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Evaluating the Transition of the European Union Member States towards a Circular Economy

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Abstract: This paper presents the assessment of the European Union member states in terms of the circular economy (CE) targets, using a combination of the Data Envelopment Analysis (DEA) method and factor analysis. This approach fills in the existing knowledge gap by providing an innovative methodology of an objectivised comparative evaluation of the degree of implementation of the CE principles by the EU countries. Assessing countries' performance in achieving the goals of the circular economy is a challenge due to the lack of a generally accepted methodology, the multitude of indicators, and the insufficient data. Countries may be compared in a narrow way, according to single indicators, but a more holistic synthetic assessment of countries is also needed to determine their position against each other. In such cases, DEA may be successfully used. The study resulted in the identification of two clusters of countries with similar profiles of relative efficiency in the CE goals' implementation. It was concluded that the position of a particular country in achieving the CE aims was strongly correlated its GDP per capita. Moreover, factor analysis showed that many CE indicators are strongly correlated with each other and may be aggregated into five meta-indicators (factors): Recycling rate of general waste, Waste production, Jobs and investments, Recycling rate of special waste, and Circular material use rate. In addition to simple rankings and indication of benchmarks, the article offers a novel concept of technology competitors which was used to group units competing for positions in the ranking.

Keywords: Data Envelopment Analysis (DEA); factor analysis (FA); circular economy (CE); sustainability; sustainable development indicators (SDI); European Union (EU)

Citation: Nazarko, J.; Chodakowska, E.; Nazarko, Ł. Evaluating the Transition of the European Union Member States towards a Circular Economy. *Energies* **2022**, *15*, 3924. https://doi.org/10.3390/en15113924

Academic Editors: Viktor Koval, Dzintra Atstaja and Ilona Skačkauskienė

Received: 23 April 2022
Accepted: 23 May 2022
Published: 26 May 2022

1. Introduction

The growing impact of human activities on the environment makes the search for viable modes of sustainable development especially urgent [1]. The term circular economy (CE) has existed in the literature since the 1960s [2]. In recent years, it gained significant notability in Europe with the introduction of the circular economy concept into the policy and strategy of the European Union (EU) in 2014 (COM/2014/0398) [3] and the launch of the first Circular Economy Action Plan of the European Commission (COM/2015/0614 Final) in 2015 [4] continued by a new Circular Economy Action Plan: For a cleaner and more competitive Europe (COM(2020)0098) [5]. The growing interest in CE is also reflected by the rapid increase in the number of scientific articles and reports [6].

Transition towards the circular economy demands a whole new logic of designing economic processes and running businesses. In the traditional linear model of production and consumption, resources are mined or grown, then transformed into goods which are then used and finally turned into waste (the so called 'produce-use-dispose', 'make-take-dispose', or 'take-make-waste' paradigms). In the circular economy, materials are repeatedly recovered and recycled—they remain in circulation for as long as possible.

Despite a noticeable change in the political discourse, academic discussion, and the public awareness, the current globally dominant economic model essentially remains focused on the efforts to increase consumption constantly, which until now was always related to the increase in production and further depletion of Earth's resources. Improvement in welfare is typically associated with an increased production and consumption. Especially now, as the world is trying to cope with the economic consequences of the coronavirus pandemic and with the unfolding geopolitical crisis, it is not easy to win the public's heart by calling for the fundamental rethinking of lifestyles, and for efforts to reconcile profitability with sustainability [7,8]. As Kirchherr notes, discussions between business practitioners, policy makers, and scholars *rest upon the CE's promise to reconcile sustainability and growth* [9]. At the same time, there is no consensus, neither among scholars nor among practitioners, that the CE paradigm guarantees social well-being for this generation and the future ones [10,11]. The European Union would need to cut off its ideological roots in the trade union for coal and steel and to prioritise long-term environmental sustainability [12].

Even though a completely circular economy is not possible in complex advanced economies [13,14], some authors view the CE as the most comprehensive and mature model capable of reconciling economic growth with sustainability and even boost the competitiveness of countries and enterprises by protecting businesses against scarcity of resources [15]. It remains to be seen, however, to what extent the paradigm shift actually occurs. As long as the old linear paradigm shapes the national economic policies (in real terms, not in rhetoric figures), there will be no single country that could come close to the ideal of a truly circular economy. Transition towards a CE must go hand in hand with the shift of the innovation paradigm [16,17] towards models such as Responsible Research and Innovation [18–22], Restorative Innovation [23], or Future-Oriented Technology Analysis [24,25], focusing not only on what is marketable but what is socially desirable and environmentally viable.

A common and widely accepted framework and the standard set of indicators measuring the CE maturity are not established yet. Assessment of the transition towards a CE based on selected indicators is the content of numerous publications that include simple and complex comparisons, qualitative and quantitative evaluation approaches [26]. One of the most exploited methods to assess sustainability, comparing the ability to transform labour, capital, and energy (including from renewable energy sources) and taking into account pollutants (e.g., greenhouse gas emissions) into the GDP, is Data Envelopment Analysis (DEA) [27]. Assessment of the state of development of the circular economy is also carried out using DEA.

Beside the numerous advantages of DEA as an objective method of creating rankings, there is a serious limitation consisting of a low classification ability in the case of too large a set of indicators in relation to the number of objects. Thus, its direct application in the case of a large set of CE indicators without limiting their number does not allow the assessment of the state of transition toward a CE. Apart from the arbitrary selection, one of the popular approaches to limiting the number of indicators is the principal component analysis (PCA)/factor analysis (FA) method. It is not always possible to use them directly, as is shown in the work. The article proposes an alternative approach consisting of the selection of the representative indicators. The position of countries compared to each was analysed, and benchmarks and technological competitors were indicated. It was proven that the performance assessment approach derived from operations research may be successfully applied to evaluate the circular economy maturity.

In this paper, the authors fill in the research gap related to the lack of works evaluating the comparative performance of the EU member states in pursuing the CE goals based on the system of indicators included in the EU methodology of CE assessment. The methodological contribution of this work consists of proposing a novel approach to a comparative evaluation of the state of transition towards a CE in a given group of countries. The cognitive added value of the paper lies in the results obtained from the analysis of the EU member states according to the developed methodology.

The article is structured as follows: first, it provides a review of papers that focus on the monitoring and assessment of countries toward a CE, and the second part assesses

EU countries in terms of CE targets combining DEA and factor analysis. The article ends with conclusions.

2. Background Literature

2.1. Circular Economy and Multitude of Related Concepts

Circular economy is a concept that has not been clearly defined in the literature so far. However, different propositions share much in common and converge towards the same paradigm [28]. Kirchherr et al. (2017) [29] view the CE as a market-based economic system that supports business models implementing the ideas of reducing, alternatively reusing, recycling, and recovering materials in the production, distribution, and consumption processes. Such reorientation of the economic system at all levels (products, companies, consumers, cities, regions, countries) shall lead to the environmental viability, welfare, and social equity for the current and future generations. The circular economy is defined in opposition to the linear 'make-take-waste' model and is understood as an extension of the concept of green economy or bioeconomy [30–33] and linked to a cleaner economy, a low emission economy, industrial symbiosis [34], industrial ecology, eco-industry [35,36], cradle-to-cradle economy [37], Tech-Ökonomie [38], zero-waste economy, 'regenerative by design' economy [39], natural capitalism [40], green engineering, ecological modernisation [41], or sustainable development in general [42–46].

The bio-based CE is an economy where materials and energy are produced and derived from renewable biological sources [47,48]. Moreover, biological resources are managed in a way that their value is maintained at the highest level as long as possible [49]. Bioeconomic orientation of the CE is particularly suitable in sectors such agriculture [50], fertilizers [51], forestry [52], marine economy, pulp and paper, food production and retail [53], feedstock [54], cosmetics, biofuels, bioplastics [55], construction, furniture as well as bio-waste management [56,57], and wastewater treatment [58]. Metic et al. propose a concept of dual circularity, noting the existence of distinct, yet overlapping, thematic areas of a technology-focused CE and bio-based CE [59]. The area where 'bio' fuses with 'tech' includes, among others, such topics as microbial production, enzyme technology, and Green Chemistry [60].

Regardless of the definition, the implementation of the principles of a circular economy and the transformation towards less wasteful systems, a more effective and sustainable use of natural resources, and the reduction of pollutant emissions, including greenhouse gases, is becoming one of the key challenges worldwide [61]. Institutional, economic, environmental, organisational, social, technological, supply chain related drivers, barriers, and critical success factors determining the transition to a CE are discussed from different perspectives and at different levels of analysis [62]. Changing the economic systems is not possible in the short term horizon, and the practices that lead to the implementation of the circular economy postulates are introduced gradually [63]. Monitoring the progress of the performance at micro, meso, and macro levels [64] towards the circular economy is a complex and demanding task, mainly because of the multidimensionality and vagueness of the concept [65,66].

2.2. Macro and Meso Levels of CE Analysis

At the macro and meso levels, researchers study sectoral or spatial (national, regional [67], municipal/urban [68,69]) aspects of CE. Those aspects were divided by Martinho and Mourão [70] into the following categories: (1) efficiency and sustainability [71–73], (2) policies, governance, and management [41,74–78], (3) product life-cycle [79,80], (4) resources and waste [81,82], (5) innovation and opportunities [83], (6) sectoral topics, (7) bioeconomy. Mhatre et al. [84] offer an exhaustive list of CE-oriented activities characteristic to different sectors of national economies. Those activities are, among others, related to: bio-based materials, by-products' utilisation, cascading materials, community involvement, design for disassembly, design for modularity, down-cycling, eco-design, eco-labelling, element recovery, energy recovery, extended producer responsibility, bio-chemicals' extraction, functional recycling, green procurement, high-quality recycling, incentivised recycling, material substitution, optimising packaging, product as a service, refurbishment, adaptable manufacturing, restoration, reuse, redistribution and resell, sharing, take back and trade-in, upcycling, maintenance and repair, virtualisation.

2.3. Micro Level of CE Analysis

At the micro level, forward-looking enterprises and organisations anticipate the emerging shift towards the CE and try to transform their operations with the aim at boosting innovation, penetrating new markets, and securing customer loyalty. Interface of entrepreneurship and the CE is an extensively explored topic [85]. Incentivising adoption of CE activities by companies (with a special focus on small and medium enterprises [86]) is also a priority of the European Union [87]. Public sector entities are also evaluated against the circularity criteria, especially with regards to public procurement procedures, internal process and operations, and public service delivery [88]. Eco-innovations [89] and new business models are proposed and validated in various sectors [90–93]. Discussion on incorporating digital technologies (Industry 4.0, Big Data, Internet of Things, Artificial Intelligence, Blockchain) into CE frameworks is currently a dynamic field [94]. Interaction between governmental policies and different business models conducive to the CE is also analysed [95].

Four macro-categories of business models aligned with the CE paradigm are distinguished: net-zero emission innovation, servitisation, sharing, product life extension, product residual value recovery [96,97]. In the CE assessment of single organisational entities, such aspects as greenhouse gas emissions, air pollution, nitrogen release, phosphorus release, water pollution, release of harmful substances, biodiversity loss, real estate maintenance, transport, space/land usage, and the procurement of electricity, energy, food, and other materials, are considered [37]. Intangible aspects of business alignment to CE principles labelled as values, mission, culture, or mindset are also studied [98].

Several frameworks of CE assessment applied at the macro level may also be used at the micro level, in single businesses and non-profit organisations: Life Cycle Assessment (LCA), social life cycle assessment (S-LCA), BS 8001:2017 Standard [99] material flow analysis (MFA), Life Cycle Sustainability Assessment (LCSA), Ecological Footprint (EC), Product Circularity Data Sheet [100]. Accounting and accountability reporting models are also indicated as important mechanisms through which enterprises and stakeholders can measure the progress, costs, and gains from the transition towards a CE [101,102]. The focus here is clearly on fulfilling certain requirements rather than benchmarking (understood as a specific management practice oriented at achieving excellence described in [103]) and comparison with other entities [104]. Depending on the chosen CE assessment approach, different groups of intended end-users may be identified: specific organisations, entities from a particular sector, managers, designers, customers, policy makers [105].

2.4. CE Metrics and Indicators

One important step towards CE mainstreaming is the development of suitable indicators that would help measure the state of transition in both absolute and relative/comparative terms [26,65,106–108]. Research on CE metrics and indicators is ongoing at all levels of analysis (micro, meso, macro), with different indicators trying to capture different dimensions of sustainability (environmental, economic, social) and core principles of the CE ('reduce, reuse, recycle, recover, remanufacture, redesign') [109]. Examples of a quantitative analysis of the CE in the European Union concern individual member states [110,111], groups of member states [112,113], regions [114,115], economic sectors [116,117], or all EU member states [118–125].

The recommended indicators measure different aspects of the CE at the company, regional, and national level [126]. Measures proposed by the EU to progress towards a circular economy at the EU and national level are composed of a set of key indicators that cover production and consumption, waste management, secondary raw materials, and competitiveness and innovation [127]. In the typology of the European Environment Agency (EEA), the indicators are divided into five groups: descriptive indicators, performance indicators, efficiency indicators, policy effectiveness indicators, and total welfare indicators [128]. Different methodologies of clustering and classification are proposed, both conceptual and empirical, to deal with the humongous number of available sustainable development indicators (SDI) [65,129–134].

2.5. DEA Method in the Evaluation of CE Goals Achievement

The DEA method plays an important role in comparative performance assessment. It allows the comparison of the efficiency of countries, regions, organisations, enterprises, and other entities characterised by the same set of inputs and outputs. DEA is broadly applied in various fields of public policy and business endeavours. It is recognised as a useful instrument of efficiency improvement and competitiveness increase [135].

The conducted literature review led to the identification of the fields of DEA application to circular economy problems. (Table 1).

Table 1. DEA applications in assessing the implementation of the circular economy.

No	Year	Objective of the Study	DEA Model	Publication
1	2019	Evaluation the eco-efficiency of the circular economy system in coal mining area Shanxi Province (China)	SBM-Undesirable super-efficiency model	Liu et al. [136]
2	2020	Measuring countries' performance in managing and exploiting their municipal solid waste	multiplier DEA model with weight restriction	Giannakitsidou et al. [137]
3	2021	Investigating efficiency performance and the dynamic evolution of industrial circular economy in Yangtze River Delta region (China)	Malmquist index based on network DEA	Ding et al. [138]
4	2021	Assessment and the monitoring of the cities and regions through the 'lens' of European Green Capital (ECG) indicators, using the available ECG data	CCR DEA	Amaral et al. [139]
5	2021	Assessing the efficiency of different sectors in the UAE based on sustainability and circularity objectives	CCR DEA	Bagheri [140]
6	2021	Appraisal and investigation of the performance of China's regional industrial CE systems	network DEA	Chen et al. [141]
7	2021	Comparison of the circular efficiency within the Visegrád Group and efficiency of Visegrád Group countries to the European Union 28 average	CCR and BCC DEA SBM	Lacko et al. [142]
8	2021	Evaluation of Chinese city urban circular economies under large datasets and fuzzy conditions	fuzzy non-radial DEA with undesirable factors	Wang et al. [143]
9	2022	Development of a Waste Management Composite Index (WMCI) as a Circular Economy indicator	Benefit-of-the-Doubt DEA	Milanović et al. [144]

The identified DEA applications concerned the assessment of CE implementation on the country (No 2, 7, 9), regional (No 4, 6), city (No 4, 8), and industrial sector (No 1, 3, 5, 6) levels. Study objectives and deployed DEA models are presented in Table 1. None of the reviewed works tackles the challenge of evaluating the comparative performance of the European Union countries in the implementation of the CE principles on the basis of a system of indicators as stipulated by the EU methodology of CE assessment (Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee, and the Committee of the Regions on a Monitoring Framework For the Circular Economy). The presented paper fills in this research gap and offers a comprehensive approach to a comparative analysis of the EU states' performance in achieving the goals of the circular economy.

3. Methods

Data Envelopment Analysis (DEA) is a linear programming technique that allows for studying the relative efficiency of decision-making units (DMU). The development of the method was initiated by the publication of Charnes, Cooper, and Rhodes (1978) [145] which was based on previous work by Farrell (1957) [146] and his concept of the 'best practice frontier' determined by the most effective units in the analysed set of units. Since its development, the DEA has become one of the most popular nonparametric benchmarking methods for measuring efficiency. A constantly expanding bibliography of the DEA method confirms its usefulness in analysing the efficiency of facilities of any complexity from almost all sectors of the economy.

The DEA method considers efficiency as the ability to produce maximum outputs at a minimum cost. Inputs and outputs must be clearly specified for each j unit in a set $(j = \{1, \ldots, j_O, \ldots, n\})$ as the vector of measurable attributes: $x_j = (\ldots, x_{ij}, \ldots), i = \{1, \ldots, r\}$ and $y_j = (\ldots, y_{rj}, \ldots), r = \{1, \ldots, s\}$. In this work, the variable return to scale super-efficiency DEA (SE-BCC) model by Andersen and Petersen [147] was employed:

$$\begin{gathered} max\phi j_O, \\ \sum_{j=1}^{n} \lambda_j x_{ij} \le x_{ij_O}, i = 1, \ldots, m,\ j \ne j_O \\ \sum_{j=1}^{n} \lambda_j y_{rj} \ge \phi y_{rj_O}, r = 1, \ldots, s,\ j \ne j_O \\ \sum_{j=1}^{n} \lambda_j = 1,\ \lambda_j \ge 0. \end{gathered} \tag{1}$$

The efficiency score ϕ of unit j_O is determined by finding a weighting vector $\lambda_j = (\ldots, \lambda_j, \ldots)$ that solves the linear programming problem. Decision-making units which achieve $max\phi \ge 1$ $(max\phi \ge 100\%)$ are efficient.

DEA determines the efficiency but also allows indicating the benchmarks: units whose linear combinations of input and output vectors are the pattern to follow. Moreover, in order to divide units into groups, the concept of technological competitors can be used. The term technology in the DEA method is used in the sense of vectors of empirical inputs x_j and outputs y_j. Technological competitors in the DEA method should not be viewed as rivals for resources or outcomes, but rather as rivals for a position in the ranking. Technological competitors may be defined by solving the DEA model formulated with the exclusion of effective objects [148]. The idea is presented in Figure 1. In the standard DEA model, the frontier is formed by units A, B, and C, and they are considered as fully, 100% efficient. In the SE-DEA model, for example, to assess the efficiency of B, this unit is excluded from the constraints; the frontier consists of A and C, so that B achieves efficiency higher than 100%. Its competitors are A and C. Efficient units B and C are the benchmarks for E, but after their exclusion, D and F are the technological competitors. The concept of technological competitors allows the grouping of objects on the basis of similarities, not the target.

The main drawback of DEA is that the ability to classify units as efficient or nonefficient decreases together with the increase in the number of attributes. The preferred number of attributes should be 3–5 fewer than the number of units [149]. It may be said that determining the inputs and outputs is one of the most difficult and challenging stages in the efficiency analysis with DEA. The choice of the analysed attributes has a huge impact on the results, but there are no formal rules that would clearly define what should be inputs and outputs in DEA models. Their selection depends on the specificity of the decision-making units and their goals, data availability, and researchers' intuition, experience, and subjective choices. Some previous works suggest establishing a list of inputs and outputs by removing variables whose exclusion causes the least changes in the efficiency scores, removing variables strongly correlated with those left in the model (those that do not significantly affect the information measured by conditional variances and partial correlations), combining DEA with principal component analysis and replacing original variables with principal components. Another approach is the Rough Sets concept of reductions to limit the number of attributes [150]. In this paper, factor analysis is applied. It is due to the fact that the correlation coefficients between variables are not very strong, whereas the principal components have negative values, which cannot be directly included in DEA.

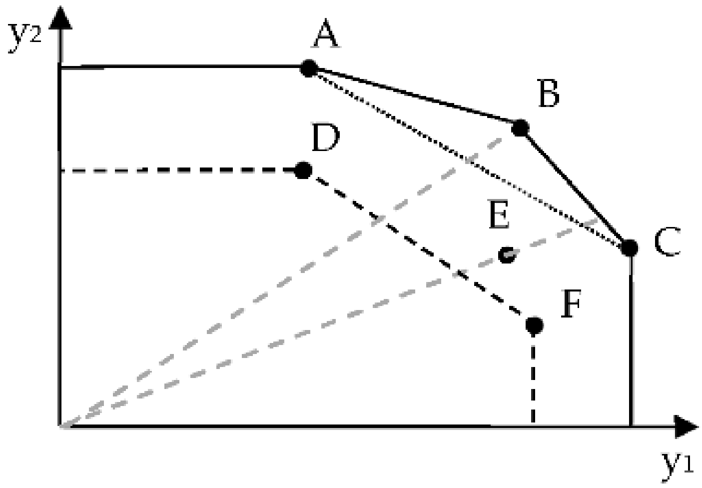


Figure 1. Frontiers in standard and super efficiency DEA models and the concept of technology competitors.

Factor analysis is a method to study the structure of multivariate observations and identify relationship between variables. By assuming that certain groups of variables represent the variability of the latent factors, a large number of variables can be reduced to a smaller set. The factor analysis for the standardised observed variable y_r ($r = \{1, \ldots, s\}$ where F_k, $k = \{1, \ldots, K\}$ denotes the factor, a_{rk} factor loadings, ε_r unique factors can be written as follows:

$$y_r = a_{r1}F_1 + a_{r2}F_2 + \ldots + a_{rK}F_K + \varepsilon_r \tag{2}$$

In order to obtain the simplest interpretation of individual factors, the factor loadings matrix can be rotated. It is assumed that the variance of y_r is the sum of common and unique variance:

$$Var(y_r) = h_r^2 + d_r^2, \text{ where } h_r^2 = a_{r1}^2 + a_{r2}^2 + \ldots + a_{rK}^2 \tag{3}$$

Cluster analysis was also used to discover the state of transition to a CE. The aim of cluster analysis is to classify objects into groups (which are not defined a priori) based on the density or distance between objects. There are several types of clustering techniques. The K-means model using Euclidean distances was employed in the research. Mathematically, assuming K as the number of clusters, n as number objects, y_j values of unit j, and μ_j as the centroid of cluster k, the objective function is:

$$min \sum_{k=1}^{K} \sum_{j=1}^{n} \|y_j - \mu_k\|^2 \tag{4}$$

Following the choice of the research methods and the set of CE-related indicators, a step-by-step research procedure was established. Figure 2 presents a flow chart of the conducted study.

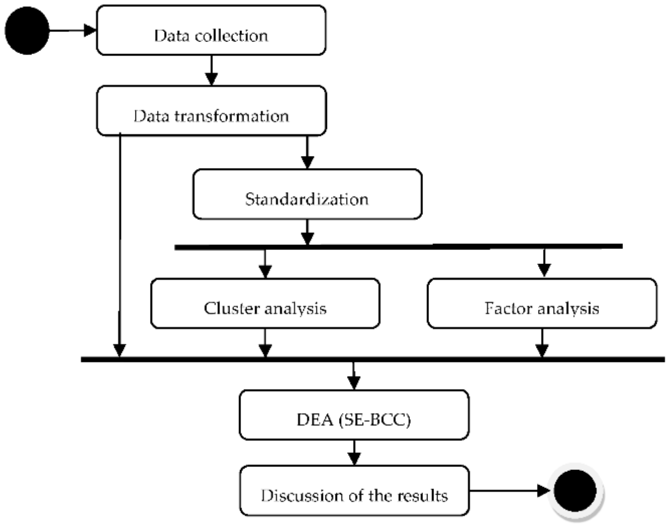


Figure 2. Research process.

4. Data

EU policies, initiatives, and assessment tools relevant to the monitoring and evaluation of the CE can be found in Europe 2020, Sustainable Development Strategy/Sustainable Development Goals, Euro indicators (PEEIS) and European Pillars of Social Right [151]. A similar set of indicators with the following focus areas of material input, eco-design, production, consumption, and waste recycling was also proposed by the European Environment Agency [152]. The indicators monitoring the CE are not unique to the CE only but are present in other UE frameworks. It is because the CE is not a closed system but directly or indirectly influences the economy, and thus the CE assessment relies both on direct and indirect indicators [153].

In this article, the EU CE monitoring framework intended to track the progress of CE implementation at the member states' level was used. The indicators' set represents 4 dimensions: production and consumption, waste management, secondary raw materials, competitiveness and innovations. According to the EU, they allow the European Commission and other policy makers to monitor the progress and evaluate the effectiveness of the EU members and inform stakeholders about current trends.

The indicators proposed by the European Commission to measure the CE development are in different units (percentage, absolute, or per capita). The first stage was to verify availability of data and their transformation to obtain comparable indicators and consistent interpretation. Indicators whose values are aggregated for the whole EU or are not collected directly (but estimated on the basis of different categories of waste) as food waste or whose interpretation without other information are problematic (e.g., about EU or non-EU exports and the dominant industry) as trade in recyclable raw materials was not included.

Table 2 includes the original data (from the EU methodology) and the 16 variables selected for further analysis (P1, P2, P3, W1, W2, W3, W4, W5, W6, W7, W8, S1, C1, C2, C3, C4) of the 27 EU counties, along with descriptive statistics. The data come from the publicly available Eurostat database (up-to-date on 17 March 2022) and cover mainly 2019 and 2018. Taking different years was possible due to the assumption that there were no radical changes in the economies of individual countries in recent years.

Table 2. EU CE monitoring framework data table.

<table>
<tr><th>Area</th><th>Indicator</th><th colspan="2">Original EU Indicator and Unit</th><th>Indicator Used</th><th>Abbrev</th><th>Average</th><th>Max</th><th>Min</th><th>Std Dev</th></tr>
<tr><td rowspan="6">Production and consumption</td><td>EU self-sufficiency for raw materials, aluminium</td><td colspan="2">Aggregated for the EU (percentage)</td><td colspan="6">Not available</td></tr>
<tr><td>Green public procurement</td><td colspan="2">N/A</td><td colspan="6">Not available</td></tr>
<tr><td rowspan="3">Waste generation</td><td colspan="2">Generation of municipal waste per capita (kg per capita)</td><td>Capita per generation of municipal waste (capita per kg) 2019</td><td>P1</td><td>2.071</td><td>3.571</td><td>1.185</td><td>0.509</td></tr>
<tr><td colspan="2">Generation of waste excluding major mineral wastes per GDP unit (kg per thousand euro)</td><td>GDP unit per generation of waste excluding major mineral wastes (thousand euro per kg) 2019</td><td>P2</td><td>15.820</td><td>37.037</td><td>1.548</td><td>8.405</td></tr>
<tr><td colspan="2">Generation of waste excluding major mineral wastes per domestic material consumption (percentage)</td><td>Domestic material consumption per generation of waste excluding major mineral wastes (percentage) 2019</td><td>P3</td><td>105.734</td><td>208.333</td><td>33.670</td><td>47.296</td></tr>
<tr><td>Food waste</td><td colspan="2">Estimated (million tonnes) based waste category, hazardousness, and NACE Rev. 2 activity</td><td colspan="6">Not available</td></tr>
<tr><td rowspan="5">Waste management</td><td rowspan="2">Recycling rates</td><td colspan="2">Recycling rate of municipal waste (percentage)</td><td>Recycling rate of municipal waste (percentage) 2019</td><td>W1</td><td>39.500</td><td>66.700</td><td>8.900</td><td>14.547</td></tr>
<tr><td colspan="2">Recycling rate of all waste excluding major mineral waste (percentage)</td><td>Recycling rate of all waste excluding major mineral waste (percentage) 2018</td><td>W2</td><td>50.630</td><td>82.000</td><td>10.000</td><td>17.502</td></tr>
<tr><td rowspan="3">Recycling/recovery for specific waste streams</td><td rowspan="3">Recycling rate of packaging waste by type of packaging</td><td>Recycling rate of overall packaging (percentage)</td><td>Recycling rate of overall packaging (percentage) 2018</td><td>W3</td><td>64.070</td><td>85.300</td><td>35.700</td><td>9.059</td></tr>
<tr><td>Recycling rate of plastic packaging (percentage)</td><td>Recycling rate of plastic packaging (percentage) 2018</td><td>W4</td><td>41.104</td><td>69.300</td><td>11.100</td><td>12.110</td></tr>
<tr><td>Recycling rate of wooden packaging (percentage)</td><td>Recycling rate of wooden packaging (percentage) 2018</td><td>W5</td><td>36.193</td><td>90.600</td><td>0.000</td><td>21.802</td></tr>
</table>

Table 2. *Cont.*

Area	Indicator	Original EU Indicator and Unit		Indicator Used	Abbrev	Average	Max	Min	Std Dev
		Recycling/recovery for specific waste streams	Recycling rate of e-waste (percentage)	Recycling rate of e-waste (percentage) 2018	W6	44.578	83.400	20.800	12.751
			Recycling of biowaste (kg per capita)	Recycling of biowaste (kg per capita) 2019	W7	69.556	189.000	0.000	51.458
			Recovery rate of construction and demolition waste (percentage)	Recovery rate of construction and demolition waste (percentage) 2018	W8	86.296	100.000	24.000	17.518
Secondary raw materials	Contribution of recycled materials to raw materials demand	End-of-life recycling input rates, aluminium (percentage), aggregated for the EU			Not available				
		Circular material use rate (percentage)		Circular material use rate (percentage) 2019	S1	9.367	30.000	1.300	7.010
	Trade in recyclable raw materials	Imports from non-EU countries (tonne)			Picture of trends in the markets for secondary raw materials (No clear interpretation)				
		Exports to non-EU countries (tonne)			Picture of trends in the markets for secondary raw materials (No clear interpretation)				
		Imports intra-EU (tonne)			Picture of trends in the markets for secondary raw materials (No clear interpretation)				
Competitiveness and innovation	Private investments, jobs, and gross value added related to circular economy sectors	Gross investment in tangible goods—percentage of gross domestic product (GDP)		Gross investment in tangible goods—percentage of gross domestic product (GDP) 2018	C1	0.140	0.250	0.020	0.049
		Persons employed—percentage of total employment (percentage)		Persons employed—percentage of total employment (percentage) 2018	C2	1.824	2.720	1.130	0.419
		Value added at factor cost—percentage of gross domestic product (GDP) (percentage)		Value added at factor cost—percentage of gross domestic product (GDP) (percentage) 2018	C3	0.977	1.560	0.360	0.230
	Patents related to recycling and secondary raw materials (number)			Patents related to recycling and secondary raw materials (number per million capita) 2016	C4	0.589	2.443	0.000	0.620

Source: https://ec.europa.eu/eurostat/web/circular-economy/indicators/monitoring-framework (accessed on 17 March 2022).

5. Research Results

The introductory examination of the collected data included the substantive and statistical analysis presented in Table 2, and the attempt to group countries. Standardisation was carried out, and countries were grouped via cluster analysis to assess the countries' development (missing data were supplemented with an average value). As a result of applying the cluster analysis procedure selected in the previous stage P1, P2, P3, W1, W2, W3, W4, W5, W6, W7, W8, S1, C1, C2, C3, C4 (missing data were supplemented with an average value), two groups were obtained (Table 3).

Table 3. Results of cluster analysis.

Cluster 1	Cluster 2
Belgium, Czechia, Denmark, Germany, Ireland, Greece, Spain, France, Italy, Luxembourg, Netherlands, Austria, Portugal, Slovenia, Finland, Sweden	Bulgaria, Estonia, Croatia, Cyprus, Latvia, Lithuania, Hungary, Malta, Poland, Romania, Slovakia

What is worth noting is that it is impossible to indicate a group of leaders in terms of all variables (Figure 3). Cluster 1 has high values for P2, W1, W2, W3, W5, W7, W8, S1, C4, and, respectively, low values for P1, P3, C1, C2, C3. Furthermore, variables W4 and W6 do not differentiate clusters.

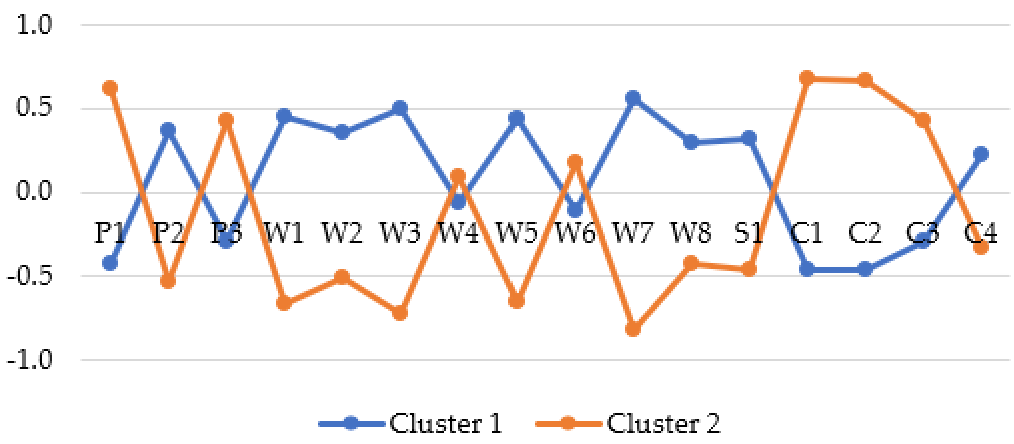


Figure 3. Means of CE monitoring indicators in the obtained country clusters.

Although GDP per capita was not included in the dataset, the clustering was generally conducted on the basis of it. In the second cluster, the average GDP per capita amounts to 14,486.4 euro, and the minimum value is 6840 euro. Treating Greece, the Czechia, Portugal, and Slovenia as exceptions and excluding them from the first cluster, the highest GDP in the second cluster (24,530 euro) would be even lower than the lowest value in the first cluster. In the first cluster, the mean is 36,233.3 euro per capita. Thus, it is justified to conclude that the indicators of the circular economy are primarily influenced by GDP. In Figure 4, the leaders are presented in terms of each indicator.

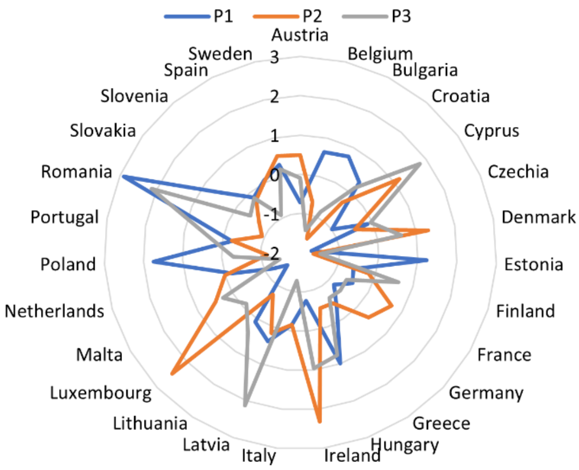
It is impossible to indicate obvious leaders on the basis of the presented data. Nevertheless, it is possible to point at leaders with respect to particular (sets of) indicators. The following countries can be distinguished: Romania in the case of P1 and P3, Luxembourg and Ireland in the case of P2, and Latvia in the case of P3. Similarly, for W1—Germany, W2—Slovenia, W3—Belgium, W4—Lithuania W5—Belgium, W6—Croatia, W7—Austria, and there are no pioneers in the case of W8. If one takes into account factor S1—it is the Netherlands, C1—Slovakia, C2—Lithuania and Latvia, C3—Croatia, C4—Luxemburg.

The DEA method allows for assigning ratings to the analysed countries. Its usefulness and adequacy are proven in many studies. Assuming a constant, identical level of inputs for each European country, weights for outputs can be adjusted to maximise the assessment of environmental performance. However, applying the DEA method to all variables does not differentiate the scores at all. The number of variables (16) is too high as compared to the number of countries (27).

To limit the number of units, the principal component method is often suggested in the literature [154]. PCA is a data space reduction method that is based on linear relationships and usually on standardised variables. However, as mentioned earlier, the values of the main components attain negative figures, which is not accepted in the DEA method.

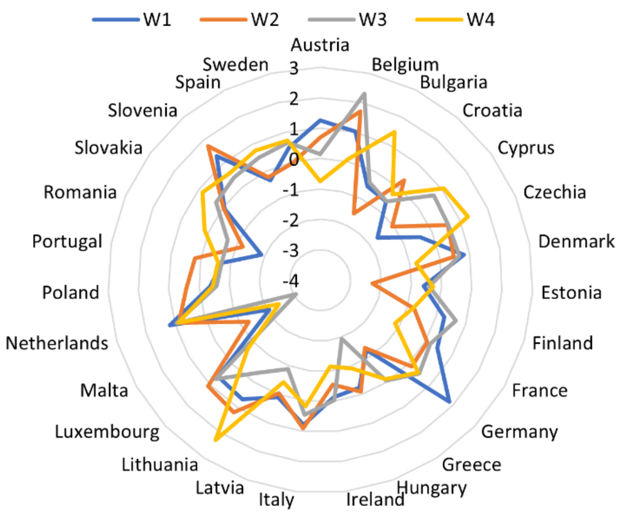
Factor analysis describes variability among observed variables with a lower number of unobserved factors. The five factors have eigenvalues greater than 1 and explain almost 75% of the variance (Table 4). Nevertheless, the use of the vector of factor values as well as the vector of components is not possible due to the output of the negative values. For this reason, a non-standard approach was used. After factors were determined, the most correlated variables were selected as representatives.

Factor 1 contains W1, W2, W3 but also three more variables with factor loadings over 0.5: W4, W5, W7. It represents the recycling rate but excluding the recycling rate of e-waste (W6) and construction and demolition waste (W8). The W6 and W8 build factor 4—recycling waste of special products. Factor 2 can be named waste generation because it has the highest factor loadings for the generation of municipal waste per capita and the generation of waste per GDP, P1 and P2, respectively. The opposite signs of P1 and P2 may suggest the following relationship: the higher generation of waste per GDP the smaller generation of waste per capita. In Factor 2, C1 (gross investment in tangible goods as percentage of GDP) also has a factor loading higher than 0.5. Factor 3 represents C2 (persons employed as percentage of total employment) and C3 (value added as percentage of GDP). It is related to investments. Considering Factor 5, one notices that S1 (circular material use rate) and P3 (generation of waste per domestic material consumption) have the higher factor loadings with opposite signs. Generally, the division of variables is consistent with the area indicated by the EU methodology. Thus, the following indicators were selected as the representatives of each discovered factor: P2, W2, W6, S1, C3. Next, the DEA scores were calculated for the representatives. Results of the computation are presented in Table 5 and in Figure 5.

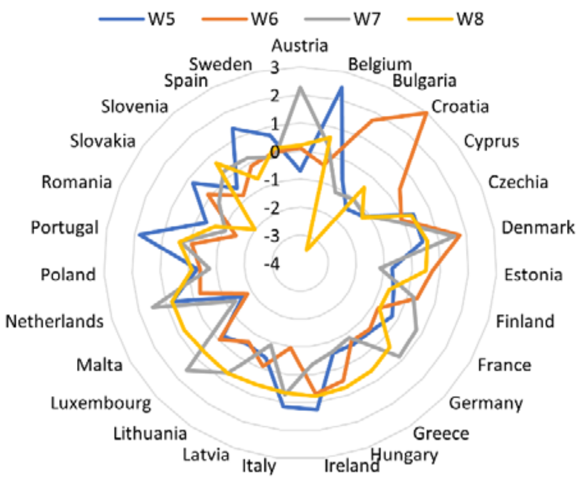


(**a**)

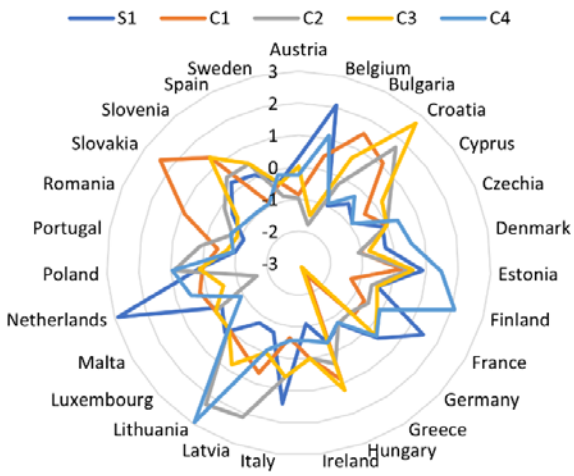
Figure 4. *Cont.*



(**b**)



(**c**)



(**d**)

Figure 4. Visualisation of standardised CE monitoring variables, respectively for variables: (**a**) P1, P2, P3; (**b**) W1, W2, W3, W4; (**c**) W5, W6, W7, W8; (**d**) S1, C1, C2, C3, C4.

Table 4. Factor loadings (Biquartimax normalised). Extract: Principal components. Numbers in red mark the indicators forming the respective meta-indicators (factors). For each factor, the indicators with the highest factor loading are marked in bold.

	F1	**F2**	**F3**	**F4**	**F5**
	Recycling rate of general waste	Waste production	Jobs and investments	Recycling rate of special waste	Circular material use rate
P1	−0.1794	−0.8420	0.0409	0.0483	−0.0363
P2	0.1523	**0.8826**	−0.0481	0.0221	−0.1499
P3	−0.2738	0.2630	0.1540	0.0154	−0.7471
W1	0.7776	0.2142	0.1171	0.0453	0.4002
W2	**0.8460**	0.1362	0.2218	0.2781	0.0925
W3	0.7068	0.0807	−0.4156	−0.3396	0.2546
W4	0.5439	−0.5090	−0.0093	−0.3471	−0.2454
W5	0.5787	−0.0989	−0.4793	0.0811	0.0482
W6	−0.0392	0.1628	0.3346	**−0.7862**	0.0946
W7	0.6738	0.4775	−0.1077	0.1181	0.3176
W8	0.1634	0.3932	0.0716	0.7374	0.1488
S1	0.4016	−0.0922	−0.1189	0.2770	**0.7625**
C1	0.1116	−0.5431	0.4971	−0.1685	−0.1191
C2	−0.1094	−0.1237	0.7425	0.0646	−0.3739
C3	0.0367	−0.0637	**0.9181**	−0.1790	0.0470
C4	0.0384	0.3112	−0.0558	−0.1122	0.6769
Variance explained	3.252	2.726	2.280	1.655	2.206
Contribution	0.203	0.170	0.143	0.103	0.138

Table 5. DEA analysis.

Country	**Code**	**Score**	**Benchmarks**	**Technological Competitors**
Croatia	HR	145.80%		Denmark, Slovenia
Netherlands	NL	129.80%		Belgium, Luxembourg
Luxembourg	LU	129.60%		Denmark, Ireland, Netherlands
Slovenia	SI	117.80%		Belgium, Croatia, Luxembourg
Belgium	BE	110.90%		Netherlands, Slovenia
Denmark	DK	106.10%		Croatia, Ireland, Luxembourg
Ireland	IE	104.90%		Croatia, Denmark, Luxembourg
Italy	IT	98.60%	Croatia, Luxembourg, Netherlands, Slovenia	Austria, France
France	FR	96.30%	Croatia, Luxembourg, Netherlands	Austria, Italy

Table 5. *Cont.*

Country	Code	Score	Benchmarks	Technological Competitors
Lithuania	LT	91.30%	Belgium, Croatia, Slovenia	Austria, Italy
Estonia	EE	90.20%	Croatia, Netherlands	Bulgaria, France
Austria	AT	89.90%	Belgium, Croatia, Luxembourg, Netherlands, Slovenia	Cyprus, Hungary, Italy, Lithuania
Germany	DE	88.70%	Croatia, Luxembourg, Netherlands	Poland, Spain
Cyprus	CY	88.10%	Croatia, Luxembourg	Austria, France
Spain	ES	84.70%	Croatia, Luxembourg, Netherlands	Czechia, Germany
Hungary	HU	84.40%	Croatia, Luxembourg, Netherlands, Slovenia	Bulgaria, Cyprus, Italy, Lithuania
Czechia	CZ	84.00%	Belgium, Croatia, Luxembourg, Slovenia	Germany, Poland, Sweden
Bulgaria	BG	80.00%	Croatia	Estonia, Hungary
Malta	MT	79.90%	Croatia, Luxembourg, Netherlands	Germany, Sweden
Poland	PL	79.90%	Belgium, Croatia, Netherlands, Slovenia	Czechia, Germany
Portugal	PT	77.70%	Belgium, Croatia, Luxembourg, Slovenia	Latvia
Sweden	SE	76.80%	Belgium, Croatia, Luxembourg	Finland, Germany
Latvia	LV	75.90%	Croatia, Luxembourg, Slovenia	Portugal, Slovakia
Slovakia	SK	73.90%	Belgium, Croatia, Luxembourg, Slovenia	Latvia
Finland	FI	70.80%	Croatia, Denmark, Luxembourg, Netherlands	Sweden
Romania	RO	51.70%	Croatia, Luxembourg	Romania
Greece	GR	51.20%	Croatia, Denmark, Netherlands	Greece

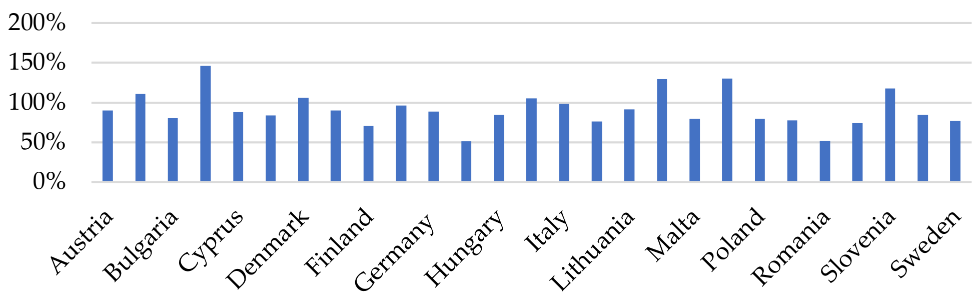


Figure 5. DEA results.

Taking into account the generation of waste, recycling rate of all waste, recycling rate of e-waste, circular material uses rate, and the value added, Croatia, Netherlands, Luxembourg, Slovenia, Belgium, Denmark, Ireland are the leaders among EU countries. The lowest performers, Greece and Romania, reach slightly over 50% efficiency.

The concept of technological competitors was used to group the countries (listed in Table 5), which is illustrated in Figure 6 with an additional indication of the direction of dependences.

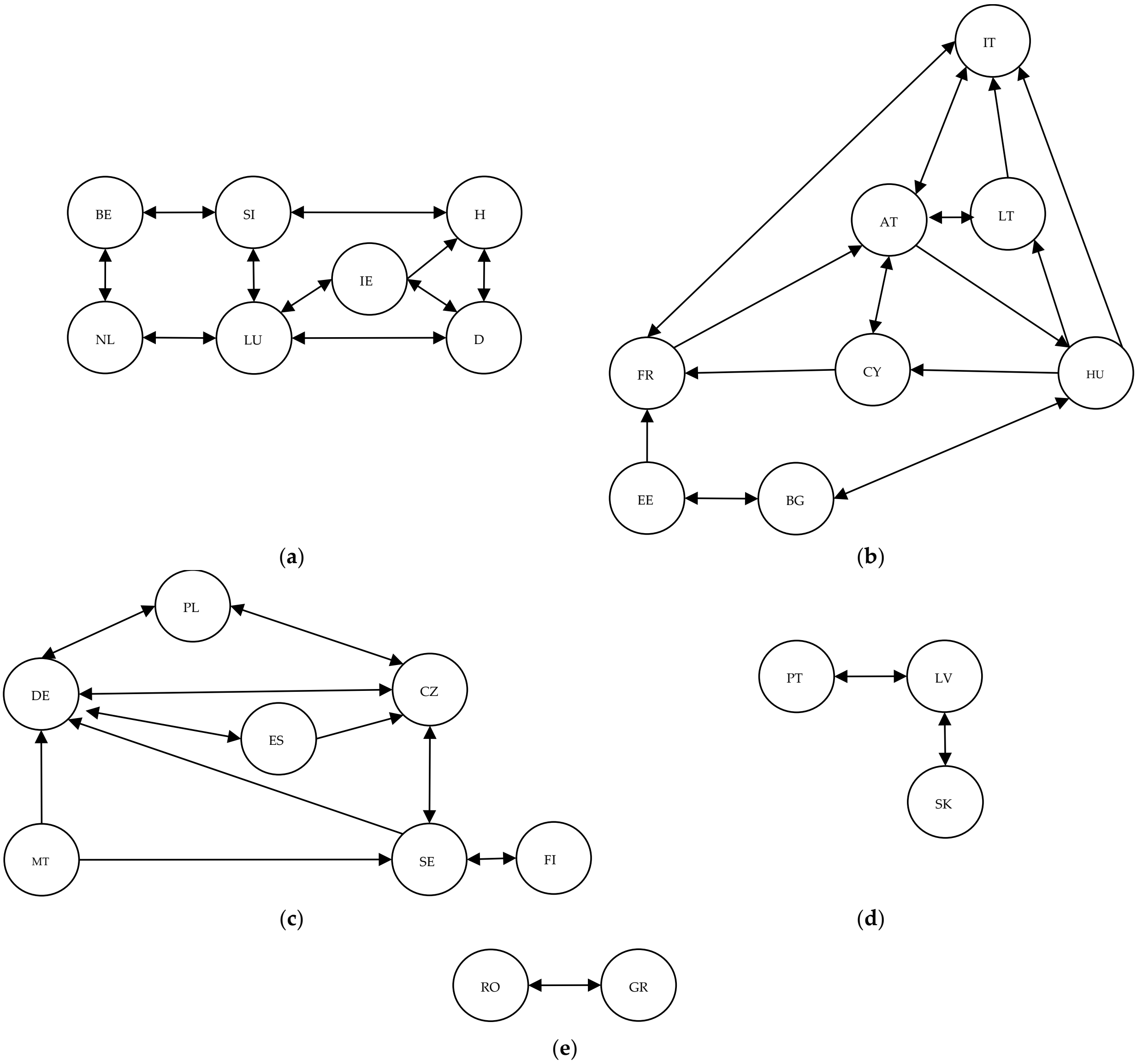


Figure 6. The competition of effective objects graph. The first graph (**a**) gathers competitors in the group of 100% efficient states. The next one presents the countries that may switch places with slight changes in data. The groups are as follows: (**b**) Estonia France, Cyprus Hungary, Austria, Italy Bulgaria, France Hungary, Lithuania; (**c**) Germany, Malta, Poland, Spain, Sweden, Czechia, Finland; (**d**) Portugal, Slovakia Latvia; € Romania, Greece. Designated groups connect countries with similar effectiveness. Group (**b**) includes countries with efficiency from 80.00% to 98.60%; group (**c**) from 70.08% to 88.70%; group (**d**) includes countries from 73.90% to 77.70%; group (**e**) consists of countries with a score slightly above 51%. The grouping allowed for the identification of similar countries that are in a sense dependent on each other in terms of the final assessment. After excluding 100% effective ones, changes in the characteristics of countries within the groups would affect the score of the remaining ones.

6. Discussion of Results

Over the past few years, the concept of the circular economy gained increasing attention around the world as a way to counteract climate change and save resources. A CE could help overcome pressures on resources arising from the estimated growth of the global population. It is hoped that transition to a CE would result in new economic opportunities [155], new jobs (in terms of type and numbers), higher productivity [156], and the improved quality of life for all thanks to the environmental recovery, health benefits, and less pressure on land and Earth's resources.

The necessity to change the economic model and to decouple growth from resource consumption is of interest not only to politicians, but also to average European citizens. As research results indicate, most Europeans believe that environmental protection is very important to them personally [157].

Whereas the general interest in the CE is well reflected in the bulk of scientific publications, the specific issue of measuring the performance of countries in achieving a CE aims is not yet sufficiently grounded in the literature. This paper is a contribution to the discussion on CE metrics and measurement. It presents a methodology of an objectivised comparative assessment of the degree of implementation of CE principles in the EU member states. The proposed approach is based on the DEA method supported by factor analysis. Circular Economy Indicators published by the European Statistical Office (Eurostat) [158] served as the input data.

The conducted calculations and the analyses performed on their basis suggest that the position of a particular country in achieving the CE aims is strongly correlated with its GDP per capita. The fact that richer economies are more advanced in achieving CE aims may indirectly imply that the implementation of CE principles requires investments and expenditures that poorer countries are unable to bear. Apparently, transition towards the CE requires costly modern technology, perpetual knowledge generation, and advanced infrastructures [23].

Factor analysis shows that many CE indicators are strongly correlated with each other and may be aggregated into meta-indicators (factors) and represented by one indicator that displays the strongest correlation with a given meta-indicator. In this situation, it is reasonable to limit the number of CE indicators, which will simplify the CE statistics and the assessment of countries' standing in achieving CE goals.

Comparative performance assessment of the EU member states allows for splitting them into three groups of countries with a similar relative efficiency in the CE goals' implementation: (90%, 130%), (70–90%), (50–70%). This shows a certain stratification within the EU when it comes to CE goals' implementation.

Thanks to the competition graphs, it is possible to indicate optimal technologies (i.e., CE indicator values) of technological competitors of particular countries so that they achieve the results at least equal to the one of the reference country.

Limitations of this approach should also be pointed out. Firstly, the obtained country ranking depends directly on the chosen evaluation criteria. Therefore, it is important that the adopted indicators are well justified on scientific grounds and are reflective of the key aspects of CE. Secondly, with 27 countries under evaluation, the number of assessment criteria should not exceed the 6–9 range. Such limitation requires a significant decrease in the number of indicators chosen from the list of the UE Circular Economy Indicators. DEA analysis results are sensitive to the choice of input and output variables. Therefore, the CE indicators should be selected diligently, and various combinations of variables should be tested for stability of results [159]. Thirdly, results obtained with DEA may be sensitive to outliers; hence, the data should undergo preliminary screening with regards to their homogeneity. Fourthly, one should keep in mind that the results change in time; thus, the static assessment of particular countries at a given point in time should be complemented with the dynamic evaluation of the change of their performance in time.

The indicated limitations are a good guidance as far as possible future research directions are concerned. The authors intend to examine the sensitivity of various combinations of CE indicators included in the country assessment, carry out simulations to evaluate the impact of outliers on the result stability, and look into the changes in CE performance of particular countries over a certain period of time.

Some policy implications may be derived from the study results. The objectivity and scalability of the DEA approach to the evaluation of CE implementation make it a suitable approach to comparing the effectiveness of CE policy packages [78] beyond the European Union. For example, benchmarking of OECD or G20 countries [160] with the use of the proposed approach is feasible. Such an internationally adoptable comparison tool will be necessary when the CE attains the status of a global policy [161,162]. Moreover, the CE agenda should not be used as an instrument of a disguised domination perpetrated by the richer countries with the aim of preserving their competitive advantage. The CE policy must not create winners and losers [163].

7. Conclusions

The contribution of this paper is manifested by the development of a robust methodology of a comparative assessment of the state of transition towards a Circular Economy in given countries with special focus on European Union members. The methodology allows for the determination of the level of a country's relative performance as well as the disclosure of the sources of its inefficiencies. Comparative analysis of this kind, performed on a regular basis according to a unified methodology, may serve as an instrument of refining the CE indicators and improving policy coordination of EU and member states in striving for ambitious CE goals. The paper also aims at promoting DEA applications in measuring relative performance of particular countries in spheres that are subject to common policies.

The results show a strong correlation between CE indicators and a certain degree of sensitivity to slight data changes. Moreover, it is impossible to select a leading country or group of countries superior to others with respect to all studied variables. In consequence, if the proposed approach is ever used to determine the streams of funding to particular EU member states, there exists a risk of manipulating the input variables and input data to serve particular interests. Transparency in this respect will be of critical importance.

The study shows that countries with higher GDP per capita perform better in terms of CE goals. This implies that poorer countries require tailored support measures oriented at the general modernisation of their economies accompanied by an increase in the efficiency of their production factors.

The journey towards a CE is only starting. There is a clear need to develop and refine tools of an objectivised assessment of countries with regards to their progress towards the CE. This paper makes a contribution to this global effort.

Author Contributions: J.N. and E.C. were responsible for the study conception and research design; J.N. and Ł.N. developed the concept and carried out the literature review; E.C. performed computation and analysis; J.N. and E.C. were responsible for data interpretation; J.N. and Ł.N. discussed the results and contributed to the final manuscript; J.N., E.C. and Ł.N. wrote and edited the text. All authors have read and agreed to the published version of the manuscript.

Funding: The publication of the article for 11th International Conference on Engineering, Project, and Production Management—EPPM2021—was financed in the framework of the contract no. DNK/SN/465770/2020 by the Ministry of Science and Higher Education within the 'ExcellentScience' programme.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Publicly available datasets were analysed in this study. These data can be found here: https://ec.europa.eu/eurostat/web/circular-economy/indicators/monitoring-framework (accessed on 17 March 2022).

Conflicts of Interest: The authors declare no conflict of interest.

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