this case countries), the results of which can be visualised well using a Hasse diagram.

Nonlinear systems are widely encountered in all areas of scientific research (whether social, natural, industrial, or other technical dimensions); modeling them poses a methodological challenge for researchers due to their complexity and nonlinear behavior [21]. The key role of research based on the application of modeling mechanisms combining different approaches in the discussion of complex, interdisciplinary scientific issues is confirmed by numerous scientific works. In the field of engineering, the work of Venczel et al. (2023) is noteworthy, in which the authors built a nonlinear viscosity model based on measurement data, whose parameters were customized using the regression method [22]. Also, noteworthy is the work of Szakács (2023) is also worth mentioning, in which the operation of a pneumatic piston is described using a mathematical model, and then the model is optimized to achieve increased efficiency [23]. Travin and his co-authors use statistical modeling and probability distribution to map the dynamics of the natural effects of technical processes, while Abramov and his colleagues

(2023) propose a new approach to analyzing and forecasting official statistics in the field of social sciences [24].

The application of DEA models for ranking purposes has been the subject of publications in a number of fields, particularly in recent years, including the environment, energy and sustainable development [24-27], which demonstrate the suitability of the approach. Although these articles relate to environmental and energy issues and focus on EU member states, they mostly examine only one aspect (e.g., GHG emissions, energy mix composition, energy consumption in certain industries) and, unlike the present study, do not perform calculations based on complex data.

3 Data and Methodology

The study will use five different approaches (TDEA, Pareto efficiency and three DEA-CWA-based (Maximin, Euclidean and Chebiseb distance function)) to rank the energy structure of the 27 EU countries by examining relevant indicators. The dataset used is the most recent available at the time of the study, 2022.

In determining the ranking criteria, the focus was primarily on the indicators related to climate change and sustainable development presented, but also on energy dependency, which is the focus of national energy policies. The ranking criteria, the associated expectation, indicators and variables used are illustrated in Table 1 below.

Table 1

Ranking criteria

Ranking criteria	Indicator	Requirement	Specific variables used
Increasing the share of renewables	Share of renewables in primary energy use	the higher	Primary energy production (TJ/1,000 people) [5, 29]
			Renewable energy production (TJ/1,000 people) [5, 29]
Reducing greenhouse gas emissions	GHG emissions per 1000 people	as low as possible	GHG emissions (kt/1,000 people) [4-5]
Energy efficiency	Energy use	as low as possible	Energy sector own energy consumption (TJ/1,000 people) [5, 29]
			Energy consumption in the industrial sector (TJ/1,000 people) [5, 29]
			Energy consumption for heating in the household sector (TJ/1,000 people) [5, 28]

Reducing energy dependence	Net energy imports	as low as possible	Energy imports (TJ/1,000 people) [5, 29]
			Energy exports (TJ/1,000 people) [5, 29]
Trends in economic performance	GDP	the higher	GDP (mEUR/1,000 people) [5, 7]

The baseline data for the indicators considered for the validation of the above criteria for the year 2022 are presented in Table A1 of the Annex, and the indicators used for the ranking are presented in Table A2 of the Annex.

The DEA models are basically oriented towards minimising inputs and maximising outputs, which in this case, in line with the specificities of the area under study, can be achieved by preferring the highest possible value of renewable energy production and the share of renewable energy production, and the lowest possible value of GDP for the other indicators (some energy use data and GHG emissions).

The statistical and mathematical details of the approaches used in the research have been presented and derived in detail in previous studies (TDEA and Pareto efficiency analysis – Dobos and Bánhidi, 2025; DEA/CWA model – Bánhidi and Dobos, 2024), and with reference to which the present study, focusing on the results of the analysis and its processing and interpretation, refrains from presenting these details again, instead providing cited sources with detailed explanations of the approaches used. [17, 19]

4 Results

In the following, the results of the ranking tests carried out – first the TDEA model, then the Pareto efficiency model, and then the three DEA models using the approach of joint weights – are presented.

4.1 Results of the TDEA Analysis

The TDEA model based on flexible weighting finds the most preferable weights for each DMU through optimization to maximize efficiency, which ensures the objectivity of the analysis. As a result of, the optimization process, the following levels of efficiency can be distinguished between EU Member States, based on the aspects under consideration.

The vector of possible weights of the DEA model can be determined by the system of equations (1) to (3). Inequalities (1) shows the upper limit of DEA efficiency $\mathbf{u}\cdot\mathbf{y}_j$, i.e. one, while inequality (2) defines the non-negativity of weights. The number of decision making units is p, and vector $\mathbf{y}_j$ is the values jth decision making unit, in this case country. The shape of the DEA models (1)-(3) that must be solved at each step:

$$\mathbf{u}\cdot\mathbf{y}_j \leq 1;\ j = 1,2,...,p. \quad (1)$$

$$\mathbf{u} \geq \mathbf{0}. \quad (2)$$

$$\mathbf{u}\cdot\mathbf{y}_k \rightarrow \max;\ k = 1,2,...,p. \quad (3)$$

After solving problems (1)-(3), we exclude efficient decision making units at every step, which in our case are countries. Then, in the next step we will solve the DEA problems again.

Table 2

Results of the TDEA model with DEA efficiencies in each step

Steps					
1		2		3	
Bulgaria	1.000				
Cyprus	1.000				
Denmark	1.000				
Estonia	1.000				
Spain	1.000				
Finland	1.000				
France	1.000				
Greece	1.000				
Croatia	1.000				
Ireland	1.000				
Lithuana	1.000				
Luxembourg	1.000				
Latvia	1.000				
Malta	1.000				
Portugal	1.000				
Romania	1.000				
Sweden	1.000				
Slovenia	1.000				
Italy	0.812	Austria	1.000		
Austria	0.698	Germany	1.000		
Poland	0.612	Italy	1.000		
Hungary	0.593	Netherlands	1.000		
Netherlands	0.559	Belgium	0.735	Belgium	1.000
Slovakia	0.533	Czeh Republic	0.708	Czeh Republic	1.000
Germany	0.413	Poland	0.617	Hungary	1.000

Czeh Republic	0.268	Hungary	0.545	Poland	1.000
Belgium	0.230	Slovakia	0.505	Slovakia	1.000

Table 2 shows that the energy structure of the 27 EU countries studied can be divided into 3 distinct levels. The overwhelming majority of countries (Layer 1 – 18 countries) are efficient and, based on the data examined, are the epitome of a good example, as the ratio between them is optimal. The 4 countries in layer 2 (Austria, Germany, Italy, and the Netherlands) do not belong to this group, but their structures are close to the best efficiency, but they have some characteristics that could be optimized to reach the most efficient level. In layer 3 there are 5 countries, Belgium and the V4 countries (Czech Republic, Poland, Hungary, and Slovakia) – these countries are further away from the efficient level; the structure that can be set up based on the aspects considered in the analysis is unstable. For these countries, it is necessary to identify the factors that lead to inefficiency, as it is by improving these factors that structures can be raised to a higher level. A common feature of these countries is the low absolute value and share of renewable energy sources compared to the EU average, based on the baseline data examined.

4.2 Results of DEA Analysis using the Approach of Common Weights

In the following, the results of the energy structure efficiency of the countries under study are presented, based on the Maximin model, which evaluates the efficiency of the energy structure of the countries under study using minimum and maximum weights, and the DEA models, which validate the minimization of the Euclidean distance and the maximum deviation (Chebyshev norm).

The vector of possible weights of the Common Weights DEA models can be determined by the system of equations (4) to (6). The efficiencies are $\mathbf{u}\cdot\mathbf{y}_j$ (j = 1,2,...,p).

$$\mathbf{u}\cdot\mathbf{y}_j \leq 1;\ j = 1,2,...,p. \quad (4)$$

$$\mathbf{u} \geq \mathbf{0}. \quad (5)$$

$$F_i(\mathbf{u}) \rightarrow \max;\ i = 1,2,3 \quad (6)$$

The objective functions of the three DEA models $F_i(\mathbf{u})$ are as follows:

Maximin model: $F_1(\mathbf{u}) = \min_{1\leq j\leq p} \mathbf{u}\cdot\boldsymbol{y}_j$,

Euclidean model: $F_2(\mathbf{u}) = \sqrt{\sum_{j=1}^{p}(\boldsymbol{u}\cdot\boldsymbol{y}_j - 1)^2}$,

Chebyshev model: $F_3(\mathbf{u}) = \max_{1\leq j\leq p}|\boldsymbol{u}\cdot\boldsymbol{y}_j - 1|$.

First, we review the DEA joint weights of the considered criteria as shown in Table 3.

Table 3
Distribution of weights across the three common weights models (%)

Weights	Renewable energy prod.	Share of renewable energy prod.	GDP	Share of renewable energy prod.	Energy sector owns energy use	Industrial sector energy use	Household heating energy use	GHG emissions
Maximin	3.68	70.44	2.46	0.00	0.43	8.70	7.89	6.40
Euclidean	0.92	79.96	1.44	0.00	4.07	3.62	0.27	9.71
Chebyshev	0.69	98.86	0.44	0.00	0.00	0.00	0.00	0.00

Table 3 shows that the three DEA models assign different weights to the dimensions under consideration, which is also the result of the different rankings.

It can be seen that the share of renewable energy production is prominent in all three models, while net energy exports are given zero weight in all models, so that this aspect is not included in the results.

The distribution of weights is most balanced in the Maximin model. In addition to the high weight of the share of renewable energy production, the energy consumption of the industrial sector, the energy consumption of households for heating and GHG emissions are characterised by almost equal weights (between 6.3 and 8.7%), followed by renewable energy production and GDP, while the energy sector's own energy consumption is the least important. For the Euclidean model, the share of renewable energy production is close to 80%, while GHG emissions are the second most important aspect, with a weight of 10%. Besides these, the aspects related to the different energy uses are the most important in the model.

In the case of the approach using the Chebyshev distance function, the share of renewable energy production is close to 99%, the remainder is shared between renewable energy production and GDP, while the other aspects have zero weight.

In conclusion, while none of the models focuses on the energy dependence dimension, all three give priority (albeit to a different extent) to indicators related to renewable energy production.

As the weights used in the DEA models are of particular importance and the objectively chosen common weights show significant differences, the ranking results show corresponding differences (Table 4).

Table 4
Results of the joint weighted DEA analysis with efficiencies

Ranking	Maximin		Euklidean		Chebysev	
		DEA		DEA		DEA
1.	Denmark	1.000	Denmark	1.000	Luxembourg	1.000
2.	Ireland	1.000	Ireland	1.000	Latvia	1.000
3.	Latvia	1.000	Latvia	1.000	Finland	0.999
4.	Portugal	1.000	Portugal	1.000	Sweden	0.974
5.	Sweden	0.964	Sweden	1.000	Austria	0.922
6.	Malta	0.927	Lithuania	0.961	Portugal	0.825
7.	Estonia	0.913	Luxembourg	0.937	Lithuania	0.776
8.	Cyprus	0.852	Cyprus	0.849	Malta	0.770
9.	Spain	0.804	Croatia	0.836	Cyprus	0.767
10.	Lithiania	0.789	Italy	0.814	Irorszag	0.708
11.	Luxembourg	0.726	Austria	0.771	Denmark	0.685
12.	Austria	0.682	France	0.712	Italy	0.673
13.	Greece	0.681	Estonia	0.708	Estonia	0.620
14.	Croatia	0.674	Spain	0.699	Croatia	0.596
15.	Italy	0.659	Greece	0.674	Germany	0.581
16.	France	0.606	Malta	0.665	Greece	0.568
17.	Netherlands	0.559	Germany	0.606	Spain	0.529
18.	Finland	0.559	Romania	0.548	Netherlands	0.492
19.	Germany	0.546	Finland	0.517	Slovenia	0.374
20.	Romania	0.465	Slovenia	0.490	France	0.364
21.	Slovenia	0.452	Netherlands	0.484	Slovakia	0.345
22.	Bulgaria	0.450	Hungary	0.453	Hungary	0.332
23.	Belgium	0.372	Slovakia	0.397	Czeh Republic	0.323
24.	Slovakia	0.367	Belgium	0.386	Poland	0.269
25.	Poland	0.654	Czeh Republic	0.316	Romania	0.268
26.	Czeh Republic	0.354	Poland	0.314	Bulgaria	0.260
27.	Hungary	0.354	Bulgaria	0.312	Belgium	0.259

As can be seen from Table 4, the results of the Maximin DEA procedure show that four countries (Denmark, Ireland, Latvia, Portugal) have the maximum efficiency of the structure (1.000), while the least efficient structure is characterised by five countries with an efficiency below 0.4 - including Belgium and the V4 countries. The majority of EU27 Member States are characterised by a medium efficiency with a score between 0.4 and 0.8.

The Euclidean DEA results reflect the high priority given to the share of renewable energy and the importance of the need to minimise GHG emissions, so that the results largely favour countries with a low reliance on fossil energy sources. The model also includes Sweden in the best structures under the Maximin approach. Bulgaria joins Belgium and the V4 countries at the bottom of the ranking, but if the last positions are interpreted from a value below 0.4, it should be noted that Hungary is more in the middle of the range with a score of 0.453 in this model. For countries with a low-level of efficiency according to the model, the low renewable share below 0.3 supports the results.

Since the renewable share plays an almost exclusive role in the Chebyshev DEA model (other factors are negligible), the results show the largest dispersion. Of the previous models, only Latvia maintains its maximum efficiency, and Luxembourg joins it among the best performers in the middle of the previous models. This model shows the highest number of low-efficiency structures, with 9 countries below 0.4. Of these, Belgium, Bulgaria, Romania and Poland have the lowest scores below 0.3, while the Czech Republic, Slovakia and Hungary are between 0.3 and 0.4, along with Slovenia and France.

Based on the above, the models used suggest that the structure used is highly efficient for Sweden, Latvia and Portugal, while the low performers are Belgium and the V4 countries. The results of some countries (e.g. Denmark, Ireland or Luxembourg) show significant variations depending on the approach used, suggesting that the efficiency of these countries is sensitive to the assumptions used in the DEA model. Among the countries with medium results, there are also several countries whose efficiency is below 1.0, but which consistently produce values close to the maximum in all three models, such as Austria, Lithuania, Cyprus or Malta.

4.3 Results of the Pareto Efficiency Model

The description of determining Pareto efficient decision making units can be found in paper [17]. For the sake of brevity, this description will not be reiterated here.

Figure 1 below illustrates the results of the Pareto efficiency model on a Hasse diagram, created with the DART program [30].

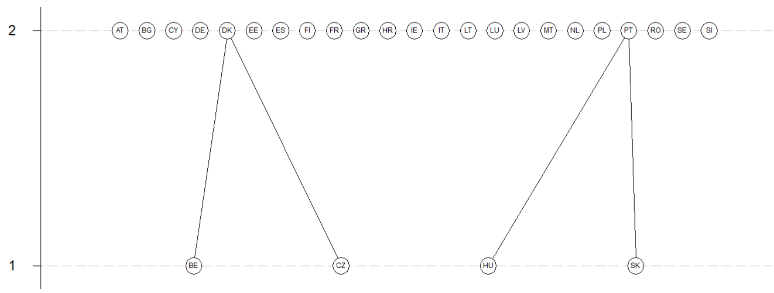

Figure 1
Hasse diagram of Pareto efficiencies between countries, generated with DART [30]

While the levels of the DEA model are composed on the basis of efficiency scores, in the case of the Hasse diagram they are organised in a relational system. At the top of the diagram are the most efficient countries, and at the lower levels are the least efficient countries in terms of the structure under consideration. Figure 1 shows Belgium, the Czech Republic, Hungary, and Slovakia at the bottom, the least efficient level, with all other countries at the top efficient level. The Hasse diagram shows direct links between countries, indicating a similar structure of the countries concerned, but also a more efficient structure of the country at the top of the link. It therefore shows a direct correlation between Belgium and Denmark, among others, but Denmark dominates Belgium because of its high efficiency level, i.e. it is more efficient in the aspects examined. The same can be said for the Czech Republic's relationship with Denmark and for Hungary and Slovakia's relationship with Portugal.

The importance of these relations is that, in the case of dominance, the example of the dominant country can serve as a model of good practice for the dominated country. By comparing the data of the dominant country with the data of the country it dominates, it is easier to identify the factors that lead to dominance rather than to a relationship of equal (equal effectiveness).

4.4 Summary of the Results Obtained with the Different Approaches

The results of the studies carried out using each approach have been analysed separately so far, and the following is a summary of the findings based on the rankings, which include both similarities and differences. The insufficient contribution of some member states may pose a structural obstacle to achieving EU energy policy objectives. The results presented in this section, based on the latest available Eurostat data, aimed to highlight the country structures and areas that need more attention (e.g., insufficient energy production, excessive energy consumption).

Based on the results of the study carried out, the EU27 countries can be divided into five groups (Table 5).

Table 5
Energy clusters of EU countries

	Group feature	Countries	Comment
1.	Highly efficient countries	Sweden, Latvia, Portugal	Good practice, exemplary structures
2.	Countries with approach-dependent performance	Denmark, Luxembourg, Ireland	Sensitivity to assumptions of DEA models - the dimension resulting in a less favourable position to be identified and improved
3.	Effective countries that are lagging behind emerging countries	Austria, Finland, Cyprus, Malta, Lithuania, Estonia, Spain	Stable countries, usually performing in the more efficient half of the midfield -stable structures that lag behind efficient performance in some aspects
4.	Low performing countries	Crotia, Greece, Italy, Netherlands, Slovenia, Romania, France, Germany, Bulgaria	Overall, countries performing in the lower half of the midfield - structures to be considered and improved
5.	Least efficient countries	Belgium, **Czeh Republic, Poland, Hungary, Slovakia**	Adopting structures that need more attention and need to be improved, "good practices"

The results show little reflection of the west-to-east decline in performance cited in the introduction, but clearly show the higher performance of the Nordic countries and the below-average efficiency of Central Europe (including the V4 countries at the heart of the study) in terms of the energy structures studied. It can also be seen that the majority of the largest countries in the Community (Germany, France, Italy) are at the least efficient level, with Spain in the positive and Poland in the negative.

All these results provide important lessons regarding the topic under investigation, as the inefficient energy structures of individual member states may hinder the fulfillment of the EU's commitments. Based on the results, it is possible not only to identify country structures that fall short of optimal efficiency and require greater attention, but also to highlight areas in need of improvement (e.g., too low a share of renewable energy production, excessive energy consumption, etc.) using recent data.

Summary, Conclusions

The present study aimed to investigate the energy structure of the EU27, with a particular focus on the V4 countries, using five different DEA models with objective weighting.

Although there are significant differences in the weights and, of course, in line with this, differences in the rankings, the same countries can be identified at the top and bottom of the hierarchy in all models.

The V4 countries (including Belgium), which are the focus of the research, are consistently ranked at the bottom of all models. A consistent negative result represents an unfavourable structure, but based on the weighting of the models used, it gives a concrete indication of a low absolute amount and share of renewable energy in total energy production and an energy use above the EU average. Accordingly, these countries require particular attention in terms of both renewable energy production and energy efficiency. Most of the countries in this group have direct links with other countries' structures, which, despite similarities, still produce significantly higher efficiency, which suggests that a detailed analysis of these links may be useful to improve the efficiency of the dominant Member States.

Beyond the main focus of the present research, it is possible to identify countries (Sweden, Latvia and Portugal) that are clearly good practitioners, as they show maximum or very close to maximum efficiency according to all methodologies. It is important that these countries maintain their favourable structures and continue to set an example for the future.

Countries in the middle can be divided into two parts: those that perform consistently well, mostly close to 1.0 efficiency, with a fundamentally good energy structure and a low performance in 1-2 dimensions at most, separating them from the top. The other part is the lower middle section of the midfield, which are not among the worst performing countries, but are far from efficient. For these Member States, the dimensions responsible for poor performance need to be identified and improved, but there may also be a need to rethink the overall structure.

For countries where there is a significant difference in ranking due to different weightings in the DEA models (countries that are highly efficient according to some methodologies but significantly less efficient according to others), it is appropriate to identify the dimension that is deteriorating efficiency due to its significant weighting in the methodology and to focus attention on improving the performance of this dimension.

It is also important to note that the DEA procedures chosen, based on joint weighting, give zero weight to the energy dependence indicator, so although the research would like to include this aspect in the ranking, the objective statistical procedures chosen do not meet this requirement.

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Appendix

Table A1

Data for EU countries in 2022, the baseline for our analysis [4], [5], [7], [28], [29]

2022	Primary energy production (TJ)	Renewable energy production (TJ)	Energy import (TJ)	Energy export (TJ)	Energy sector own energy use (TJ)	Industrial energy consumption (TJ)	Household energy use for heating (TJ)	GHG-emission (kt)	Population (1,000 people)	GDP (mEUR)
BE	664 848	179 020	3 438 341	1 582 923	90 887	401 119	217 667	108 464	11 618	554 214
BG	550 871	117 255	538 978	233 912	47 600	113 073	41 206	49 543	6 839	85 801
CZ	1 058 474	232 574	1 005 308	272 753	80 500	276 913	210 343	121 878	10 517	276 266
DK	416 376	211 897	733 634	425 112	38 973	99 147	96 700	43 862	5 873	380 618
DE	4 074 315	2 066 790	9 758 105	1 613 969	481 202	2 237 818	1 585 298	781 762	83 237	3 876 810
EE	196 451	80 249	113 452	100 137	6 921	15 005	29 385	14 464	1 332	36 011
IE	131 268	71 044	558 442	68 230	8 799	89 534	66 316	67 633	5 060	506 282

GR	219 977	150 532	1 574 360	782 037	66 608	107 414	102 577	76 852	10 460	206 620
ES	1 505 507	842 297	5 311 990	1 323 924	339 547	751 387	235 990	261 869	47 433	1 346 377
FR	4 513 388	1 188 439	6 104 142	1 300 328	237 924	1 059 350	1 047 493	391 233	67 872	2 639 092
HR	155 025	101 385	369 763	154 479	17 970	47 247	64 621	21 391	3 862	68 370
IT	1 453 232	1 095 951	6 374 437	1 385 132	313 352	1 031 067	845 849	398 268	59 030	1 962 846
CY	10 763	10 281	110 905	753	975	10 497	5 566	9 273	905	27 777
LV	122 430	121 916	161 193	87 983	3 448	37 932	29 968	15 513	1 876	38 386
LT	85 725	76 693	596 201	375 226	23 769	39 937	44 363	12 893	2 806	67 437
LU	13 633	11 897	153 420	7 083	69	22 726	15 175	9 497	645	77 529
HU	445 208	144 942	850 712	157 693	40 245	180 386	175 240	53 529	9 689	168 550
MT	2 038	2 038	127 560	1 504	197	3 098	1 024	2 648	521	17 432
NL	1 015 897	364 275	7 845 558	5 199 944	195 506	513 287	217 389	168 060	17 591	958 549
AT	508 030	434 666	1 184 383	173 533	64 404	319 026	191 056	70 352	8 979	447 218
PL	2 484 953	563 092	2 692 013	669 822	243 348	631 124	545 382	347 790	36 890	656 153
PT	282 315	276 169	909 200	214 227	43 200	188 261	39 980	54 656	10 352	242 341
RO	930 865	239 930	701 613	271 668	77 901	240 312	203 233	63 526	19 042	284 174
SI	126 080	40 326	273 804	129 905	4 028	49 441	26 871	15 507	2 107	57 038
SK	282 548	91 012	684 231	199 764	42 073	132 636	78 839	29 958	5 435	109 762
FI	820 796	532 426	929 954	367 966	52 486	408 277	155 193	51 785	5 548	267 687
SE	1 494 692	941 180	1 347 022	809 391	80 628	466 820	166 051	5 857	10 452	561 785

Table A2

Data for EU countries included in the 2022 survey

2022	Renewable energy production (TJ/ 1,000 people)	Renewable energy share	Net energy exportexport (TJ/ 1,000 people)	Energy sector own energy use (TJ/ 1,000 people)	Industrial energy consumption (TJ/ 1,000 people)	Household energy use for heating (TJ/ 1,000 people)	GHG-emission (kt/ 1,000 people)	GDP (mEUR/ 1,000 people)
	→ max	→ max	→ max	→ min	→ min	→ min	→ min	→ max
BE	15.4	0.3	-159.7	7.8	34.5	18.7	11.5	49.9
BG	18.1	0.2	-47.1	7.3	17.4	6.4	7.7	13.3
CY	11.4	1.0	-121.8	1.1	11.6	6.2	11.3	32.5
CZ	22.1	0.2	-69.7	7.7	26.3	20.0	11.6	27.3
DE	24.8	0.5	-97.8	5.8	26.9	19.0	9.4	47.5
DK	36.1	0.5	-52.5	6.6	16.9	16.5	7.7	65.1
EE	60.3	0.4	-10.0	5.2	11.3	22.1	11.6	27.4
ES	17.7	0.6	-84.0	7.2	15.8	5.0	6.1	28.9
FI	96.0	0.6	-101.3	9.5	73.6	28.0	9.5	48.0
FR	17.5	0.3	-70.7	3.5	15.6	15.4	5.8	39.1
GR	14.4	0.7	-75.7	6.4	10.3	9.8	8.0	19.9
HR	26.2	0.7	-55.7	4.7	12.2	16.7	5.6	17.5
HU	15.1	0.3	-72.1	4.2	18.8	18.2	5.6	17.6
IE	13.8	0.5	-95.1	1.7	17.4	12.9	13.2	101.1
IT	18.6	0.8	-84.5	5.3	17.5	14.3	6.8	33.8
LT	27.3	0.9	-78.8	8.5	14.2	15.8	4.8	24.0
LU	18.4	0.9	-226.7	0.1	35.2	23.5	14.7	120.1
LV	65.0	1.0	-39.0	1.8	20.2	16.0	8.5	19.2

MT	3.9	1.0	-242.3	0.4	6.0	2.0	18.3	35.1
NL	20.7	0.4	-150.4	11.1	29.2	12.4	11.6	56.5
AT	48.4	0.9	-112.6	7.2	35.5	21.3	7.8	49.9
PL	15.3	0.2	-54.8	6.6	17.1	14.8	9.5	17.9
PT	26.5	1.0	-66.7	4.1	18.1	3.8	5.5	23.4
RO	12.6	0.3	-22.6	4.1	12.6	10.7	3.3	14.8
SE	90.0	0.6	-51.4	7.7	44.7	15.9	1.2	52.8
SI	19.1	0.3	-68.3	1.9	23.5	12.8	7.4	27.0
SK	16.7	0.3	-89.1	7.7	24.4	14.5	5.5	20.3