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IMPLEMENTATION OF CIRCULAR ECONOMY PRINCIPLES IN THE USE OF ENVIRONMENTAL TECHNOLOGIES AND CLIMATE CHANGE MITIGATION IN EUROPEAN UNION COUNTRIES

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ABSTRACT: Nowadays, a new trend consistent with the goals of sustainable development, the main purpose of which is to resolve environmental dilemmas related to the intensive use of natural resources, increasing greenhouse gas emissions, and irrational use of products, is the circular economy. This article aims to identify actions taken by EU countries from the perspective of achieving a sustainable level of management of materials, products, and raw materials for the transformation towards a circular economy. During the research process, data from Eurostat, OECD, and PORDATA databases were compared. The research was carried out using cluster analysis, the EDAS method, and the grouping of linearly ordered objects. The research results show that the European Union countries studied have not yet achieved the strategic goals set in the CEAP1 and 2 action plans. Moreover, specific principles of the circular economy are implemented in different ways. The results of the conducted research provide suggestions for the management of the countries' economies regarding the course of action aimed at the complete implementation of programmes resulting in the reduction of the amount of waste and raw materials used. Moreover, they may influence decisions to modify the regulations concerning the creation of a new economic model following the 5R principle.

KEYWORDS: circular economy, environmental technologies, sustainable development, pro-environmental transformation indicator, CEAP1 and 2

Introduction

Nowadays, one of the main challenges that the economies of the countries in the European Union (EU) are struggling with is the search for solutions aimed at counteracting and combating the negative effects of environmental degradation. Environmental pollution is a consequence of the use of technologies that were initiated in the 19th and 20th centuries.

The current socio-economic model is based on a linear paradigm of consumption (linear economy model), which reflects the take-make-waste principle. According to this view, companies exploit natural resources used in the production process of goods delivered to consumers, who then dispose of the used products. This type of business model is distinguished by the predominance of the obtained economic benefits, with little consideration of social and ecological dilemmas (including systematically generated pollution) (Sauvé et al., 2016). The material flow pattern in the economy is subject to unfavourable assessment because it is impossible to subordinate it to the designated principles of sustainable development (SD).

Preventing climate change obliges entities operating in the economy to be responsible for the level of environmental quality resulting from the responsible use of resources and involvement in the process of eliminating their negative impact. In connection with this, the generated products, identically to materials and raw materials, should survive in the economic system for a relatively longer period. In addition, the process of waste generation should also be reduced. The above provisions constitute a strategic assumption of the concept of a circular economy (CE), the key intention of which is to abandon the "take-make-use-dispose" procedure, in favour of a largely sustainable management of resources.

Nowadays, the implementation of CE assumptions is the main goal of the economic policy of many countries in the world, including China, Denmark, Finland, Japan, Canada, Germany, the United States, Sweden, and Great Britain. Thus, this type of concept is considered to be the fundamental direction of structural changes (Hobson & Lynch, 2016; Zhu et al., 2010; Lieder & Rashid, 2016; Elia et al., 2017; Liu, 2012; Winans et al., 2017). Nevertheless, the EU has become an important actor in the field of sustainable development from a global and regional perspective.

The transition to this type of closed-loop system should have a positive impact on the implementation of the assumptions of a sustainable, low-emission, and competitive economy, in which limited raw materials are effectively managed. The introduction of CE principles is associated with the possibility of achieving economic and social benefits and shaping a structure in which the economy, society, and the environment are coordinated in the implementation of sustainable development goals (SDG) (Xuan et al., 2011).

The raw material cycle system in CE is based on closing the loop of material flow, utilising reusing, recycling, processing, and reusing them in circulation during subsequent production processes to produce an identical or modified product. Thus, this kind of behaviour is a consequence of creating products that maintain added value as long as it is possible while reducing emissions and excessive waste generation in parallel (Hobson & Lynch, 2016).

Therefore, the key assumption of the conducted analyses is to find an answer to the research question: To what extent do the ambitious CEAP1 and CEAP2 action plans aimed at developing a circular economy contribute to reducing the negative effects of excessive waste production, resource exploitation, greenhouse gas emissions, and energy use in European Community countries?

The main objective of the article is to identify the actions taken by EU countries from the perspective of achieving a sustainable level of management of materials, products, and raw materials for the transformation towards a circular economy.

Based on the specified objective and research question, a hypothesis was established, assuming that the assimilation of the circular economy is carried out at a varied pace of striving to narrow and close material and energy loops in adapting resources to reduce energy intensity, waste, and greenhouse gas emissions in the process of material circularity at the national level in the EU.

The subject matter discussed in this article has not been the subject of research to determine the significance of environmental resources and technologies used to implement an economic model based on closed circulation in the economic system of EU countries. For this reason, this study aims to supplement the information in the research conducted so far, which focuses on the characteristics and development of the CE concept in EU countries.

DOI: 10.34659/eis.2025.93.2.1004

Literature Review

Transforming the Circular Economy

Dynamic processes of economic development, industrialisation, and globalisation observed in the 20th century have significantly influenced the constantly progressing degradation of the natural environment. The consequences of the perceived climate changes, which are the result of increasing emissions of carbon dioxide and other greenhouse gases, will in the future be distinguished by an unfavourable impact on the functioning of the economic system, societies, and the development of countries. The response to the above conditions is the implementation of the principles and objectives of the SD concept in the micro- and macroeconomic scope and the adaptation of tasks supporting their implementation, which result from the application of the circular economy model.

The main goal of the EU today is to implement the SD strategy by integrating the processes of economic development, environmental protection, and social justice, along with implementing the assumptions of the CE concept. This type of programme is an extension and specification of the SD plan. The basis for creating the CE paradigm was the imperfection of the SD idea, which concerned the use of only a linear management option, per the principle of "take – make – throw away", without reusing resources (Bartoszczuk, 2023).

Therefore, CE should be considered from the perspective of a new economic development strategy, which, based on the idea of SD, constitutes a critical position for the consumerist way of managing modern economies and societies, contributing to the consumption of natural resources and generating a significant amount of waste. Therefore, this type of innovative procedure provides for a transition from a linear model of the economy towards a circular one, according to which the waste generated is transformed into raw materials (Oluleye et al., 2022).

It was estimated that the CE concept would be defined 211 times in the literature by 2023 (Kirchherr et al., 2023; Figge et al., 2023). However, the most popular formulation analyses it from the perspective of reviewing the 114 definitions existing until 2017 as an economic system based on business models that replace the concept of "end of life" with reduction, alternative reuse, recycling, and recovery of materials in production/distribution and consumption processes, operating at the micro (products, enterprises, consumers), meso (eco-industrial parks) and micro (cities, regions, nations and beyond) levels, to achieve sustainable development, which means creating environmental quality, economic prosperity, and social equality, for the benefit of present and future generations (Kirchherr et al., 2017).

CE should be considered from the perspective of a multi-level resource use system that stipulates the complete closure of all resource loops. Recycling and other means that optimise the scale and direction of resource flows contribute to the circular economy by supporting practices and activities. In its perfect conceptual form, all resource loops are fully closed. In its imperfect, realistic form, some use of primary resources is inevitable (Figge et al., 2023). Although it is not a new approach to resource management, it has gained popularity in recent times (Calisto Friant et al., 2020; Nobre & Tavares, 2021). This type of solution is an alternative to the linear economic model, which, as a result of the transformation process, is replaced by a closed loop of material flow, shaping feedback cycles per the principle: resources-products-resources.

The strategic goal of CE is to reduce the use of natural resources, waste, and energy losses by slowing down, closing, and narrowing material and energy loops. Among the listed procedures, the most specialised one is closing material loops, which involves reusing the same materials through a recycling process (Corvellec et al., 2022). The next procedure is a slightly broader focus on the economy, which involves slowing down material flows by aiming to extend the period of use of products and delaying their ageing process (Kennedy & Linnenluecke, 2022). The last solution in the process of raw material flow is the narrowing of material loops, which results from the highly efficient use of natural resources, materials, and products. The intensification and dissemination of resource-efficient production technologies and the shift of consumption patterns to less resource-intensive goods and services are of fundamental value in this procedure (Bocken et al., 2016).

Currently, a difficult task for EU countries to implement within SD is the transformation of the economic system from a linear model to a circular one (Sobol, 2019). This is done by implementing the 3R, 4R, and 5R principles. Due to the imperfection of the analysed management model based on the principles of conduct resulting from the take-make-use-dispose assumption, without the possibility of re-accessing depleted resources, it is necessary to introduce activities aimed at a circular flow of materials. Within this type of management model, three main procedures can be distinguished per the 3R assumptions (Uvarova et al., 2023):

- reduce, i.e., reducing waste production;
- reuse, i.e., extending the life cycle of products;
- recycle, i.e., transforming waste into secondary raw materials.

The justification for using the indicated concept is the multiplication of the use of secondary raw materials used in the production process and the reduction in the use of energy and natural resources. The 3R principles were the foundation for the preparation of the 4R concept based on the Canadian formula 4V + OGES. Thanks to it, the refuse principle was introduced, i.e., avoiding products that cause difficulties both in their later processing and reuse (Korhonen et al., 2018). The 3R and 4R principles were then extended, in line with the Swiss rule, to 5R, which concerns rot, i.e., composting and purchasing biodegradable products (Agyapong et al., 2024).

The current increase in environmental degradation, excessive resource extraction, and fundamental changes in the state of the climate system have contributed to the need for countries to respond to the identified threats to the functioning of economies. The above-mentioned reasons have prompted EU member states to develop and implement non-traditional economic models in which the principles of circularity (5R) are considered the optimal possibility of achieving SD goals.

Programme assumptions and technological solutions in the circular economy

In the last twenty years, the implementation of CE principles was initiated in the area of the countries belonging to the EU. The first assumptions regarding this type of management model were announced in the EU strategic document "Europe 2020", adopted on 3 March 2010 as a strategy aimed at achieving smart, sustainable, and inclusive economic growth. In 2011, one of the goals of this strategy was to adopt the assumptions of the "Roadmap to a Resource Efficient Europe". This programme was one of the first to recognise the key importance of implementing the CE concept in terms of improving the security of supply, sustainable management of natural resources, intensive reuse, recycling, and substitution of raw materials and saving materials (Domenech & Bahn-Walkowiak, 2019).

Another initiative was the policy established in 2012 on "Innovating for Sustainable Growth: A Bioeconomy for Europe" (European Comission, 2012; Loiseau et al., 2016; Chen, 2024; Huang, 2024).

In July 2014, another document was launched, entitled "Towards a circular economy: A zero waste programme for Europe", containing regulations within the CE framework. (European Commission, 2014). This communication emphasised for the first time that the transformation of the economy towards a circular economy is a necessary condition for the implementation of the intentions undertaken to implement the resource efficiency idea set out in the Europe 2020 strategy (Campeanu, 2016).

In December 2015, the European Commission submitted another key document relating to the CE concept entitled "Closing the Loop – An EU Action Plan for the Circular Economy" (CEAP1). This communication referred to the assumptions included in the strategy "Towards a circular economy: A zero waste programme for Europe" and included a roadmap developed for the implementation of CE principles related to each stage of the product life cycle (Pinyol Alberich et al., 2023).

It also presents 54 detailed solutions to ecodesign, as well as strategically advanced concepts related to plastics and chemicals. The document also includes guidelines for the functioning of the economy in problem areas, such as plastics, food waste, construction, critical raw materials, mining and industrial waste (biomass, bioproducts), consumption, and public procurement (Calisto Friant et al., 2021).

The document includes the obligation to support actions undertaken in the field of innovation and investment, the aim of which is to stimulate the process of transition to CE. The scope of the projects concerns all stages occurring in the value chain, i.e., production, consumption, repair, and regeneration, up to waste management, obtaining secondary raw materials re-introduced into the economic circulation to narrow and close material and energy loops (Dziekański et al., 2024). Thus, the principles were defined, with the aim of maintaining the value of products and resources in the

DOI: 10.34659/eis.2025.93.2.1004

economy until this task is feasible, to minimise waste generation, and to emphasise the durability of products and their reuse in circulation.

Another strategy announced at the end of December 2019 is the "European Green Deal" (EGD), one of the cornerstones of which is CE and bioeconomy, promoting the principles of using sustainable and environmentally friendly production cycles. It refers to the overall economic strategy and many problem areas concerning EU policy (Aszódi et al., 2021). EGD is an integral component of the concept developed by the European Commission aimed at implementing the UN 2030 Agenda for Sustainable Development and the sustainable development goals (SDGs) (European Commission, 2021; European Commission, 2019; Ziemacki, 2021; Wyszkowska & Filipiak, 2024). The EGD strategy is implemented by striving for circularity, competitiveness, and innovation in the EU economic system.

In connection with the implementation of the EDG assumptions, on 14 July 2021, the European Commission announced the "Fit for 55" legislative package, which consists of drafts amending existing legal standards or establishing new ones (European Commission, 2019). The purpose of the established legislative proposals is to adapt climate, energy, transport, and tax policies to the requirements of achieving the goal of reducing greenhouse gas emissions by at least 55% by 2030 compared to 1990 in the EU Member States (European Commission, 2021). As a result, such actions should lead to the achievement of planned climate neutrality in 2050.

On 10 February 2021, the European Parliament adopted the "New Circular Economy Action Plan for a Cleaner and More Competitive Europe" (CEAP2), which is a continuation of CEAP1 and EDG (European Commission, 2020). The CEAP2 strategy includes an additional 35 actions to support a largely circular economy. In addition, the plan under review also sets another ambitious target of doubling the EU's circular material use rate by 2030 (Iwaszczuk & Posłuszny, 2021).

The new action plan specifies the detailed assumptions required for the gradual implementation of the circular economy model regarding the sustainable product policy following the supplementation of the Ecodesign Directive. The projects implemented under CEAP2 aim to determine the competitiveness and resilience of the economy as a result of the reduction in greenhouse gas emissions in the industry (European Commission, 2020).

The above analysis shows that transforming the economic systems of EU countries into a new circular economy, preventing threats to biodiversity, and reducing pollution levels, will require immediate responses in all sectors of the economy. As a result, the EU should apply procedures aimed at implementing new investments in environmentally friendly technologies, supporting industrial investments, adapting ecological and inexpensive forms of transport, reducing the emissions of the energy sector, ensuring significant energy efficiency, and cooperating with international contractors to agree on realistic environmental standards.

The typical way to proceed in a rapidly changing economic environment is to develop modern environmental technologies (ET). Technology transfer and ecological innovations are a requirement in the process of achieving environmental goals and enabling the development of the so-called "green economy" (Dao et al., 2024b).

At the same time, ET and eco-innovation (EI) can support the process of implementing the SD concept. Intensified growth of environmental technologies is also one of the strategic goals of implementing the sustainable production programme. In the literature, the terms ET and EI are not clearly and uniformly defined. The first concept concerns technologies whose use results in minimising the negative impact of industry and the services sector on the natural environment (Dao et al., 2024a). Thus, ET is implemented to reduce costs by reducing energy and raw material consumption and improving competitiveness while reducing greenhouse gas emissions and waste. The indicated benefits are also an important factor in the development of EU countries (European Commission, 2004).

The involvement of capital in ET, facilitating the rational use of resources, has a positive impact on individual sectors of the economy. Therefore, the implementation of modern environmental technologies is a significant challenge for modern economies.

It is widely accepted that EIs aim to develop new products and processes that are designed to provide benefits to buyers and business managers while minimising adverse environmental impacts (Aaltonen et al., 2024; Rodríguez-Rebés et al., 2024). The purpose of EI is to protect environmental resources, including air, water, land, flora, fauna, and landscape, as well as society, from the adverse impact of economic activity (Kiefer et al., 2017; Chistov et al., 2023). EI also refers to changes in consumption and production patterns and the dissemination of technologies, products, and services that

DOI: 10.34659/eis.2025.93.2.1004

minimise environmental impacts (Chaparro-Banegas et al., 2023). They aim to reduce the negative impact of economic activity on the environment by reducing energy consumption, the use of natural resources, and the emission of harmful substances (Ottman et al., 2006). New environmental technologies and eco-innovations include the following types (Leszczyńska, 2011; Dewick & Foster, 2018; Andersen, 2010):

- additive technologies that are not part of the production process, but are an additional solution to meet environmental requirements, not eliminating the causes of pollution, but the effects of their formation;
- integrated technologies that part of the production process, by minimising the generation of pollution "at source", they contribute to the elimination and prevention of waste and the reduction of resource consumption;
- "End-of-pipe" technologies are devices designed to protect the environment. However, they do not have a direct impact on the production process (the process can function without their participation), but they still reduce or eliminate pollution after it has been produced;
- closed-loop technologies that minimise the flow of materials and energy by changing products and production methods, thus providing a competitive advantage to companies and sectors;
- technological eco-innovations, i.e., products and processes, and in particular technologies (reactive, called additive, "end-of-pipe" technologies; preventive technologies implemented as integrated solutions or "clean technologies" aimed at preventing pollution);
- eco-innovations that are expanding, additive, i.e., solving environmental problems ex-post, referring to the concept of "end-of-pipe" technology;
- integrated eco-innovations, i.e., solutions similar to those used but reducing pollutant emissions (so-called "cleaner" technologies).

Nowadays, it is assumed that environmental technologies and eco-innovations are tools whose application should aim to support the achievement of environmental and SDG related to reducing pollution, minimising the greenhouse effect by reducing the amount of greenhouse gases, and promoting new models of production and consumption.

Materials and Methods

The research procedure used databases made available in international statistics for the indicated EU countries, which are compiled by the Statistical Office of The European Communities (Eurostat), the Organisation for Economic Co-operation and Development (OECD), and Statistics about Portugal and Europe (PORDATA). The collected data was verified by statistical analysis using the STATISTICA, RStudio, and MATLAB&Simulink programmes.

Multivariate statistical analysis method – cluster analysis

Cluster analysis (CA) is considered a classification method that groups identical observations into subsets that are internally undifferentiated and, at the same time, distinctive from the rest. The ordering process is carried out per a defined probability measure and an adopted algorithm (Kusyi et al., 2024). The basic purpose of clustering is the multidimensional division of the data set into clusters so that the components in the same group are comparable but, at the same time, the most divergent from the components in the clusters (Alvarez-Garcia et al., 2024; Afifi et al., 2019). The methodology for grouping objects is presented in Appendix 1.

EDAS average pattern method and linear ordering by the standard deviation method

Nowadays, we can see a rapid intensification in the development of multi-criteria methods (MCDM – Multi-Criteria Decision-Making). They have developed patterns that can be used to evaluate the analysed decision variants. Concerning the specified criteria and the weights of these assumptions determining their significance in the problem under consideration, it is common to perform a linear ordering of variants together with the designation of a model. One of the latest procedures used to resolve diverse real decision problems is the EDAS method (Evaluation Based on Distance from Average Solution) proposed in 2015 (Keshavarz-Ghorabaee et al., 2015). The results obtained during the analysis are based on the average solution representing normalised data, which significantly reduces the possibility of deviation from the best solution (Tadić et al., 2019; Fan et al., 2019). To diagnose alternatives, the average solution (AV) is used. On the other hand, the positive (PDA) and negative average distance (NDA) are two separate ways of deciding that are used in the classification of alternatives. Thus, the best possibility is selected depending on these two distances (Torkayesh et al., 2023; Yazdani et al., 2020; Kahraman et al., 2017). The analysis was performed according to the procedure presented in (Chatterjee et al., 2018; Torkayesh et al., 2023; Ashraf et al., 2023; Batool et al., 2022) see Appendix 2.

In connection with the conducted research procedure using the EDAS method, Shannon entropy was used to determine the weights. It allowed for determining the level of incorrectness of the tested states and distributions of random variables. According to the formula below, the entropy H(X) of a discrete random variable X is defined as the sum:

$$H(X) = -\sum_{i=1}^{r} P_i \log_2 P_i, \qquad (1)$$

where:

$P_i = P(X = x_i)$ is the probability that the random variable X takes the value , while r is the number of values of the random variable X.

During the next stage of the analysis, the values of the synthetic variable (AS) obtained in the previous stage of the study constituted a criterion for linear ordering of objects using the standard deviation method. In this type of method, the variant typology procedure is based on the study of the deviations of the aggregated variable values obtained in the penultimate stage of the EDAS algorithm about the arithmetic mean of this variable (Xu & Cai, 2008). The variants obtained are classified into one of the following four groups: group I: $AS \geq \bar{x} + \sigma$ very high level; group II: $\bar{x} + \sigma > AS \geq \bar{x}$, high level; group III: $\bar{x} > AS \geq \bar{x} - \sigma$, medium level; group IV: $AS < \bar{x} - \sigma$, low level.

Pro-environmental transformation measure

The analysis of the obtained values of the AS and CI (Circularity Index) parameters led to the creation of the author's pro-environmental transformation index (PETI) defined by the formula:

$$PETI = \frac{AS\ (t_1, \ldots, t_n)}{CI\ (t_1, \ldots, t_n)} * 100, \qquad (2)$$

where:

AS – evaluation result in the EDAS method,

CI – Circularity Index,

$t_1, \ldots, t_n$ – time intervals studied.

The following PETI index values were indicated:

- PETI = 0, means that the country's economy is not taking any action to transition to a green economy and counteract climate change and that CE principles are not being implemented (no transformations or changes);
- PETI = 10, the country's economy is taking rapid action to transition to a green economy and counteract climate change, and there is an intensive level of implementation of CE principles (strong transformations and changes);
- PETI < 10, significant actions are being taken in the country's economy aimed at transitioning to a green economy, and combating climate change and there is a high level of implementation of CE principles (higher transformations and changes);
- PETI > 10, in the country's economy, negligible actions are being taken to transition to a green economy and counteract climate change, and there is a low level of implementation of CE principles (minor transformations and changes).

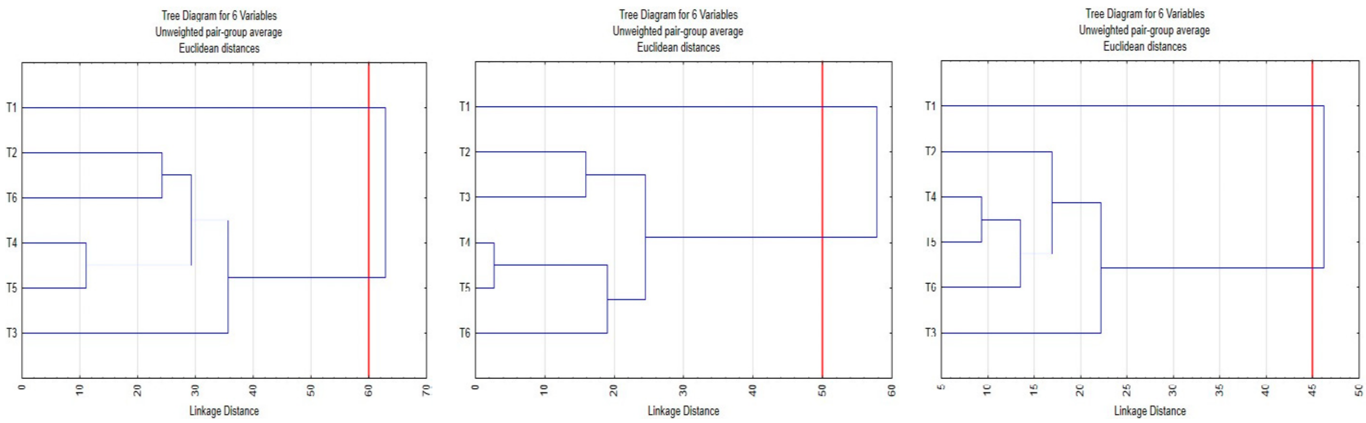
DOI: 10.34659/eis.2025.93.2.1004

Results

Development of environmental technologies supporting sustainable development in EU countries

The collected empirical data allowed us to determine the stage of development of environmental protection technologies that are used to achieve the level of circularity of material management in EU countries. To group the studied technological solutions contributing to the implementation of the SD concept in the years 2010-2022, the CA method was used according to the classification of average connections using the Euclidean distance. As a result of the application of hierarchical grouping, a dendrogram was obtained in which an identical division into four clusters can be distinguished in the years 2010-2022 (see Figure 1).

In 2010, the four clusters identified were formed by groups: two-element (two clusters) and one-element (two clusters) (see Figure 1a). The grouping of the EU countries developing ET with the highest level of circularity in their economies in the process of implementing the principles of sustainable development takes into account two solutions: climate change adaptation technologies (T6) and general environmental management systems (T2). The second cluster concerns climate change mitigation in information and communication technologies (ICT) (T4) as well as the application of technologies for the capture, storage, sequestration, or removal of greenhouse gases (T5). The third cluster in a single-element configuration includes environmental protection technologies (T1). The last, also single-element, cluster concerns climate change mitigation technologies related to energy generation, transmission, or distribution (T3).



a) b) c)

Figure 1. Dendrogram of the classification and course of agglomeration of environmental technologies from the perspective of the sustainable development concept: (a) for 2010; (b) for 2015; (c) for 2022

Source: authors' work using the Statistica package.

Based on the CA analysis, the clusters included: 1. integrated technologies, 2. additive technologies, 3. "end-of-pipe" technologies, and 4. closed-loop technologies.

According to research conducted in 2010, the dynamic development of integrated T6 technologies concerned RO – 17.33%, LV – 11.7%, and LT – 9.21. The smallest increase in solutions of this type was observed in BG – 0.34%, CZ – 0.74%, and MT – 1.02%. In addition, a significant increase in integrated technologies in the T3 range was observed in DK – 22.85%, PT – 13.82%, and LT – 11.26%. However, solutions of this type were disseminated to a minimal extent in BG – 3.5%, HR – 3.72%, and SE – 3.73%. The second group of technologies, called additive (T4), was most developed in EE – 10.81%, RO – 1.13%, and SK – 1.01%. On the other hand, the lowest rate of development of this type of technology concerned HR, LV, LT – 0.01%; CZ, LU – 0.02%; CY and MT – 0.03%. In turn, the general environmental management systems (T2) were most often expanded in LT – 15.35%, PT – 9.03%, and SE – 9.02%. Programmes of this type were occasionally distributed in AT – 1.37%, SI – 1.97%,

DOI: 10.34659/eis.2025.93.2.1004

and MT – 2.12%. The third type of technology, the so-called “end-of-pipe” technology, was developed using T5 solutions among the following countries: LU – 0.92%, IE – 0.19%, PT, DE, and DK – 0.17%. A slight increase was observed in BG, LT – 0.01%; BE, HR – 0.02%, and LV – 0.03%. The dynamic development of the fourth category of closed-loop technologies in the T1 range was most frequently seen in LT – 28.64%, DK – 25.83%, and SK – 18.04%. In turn, relatively little interest in solutions of this type was identified in LV – 2.93%, SI – 6.14%, and IE – 9.01% (see Fig. 2).

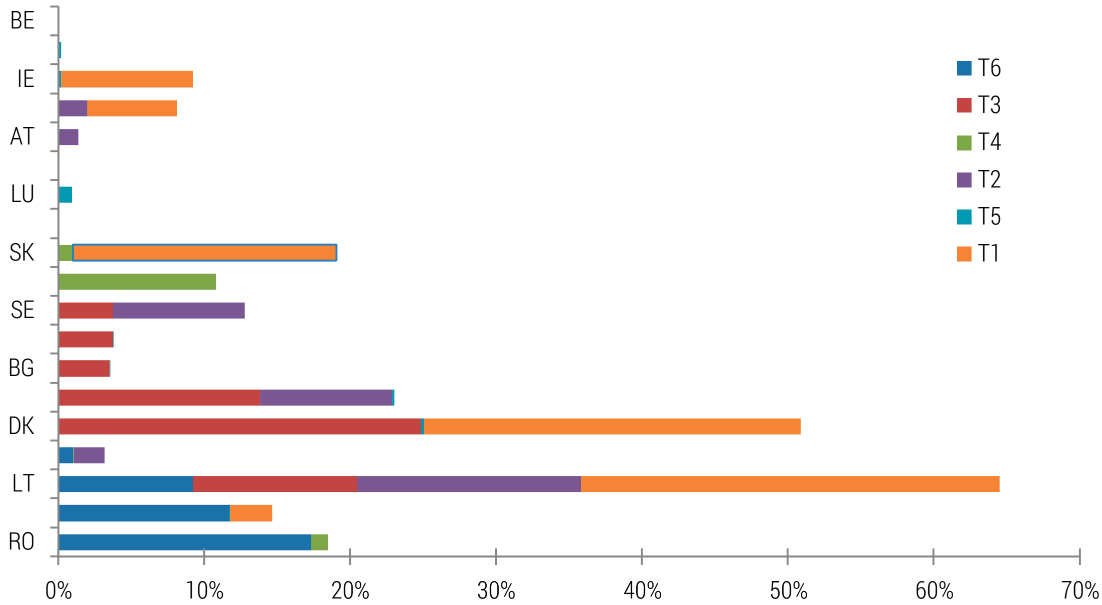


Figure 2. Development of pro-ecological technologies in EU countries in 2010

In the next year accepted for analysis, 2015, four clusters were distinguished and divided into single-element (2 clusters) and two-element (2 clusters) groups (see Figure 1b). The first group, consisting of two components, consisted of climate change mitigation technologies related to energy production, transmission or distribution (T3) and systems used for general environmental management (T2). The second cluster was also shaped by two components, in which the development of environmental technologies was related to the capture, storage, sequestration, or removal of greenhouse gases (T5) and climate change mitigation in ICT solutions (T4). The next single-element cluster was formed by technologies related to the environment (T1). The fourth cluster, also with one element, included technologies of adaptation to climate change (T6). Based on the research conducted in 2015, it should be stated that the development of additive technologies of the T2 type took place in LT – 9.39%, HR – 6.84%, and MT – 6.79%. In turn, the lowest growth in this type of technology, grouped in the analysed cluster, concerned AT – 0.9%, CY – 1.2%, and IE – 1.54%. The same cluster includes integrated technologies of the T3 category, with dynamic intensification observed in DK – 11.82%, BG – 10.24%, and SK – 10.49%. The lowest increase in the technologies studied was achieved in the following countries: LV – 1.2%, CZ – 2.18%, and IT, RO – 2.2%. The second set includes tools based on the T5 end-of-pipe technologies that are developing relatively dynamically in BE – 0.36%; NL, PT – 0.33%, and HU – 0.32%. A slight intensification occurred in RO, SI, SK – 0.01%, FI – 0.05%, and SE, DK – 0.06%. In the same grouping, another type of additive technology, type T4, was classified, with the largest increase observed in SE – 1.68%, FI – 1.58%, and IE – 0.93%. The lowest rate of their dynamisation was recorded in BG, CZ, HR, LV, and SK – 0.1%; FR – 0.3%, and DK, IT, and SI – 0.11%. The next grouping concerned the development of closed-loop T1 technologies, which were intensively developed in BG – 25.35%, DK – 18.76%, and SK – 18.67%. Their growth was limited in CY – 2.28%, RO – 5.94%, and LV – 6.17%. The final ranking consisted of T6 integrated technologies with significant growth in the areas LV – 16.44%, RO – 6.90%, and GR – 2.83%. However, the lowest rate of their growth was identified in DE – 0.88%, CZ – 0.89%, and AT – 0.90% (see Figure 3).

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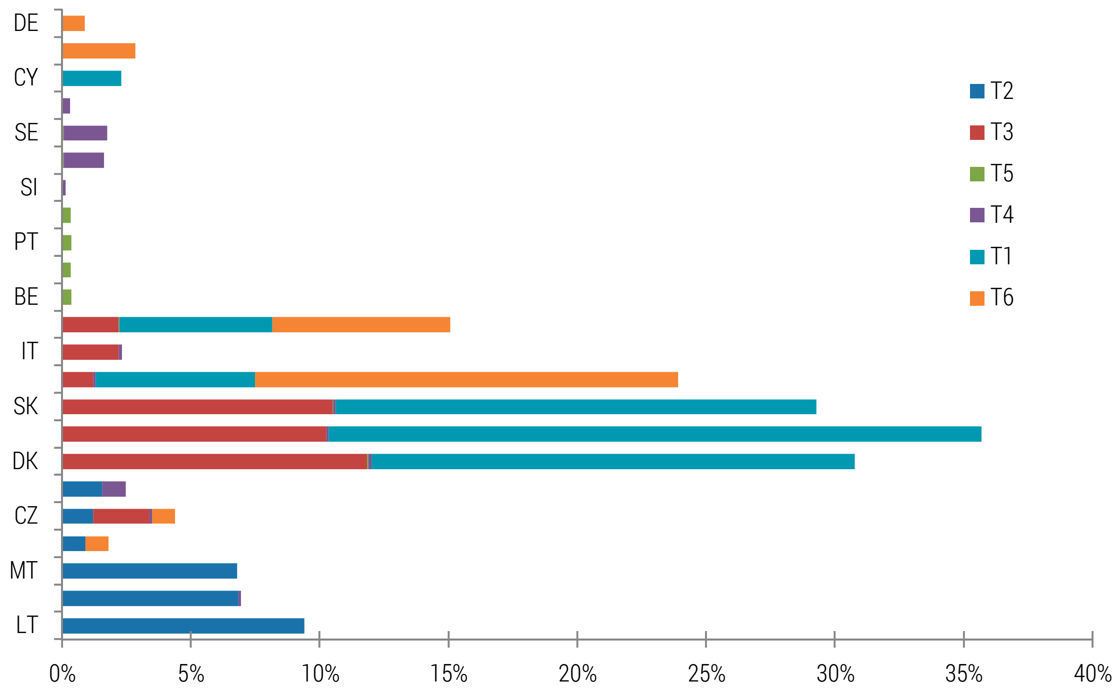


Figure 3. Development of pro-ecological technologies in EU countries in 2015

Similarly, in the last year studied (2022), the dendrogram classified the ET development stage into four clusters. On their level, groups with a single-element (3 groups) and three-element (1 group) structure were formed. (see Figure 1c). The first independent single-element cluster was formed by environmental technologies (T1). The next three-element cluster concerned climate change adaptation technologies (T6), solutions enabling the capture, storage, sequestration, or removal of greenhouse gases (T5), and climate change mitigation tools in ICT technologies (T4). The third single-element cluster was formed by climate change mitigation technologies related to energy generation, transmission, or distribution (T3). The last, fourth and also single-element, cluster consolidated general environmental management systems (T2). Research conducted for the 27 EU countries in 2022 indicates that the first cluster concerned the intensive development of closed-loop technologies (T1) in the areas DK – 21.96%, CY – 16.59%, and AT – 13.96%. The smallest increases occurred in PL – 0.91%, HR – 2.73%, and EE – 3.3%. The second list also consolidated integrated technologies (T6) that are developing dynamically in RO – 8.50%, LV – 6.86%, and CY – 6.50%. The lowest level of their development was observed in the following countries EE, LU – 0.12%, HU – 0.33%, and AT – 0.68%. The analysed cluster also included "end-of-pipe" technologies (T5), which saw a significant increase in LV – 8.57%, MT – 5.05%, and PL – 1.57%. In turn, a small increase in this type of technology occurred in HR – 0.01%; EE, SE – 0.02%; BG, LU, PT and RO – 0.04%. In addition, the group in question also includes additive technologies (T4), which are developing faster in the areas SE – 2.29%, GR – 2.01%, and LV – 1.71%. The lowest rate of dynamisation of this type of technological solution occurred in LT – 0.03%, PT – 0.03%, and CZ – 0.07%. The third cluster consisted of T3 integrated technologies, which developed significantly in CY – 14.43%, DK – 14.41%, and AT – 5.48%. However, minimal increases were observed in HR – 0.01%, EE – 0.47%, and PL 0.80%. The last group also included additive technologies T2, with active development in BG – 5.52%, SK – 5.24%, and FI – 5.11%. In turn, slight intensification occurred in the areas MT – 0.04%, CY – 0. 12%, HR – 0.12%, and AT – 0.68% (see Figure 4).

The above studies show that, in the selected five- and seven-year time intervals, an increasing number of single-element clusters can be distinguished. Thus, it should be stated that the EU countries studied are distinguished by a varied pace of development of environmental technologies. They affect the mitigation of climate change and adaptation to its fluctuations as a result of adapting resources to reduce energy intensity, reduce waste, and minimise greenhouse gas emissions in the process of circularity of materials.

DOI: 10.34659/eis.2025.93.2.1004

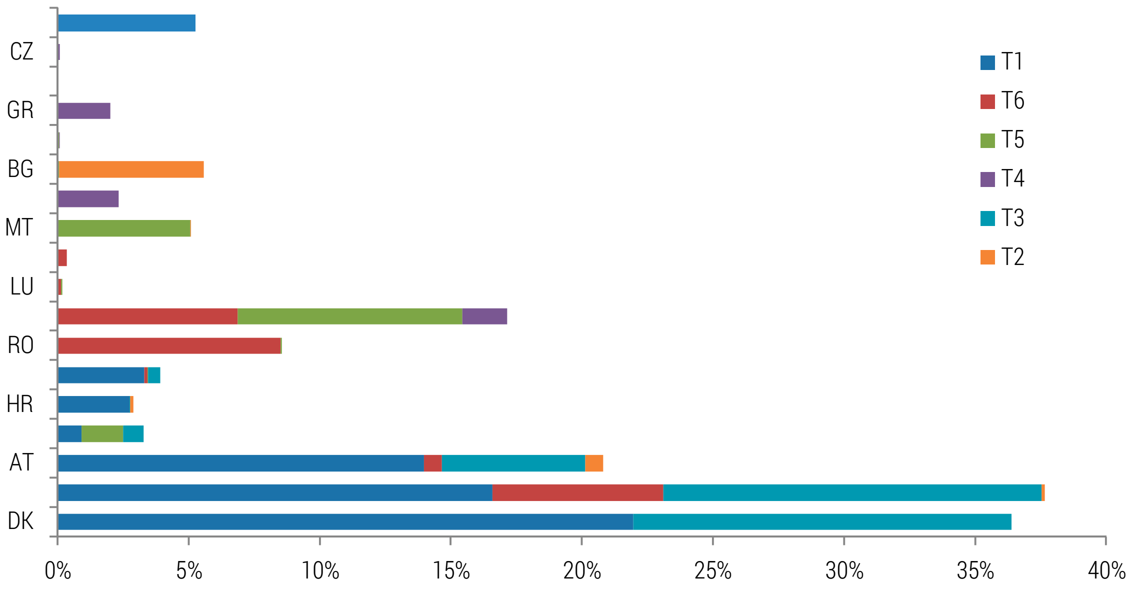


Figure 4. Development of pro-ecological technologies in EU countries in 2022

Shaping the circular economy in EU countries

The task of the analysed new circular economy model is to make economic development independent from the use of limited resources. For this reason, the level of differentiation of EU countries due to the degree of implementation of CE principles using the average EDAS pattern method is presented (see Table 1).

Table 1. Ranking of indicators of the application of circular economy principles in EU countries according to the EDAS method

EU Country	2010				2015				2022			
	AS	V	SKE	Ranking EDAS	AS	V	SKE	Ranking EDAS	AS	V	SKE	Ranking EDAS
BE	0.405	111%	1.502	13	0.242	109%	1.807	15	0.332	144%	1.255	9
BG	0.410	119%	1.561	12	0.288	104%	1.370	12	0.241	259%	1.968	15
CZ	0.401	108%	1.466	15	0.267	100%	1.450	14	0.307	138%	1.126	10
DK	0.412	123%	1.436	11	0.093	129%	0.921	25	0.125	58%	0.435	24
DE	0.967	55%	-0.198	1	0.951	49%	-0.217	1	0.928	-13%	-0.290	1
EE	0.377	128%	1.254	16	0.135	122%	0.957	21	0.154	107%	0.833	22
IE	0.374	134%	1.673	17	0.163	131%	1.759	18	0.183	214%	1.545	17
GR	0.418	95%	1.509	10	0.284	92%	1.357	13	0.267	131%	0.923	14
ES	0.588	62%	0.309	3	0.583	57%	0.733	3	0.568	36%	0.464	3
FR	0.617	71%	0.559	2	0.637	64%	0.354	2	0.580	9%	0.133	2
HR	0.356	129%	1.086	22	0.151	115%	0.844	20	0.171	116%	0.897	20
IT	0.560	68%	0.505	4	0.577	58%	0.396	4	0.464	35%	0.443	6
CY	0.340	156%	1.973	24	0.098	142%	1.816	24	0.101	316%	1.903	25
LV	0.289	141%	1.149	26	0.177	123%	1.041	16	0.160	122%	0.983	21

DOI: 10.34659/eis.2025.93.2.1004

EU Country	2010				2015				2022			
	AS	V	SKE	Ranking EDAS	AS	V	SKE	Ranking EDAS	AS	V	SKE	Ranking EDAS
LT	0.350	144%	1.732	23	0.132	116%	0.992	23	0.131	192%	1.319	23
LU	0.363	147%	1.292	20	0.085	159%	1.627	26	0.091	199%	1.432	26
HU	0.371	117%	1.452	18	0.176	106%	1.235	17	0.194	213%	1.410	16
MT	0.308	179%	2.382	25	0.003	150%	2.022	27	0.007	438%	2.186	27
NL	0.033	123%	-0.558	27	0.338	85%	1.332	9	0.465	119%	1.188	5
AT	0.448	103%	0.897	7	0.313	101%	0.948	11	0.348	73%	0.770	8
PL	0.466	85%	0.580	6	0.394	73%	0.405	6	0.486	63%	0.720	4
PT	0.403	99%	0.834	14	0.326	91%	0.848	10	0.307	99%	0.834	11
RO	0.419	94%	0.646	9	0.343	83%	0.804	8	0.280	124%	0.987	13
SI	0.370	121%	0.903	19	0.161	125%	1.171	19	0.180	128%	0.976	19
SK	0.356	121%	1.392	21	0.135	113%	1.379	22	0.181	183%	1.286	18
FI	0.442	90%	0.492	8	0.345	88%	0.470	7	0.292	68%	0.645	12
SE	0.479	97%	0.956	5	0.408	92%	0.851	5	0.365	78%	0.878	7
Total EU countries												
		0.419				0.289				0.293		
σ		0.152				0.207				0.194		
V		36%				72%				66%		
SKE		1.361				1.484				1.460		

where: — average, σ – Standard deviation V – Coefficient of variation, SKE – skewness.
Source: authors' work using the MATLAB&Simulink package.

The ranking of countries and grouping of objects using the standard deviation method reveals inequalities resulting from the level of application of the principles of the analysed economic model by the studied countries. In 2010, the range for the analysed variables between the maximum value for DE – 0.967 and the minimum for NL – 0.033 was 0.934. During the next five years (2015), the difference between the highest degree for DE – 0.951 and the lowest occurring in MT – 0.003 was 0.948. In turn, in the seven-year time interval to the last analysed year of 2022, the discrepancy occurring in the optimal range for DE – 0.928 and insignificant concerning MT – 0.007 reached the lowest level so far, equal to 0.921.

The leading position in the ranking is occupied by DE, which is distinguished by significant values of diagnostic features. In the case of the indicated country, the highest implementation rate of CE principles in the years 2010-2022 concerned the intensity of greenhouse gas emissions and energy consumption (C1 in 2010 – 93%; 2015 – 88%, 2022 – 85%), energy intensity of the economy (C18 in 2010 – 82%; 2015 – 66%; 2022 – 55%), net greenhouse gas emissions (C7 in 2010 – 73%; 2015 – 70%; 2022 – 60%), and recycling of packaging waste (C30 in 2010 – 73%; 2015 – 69%; 2022 – 68%).

The last place in the ranking, which was prepared for 2010, was taken by NL. In the indicated country, CE assumptions were implemented through the production of electricity by wind farms (C13 – 343%), nuclear power plants (C15 – 341%), and minimising the intensity of carbon dioxide emissions in the economy (C19 – 335.9%). However, only a negligible extent was undertaken to increase the domestic consumption of materials obtained from waste intended for final processing and disposal (C26 – minus 1623.5 to reduce the final energy consumption (C2 – 3.35%) and primary energy (C6 – 4.32%) as well as the share of renewable energy in the gross final energy consumption (C16 – 3.9%). In 2015 and 2022, MT was ranked 27th, in which the CE concept was implemented through total electricity production (C8 in 2010 – 182%; 2015 – 112%; 2022 – 190%) and the use of gas (C11 in 2010 – 1%; 2015 – 125%, 2022 – 164%) and domestic consumption of biomass materials (C24 in 2010 – 567.70%; 2015 – 634.10%; 2022 – 571.6%). In turn, little popularity was recorded for solutions influencing marginal energy consumption (C2 in 2010 – 1.21%; 2015 – 1.3%; 2022 – 1.14%), greenhouse gas emissions implemented per the objectives of the "Europe 2020" strategy (C20 in 2010 – 1.1%; 2015 and 2022 – 1.3%) and the production of electricity by nuclear power plants (C15 in 2010, 2015 and 2022 – 1%).

In the next stage of the study, the coefficient of variation (V) was determined, which indicated the variation resulting from the application of norms and standards applicable to the CE concept among the 27 EU countries. In 2010, this indicator reached the lowest value of 36%, at the same time indicating moderate variation. In 2015, this parameter reached the highest value of 72% and indicated a very high variation in the implementation of the principles of pro-environmental transformation. In turn, during the last year under review, the coefficient of variation was at the level of 66%, which meant high variation in the rules of conduct resulting from the implementation of the CE model.

However, in the EU27, a division can be observed between individual countries, which is a consequence of the application of only selected CE requirements. In 2010, it concerned very high variability for all EU26 countries (except DE, where a large disproportion was observed; 55%). In 2015, large variability was also observed for DE (49%), ES (57%), and IT (58%), and very large for the other EU countries examined. In turn, during the last examined year of 2022, disproportions in the use of CE principles were very small in DE (-13%) and FR (9%), and moderate diversification was observed in ES (36%), IT (35%), a high degree was characterised by DK (58%) and a very large scale was demonstrated by the other EU countries examined.

In turn, to determine the nature of the variation in the values of the analysed variables, the skewness coefficient (SKE) was used. Its role was to distinguish the years in which the analysed EU countries made significant and minor implementations resulting from the CE concept. Based on the indicated criterion, a configuration of right-sided skewness with a strong asymmetry of distribution was identified for all EU countries in 2010 (SKE assumed a value of 1.361), 2015 (SKE equals 1.484), and 2022 (SKE amounted to 1.460).

In the first year under study (2010), the application of solutions aimed at minimising the use of raw materials, waste generation, reducing greenhouse gas emissions, and the level of energy use was characterised by an asymmetric distribution with a very weak negative left-sided skewness for DE and a positive right-sided skewness for ES. A left-sided, negatively skewed distribution with weak asymmetry was observed in NL. On the other hand, a right-sided positive asymmetry was characteristic of FR, PL, FI, IT, and RO. A moderate right-sided asymmetry was observed in HR, LV, AT, PT, SI, and SE, and a strong one in BE, BG, CZ, DK, EE, GR, LU, HU, and SK. On the other hand, a very strong asymmetry of the distribution was observed in IE, CY, LT, and MT.

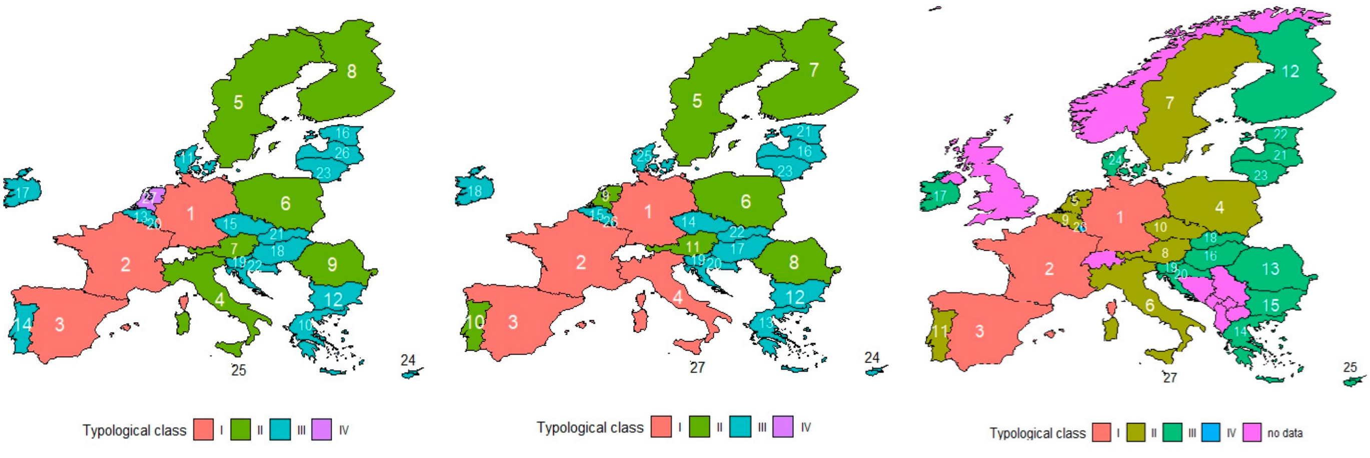
In the next five years, i.e., until 2015, DE was characterised by left-sided skewness with a very weak asymmetry of the distribution. Positive right-sided differentiation of this type of structure was observed in FR and IT. A weak direction of asymmetry of the distribution was observed in ES, PL, and FI. A moderate degree of asymmetry was observed in DK, EE, HR, LV, LT, AT, PT, RO, and SE. A strong coefficient of asymmetry was observed in BG, CZ, GR, HU, NL, SI, and SK. On the other hand, a very strong direction of asymmetry was observed in BE, IE, CY, LU, and MT.

During the last seven-year study period, which ends in 2022, a negative left-sided distribution was observed in the case of very weak asymmetry for DE and a positive right-sided distribution in the case of FR. A weak asymmetric skewness coefficient was typical for DK, ES, IT, AT, PL, and FI. On the other hand, its moderate value characterised the countries EE, HR, LV, NL, PT, RO, SI, SE, CZ, and GR. A strong asymmetry of the distribution was distinguished by BE, IE, LT, LU, HU, and SK. On the other hand, a very strong skewness of the distribution of the analysed data concerned BG, CY, and MT.

Based on the determined measures using the distance-based assessment method (EDAS) for multi-criteria classification of objects, a linear ordering of EU countries was performed, taking into account the value of the aggregate variable. As a result, typological classes were identified, presenting the division of EU countries according to the intensity of implementation of solutions aimed at maximally maintaining the value of products, components, and materials and reducing waste and environmental pollution related to mitigating climate change. The results of the analysis are presented in Table 2.

Table 2. Typological classification of EU countries by the intensity of the procedure of the requirements of the circular economy in the period 2010-2022

Typological class	Synthetic measure AS		Number of states	Countries (value of a synthetic measure)
	limit values	level		
year 2010				
I	≥0.571	very high	3	DE (0.967), FR (0.617), ES (0.588)
II	<0.419-0.571)	high	6	IT (0.560), SE (0.479), PL (0.466), AT (0.448), FI (0.442), RO (0.419)
III	<0.267-0.571)	medium	17	GR (0.418), DK (0.412), BG (0.410), BE (0.405), PT (0.403), CZ (0.401), EE (0.377), IE (0.374), HU (0.371), SI (0.370), LU (0.363), Sk (0.356), HR (0.356), LT (0.350), CY (0.340), MT (0.308), LV (0.289)
IV	<0.267	low	1	NL (0.033)
year 2015				
I	≥0.496	very high	4	DE (0.951), FR (0.637), ES (0.583), IT (0.577)
II	<0.496-0.289)	high	7	SE (0.408), PL (0.394), FI (0.345), RO (0.343), NL (0.338), PT (0.326), AT (0.313)
III	<0.289-0.082)	medium	15	BG (0.288), GR (0.284), CZ (0.267), BE (0.242), LV (0.177), HU (0.176), IE (0.163), SI (0.161), HR (0.151), EE (0.135), SK (0.135), LT (0.132), CY (0.098), DK (0.093), LU (0.085)
IV	<0.082	low	1	MT (0.003)
year 2022				
I	≥0.487	very high	3	DE (0.928), FR (0.580), ES (0.568)
II	<0.487-0.293)	high	8	PL (0.486), NL (0.465), IT (0.464), SE (0.365), AT (0.348), BE (0.332), CZ (0.307), PT (0.307)
III	<0.293-0.099)	medium	14	FI (0.292), RO (0.280), GR (0.267), BG (0.241), HU (0.194), IE (0.183), SK (0.181), SI (0.180), HR (0.171), LV (0.160), EE (0.154), LT (0.131), DK (0.125), CY (0.101)
IV	<0.099	low	2	LU (0.091), MT (0.007)



a) 2010 b) 2015 c) 2022

Figure 5. Diversity of EU countries in terms of implementation of circular economy principles: a) in 2010; b) in 2015; c) in 2022

Source: authors' work using RStudio.

According to the conducted research, it should be stated that the progress in implementing CE solutions and principles among the surveyed countries is reflected in the varied scope and slow pace (see Figure 5).

In the years 2010-2022, DE, FR, ES, and, additionally in 2015, IT formed the first typological class and thus distinguished themselves with a very high intensity of implementing rules in the scope of CE. The mentioned countries were characterised by the application of solutions in the scope of green economy (C13, C14), environmental protection (C19, C20), and waste management (C27), which contribute to functioning per CE.

In turn, the high intensity of actions taken resulting from the assumptions of this type of production and consumption management model was recognizable for 6 (in 2010) and 7 (in 2015 and 2022) EU countries grouped in typological class II. The concentration of this type was distinguished by a high level of analysed variables. Countries classified in this class were characterised by a high degree of application of CE principles, which result from the use of renewable energy sources (C3, C5), including wind energy (C13), reduction in carbon dioxide emissions (C19), and reduction in dependence on raw materials (C28).

The dominant class III was characterised by an average intensity of adaptation of the EU countries studied to CE standards. This type of association consisted of 17 (in 2010), 15 (in 2015) and 14 (in 2022) countries. The entities studied were distinguished by an average intensity of implementation of EU CE regulations in the field of electricity production (C8), including that from hydroelectric power plants (C12), reducing the energy intensity of the economy (C18), and the use of recycling extending the life cycle of packaging (C30).

The final typological class IV includes countries (1 in 2010 and 2015, 2 in 2022) that achieved the lowest value in the intensity of implementing circular economy procedures. Thus, the countries studied achieved the weakest results, because they were characterised by the lowest indicator of energy production from renewable sources, including wind (C13) and nuclear (C15), product recycling (C28), and waste for final processing (C10).

Based on the conducted research, it should be concluded that the dynamics of implementation of solutions necessary to achieve the assumed CE goals in EU countries are characterised by a slow pace.

The basis for the disproportions in the level of circularity of the 27 EU countries is the amount of secondary raw materials and resources intended for reuse, as well as changes in the structure of exchange and production of national economies. Thus, a high circularity indicator occurs in countries where the amount of waste obtained in the recovery process is high. This measure can also take high values if the domestic consumption of materials is low. If it reaches an average value, it informs about the use of materials and their recovery in individual countries. A low circularity indicator indicates, in particular, a significant scope of overconsumption. On the other hand, a negative value of the indicator means high domestic consumption of materials and the absence of their recycling process.

Pro-ecological management of EU countries' resources in the context of sustainable development

The final stage of the research consisted of determining the effectiveness of transforming the linear cycle into a closed loop (see Table 3). Determining the PETI index value contributed to the observation of radical changes in the methods of production and consumption in the 27 EU countries in the years 2010-2022. In addition, it enabled the differentiation of countries due to the staged process of implementing pro-environmental solutions.

Based on the value of the analysed indicator in 2010, a significant division of countries should be noted, due to the degree of implementation of assumptions based on reasonable and sustainable use of resources. The first group includes the countries FR, DE, ES, IT, PL, SE, AT, FI, DK, BE, CZ, EE, HU, SI, LU, SK, LT, MT, and NL representing low values of the indicator (PETI<10). Therefore, if the proposed measure adopts lower parameters, it means that the country achieves a higher level in the process of minimizing energy consumption, greenhouse gas emissions, and the amount of waste while maximizing recycling, leading to narrowing or closing material and energy loops. Moreover, it should be concluded that the EU countries studied are distinguished by significant involvement in the implementa-

DOI: 10.34659/eis.2025.93.2.1004

tion of the SD concept, which is a requirement obliging the modification of the previously applicable management paradigms and the transformation of the economy from a linear model to a circular one.

Table 3. The pro-environmental transformation index of the 27 EU countries

UE country	CI 2010	CI 2015	CI 2022	CG 2010	CG 2015	CG 2022	PETI 2010	PETI 2015	PETI 2022
DE	11.2	11.7	13.0	88.8	88.3	87.0	8.6	8.1	7.1
FR	17.5	18.7	19.3	82.5	81.3	80.7	3.5	3.4	3.0
ES	10.4	7.5	7.1	89.6	92.5	92.9	5.7	7.8	8.0
IT	11.5	17.2	18.7	88.5	82.8	81.3	4.9	3.4	2.5
SE	7.2	6.7	6.1	92.8	93.3	93.9	6.7	6.1	6.0
PL	11.1	11.9	8.4	88.9	88.1	91.6	4.2	3.3	5.8
AT	6.8	11.2	13.8	93.2	88.8	86.2	6.6	2.8	2.5
FI	10.7	4.9	0.6	89.3	95.1	99.4	4.1	7.0	48.7
RO	3.5	1.7	1.4	96.5	98.3	98.6	12.0	20.2	20.0
GR	2.5	1.8	3.1	97.5	98.2	96.9	16.7	15.8	8.6
DK	8.0	8.3	7.4	92.0	91.7	92.6	5.2	1.1	1.7
BG	2.1	3.1	4.8	97.9	96.9	95.2	19.5	9.3	5.0
BE	13.6	18.2	22.2	86.4	81.8	77.8	3.0	1.3	1.5
PT	1.8	2.1	2.6	98.2	97.9	97.4	22.4	15.5	11.8
CZ	5.3	6.9	11.9	94.7	93.1	88.1	7.6	3.9	2.6
EE	9.1	11.7	16.0	90.9	88.3	84.0	4.1	1.2	1.0
IE	1.8	1.9	1.8	98.2	98.1	98.2	20.8	8.6	10.2
HU	5.2	5.8	7.9	94.8	94.2	92.1	7.1	3.0	2.5
SI	5.9	8.6	9.4	94.1	91.4	90.6	6.3	1.9	1.9
LU	23.4	9.5	5.2	76.6	90.5	94.8	1.6	0.9	1.7
SK	5.1	5.1	9.1	94.9	94.9	90.9	7.0	2.6	2.0
HR	1.6	4.6	5.8	98.4	95.4	94.2	22.3	3.3	2.9
LT	3.9	4.1	4.1	96.1	95.9	95.9	9.0	3.2	3.2
CY	2.0	2.4	3.2	98.0	97.6	96.8	17.0	4.1	3.2
MT	5.3	4.6	15.1	94.7	95.4	84.9	5.8	0.1	0.0
LV	1.2	5.3	5.4	98.8	94.7	94.6	24.1	0.9	3.0
NL	25.5	26.6	27.5	74.5	73.4	72.5	0.1	1.3	1.7

where: AS is the same as in Table 1, CI – circularity index, CG – circular gap, PETI – pro-environmental transformation index.

The second group was formed by the countries RO, GR, BG, PT, IE, HR, LV, and CY, which had a high level of the proposed indicator (PETI>10). This means a hierarchical method of dealing with resources, in which, during the first stage, actions are taken to reduce waste and limit gas and dust emissions. The next phases concern the maximum reuse of raw materials. In turn, the final stage consists of utilising materials to slow down, close, and narrow material and energy loops. Therefore, if it takes on a high numerical value, then the countries are characterised by low efficiency in reusing materials and a low level of implementation of rules aimed at narrowing and closing material loops. Thus, the indicated EU countries take insufficient actions in the implementation of the intentions of a sustainable, low-emission, resource-efficient, and competitive economy. In the year under review, it can be

DOI: 10.34659/eis.2025.93.2.1004

noticed that the indicator for NL has a value close to zero (PETI = 0). This type of situation is related to non-compliance with applicable rules and procedures and, therefore, improper management of resources in the pursuit of closing material loops (see Figure 6).

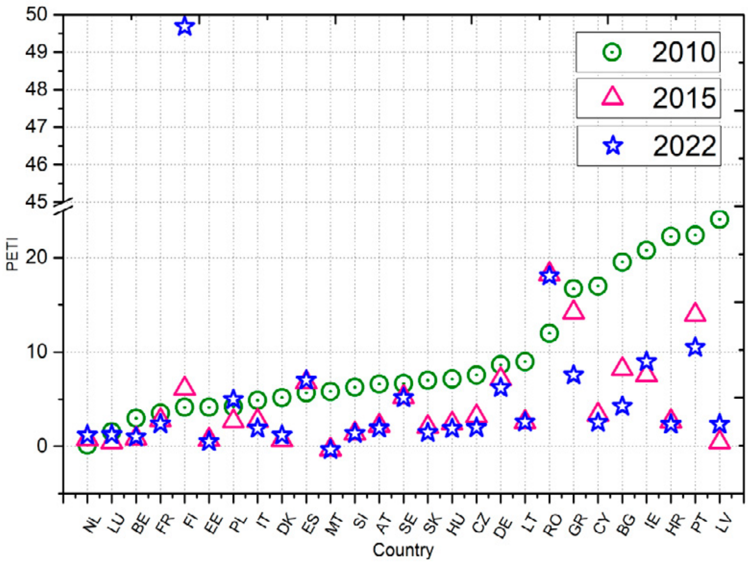


Figure 6. The value of the pro-environmental transformation indicator

In 2015, in comparison to the previous research period, the disproportions between the 27 EU countries, which result from the pace of change in production and consumption systems to the requirements of functioning based on the circular model, decreased. The first group is formed by countries characterised by a low level of the PETI index (<10). This group consists of LU, LV, DK, EE, NL, BE, SI, SK, AT, HU, LT, HR, PL, IT, FR, CZ, CY, SE, FI, ES, DE, IE, and BG. The next group consists of three countries PT, GR, and RO, which were distinguished by a high index value (PETI>10). In the year under review, MT can also be distinguished, as it was characterised by a value close to zero (PETI = 0).

In the final year of the analyses, 2022, the group with a low level of the indicator (PETI<10) concerned 22 countries: EE, BE, DK, NL, LU, SI, SK, HU, IT, AT, CZ, HR, LV, FR, CY, LT, BG, PL, SE, DE, ES, and GR. A significant level of the pro-environmental transformation indicator was characteristic only of four countries (PETI>10) FI, RO, PT, and IE. On the other hand, its level equal to zero, identically to the previously analysed period, was represented by MT.

Based on the conducted research, it should be noted that none of the EU countries studied so far fully respect the CE assumptions, which result from the maximum reduction of waste generation and its reuse in the form of secondary raw materials. This type of situation is indicated by the significant level of differentiation and the pace of changes introduced to close the circulation of raw materials in EU countries. They are estimated using the circularity gap analysis (CG), (Aguilar-Hernandez et al., 2019).

Based on the conducted research, it should be concluded that there is a recognisable and significant differentiation in the level of application of CE principles among the 27 countries belonging to the EU. According to the results of the conducted analyses, it can be noticed that if the percentage of non-renewable raw materials in the economy that are outside the closed circuit decreases, then the effectiveness of actions taken by individual countries in the sphere of environmental protection intensifies. On the other hand, increasing the level of recovered materials returned to the economy results in minimising actions related to the implementation of assumptions aimed at the sustainable use of resources in the process of transformation, conditioning a low-emission, resource-efficient, and competitive economy.

In addition, the degree of circularity of the economy in the EU deteriorates in each analysed period. This situation is primarily due to the growing extraction and use of materials and energy in the countries studied. Their increased exploitation is the result of the accumulation of crises after

2019, including health, economic, inflation, energy, and war. Events of the last few years, such as the Covid-19 pandemic, the war in Ukraine, and the indicated crises and restrictions in the availability of raw materials, have highlighted the complexity and intensity of problems related to the dependence of EU countries on imports of products and materials from China and fossil fuels mainly from Russia. Based on the conducted research, it should be concluded that, since 2015, significant progress has been noticeable in the implementation of CE assumptions, however, it was insufficient and slow. In the last analysed year, the above-mentioned events additionally slowed down the process of transition from a linear economy model to a circular one or contributed to its reversal and resulted in identical outcomes to those in 2010, i.e., before the European Commission adopted the first EU action plan on CE, the so-called CEAP-1. Thus, they harmed the progress in the implementation of principles aimed at the sustainable use of resources.

The current economic uncertainty in the world contributes to the growth of asymmetry in the implementation of CE principles in individual EU countries. Therefore, according to the results of the conducted research, it is necessary to confirm the hypothesis that the unification of the circular economy principles is taking place at a different pace in the pursuit of narrowing the material and energy loops and adapting resources to reduce energy intensity, waste, and greenhouse gas emissions in the process of circularity of materials in the EU at the national level.

Conclusions

Threats related to climate change, environmental degradation, and depletion of energy and material resources result from the use of an inappropriate model of raw material management. The linear economy model currently operating in most countries results in the inappropriate use of natural resources, and increased material and energy consumption of the economy, while reducing productivity and energy efficiency. In such a situation, one of the strategic goals of the EU is to take action to create a sustainable, low-emission, resource-efficient, and competitive economy.

It should be concluded that the defined principles of the 5R circular economy not only play a key role in the process of creating a sustainable, low-emission, and competitive economy, but also influence the increase in the efficiency and innovation of resource use. An economic system of this type is based on the efficient use of resources while simultaneously using ET. Thus, the CA analysis for the 27 EU countries shows that ET is optimising tools that enable the implementation of the designated environmental goals in the field of CE.

As a result, integrated technologies for mitigating climate change related to energy generation, transmission, or distribution (T3) were most frequently used by the economies of countries representing the old EU: DK, PT, and AT, and the new EU: LT, BG, SK, and CY. The next implemented solution in this area was climate change adaptation technologies (T6), which were most frequently used by the economies of the old EU countries RO, LV, LT, and GR, as well as one country from the new EU – CY. The next group consisted of additive technologies for general environmental management (T2), usually implemented in the new EU countries LT, HR, MT, BG, and SK, and the old EU of PT, SE, and FI. In their scope, tools enabling climate change mitigation in ICT technologies (T4) were also used, which were most frequently implemented in 2010 in the new EU in EE, RO, and SK, in 2015 in the old EU in SE, FI, and IE, and in 2022 in both the old and new EU in SE, GR, and LV. The third type of environmental technology was the so-called "end-of-pipe" solutions that ensure the capture, storage, sequestration, or removal of greenhouse gases (T5). They have been most often used since 2010 in the old EU countries in LU, IE, PT, DE, and DK, and since 2015 they have been used in BE, NL, and PT. In turn, in 2022 they were used in the areas of LV, MT, and PL, i.e., in the new EU.

According to the adopted CE model, EU countries are also obliged to implement the fourth type of closed-loop technologies, i.e., those related to the environment (T1). Solutions of this type were used in 2010 by the new EU countries of LT and SK and the old EU: DK, in 2015 by BG, SK (new EU), and SI (old EU), and in 2022 by DT, AT (old EU), and CY (new EU). It should be concluded that the listed environmental technologies are implemented in the economies of the 27 EU countries studied at a different pace.

Moreover, the results of the conducted research prove that, among the analysed EU countries, there are significant disproportions in the progress of implementing the CE principles. The countries that implement the CE concept to the highest extent include the old EU countries: DE, FR, and ES (in the years studied classified from 1st to 3rd places according to the EDAS ranking). In turn, the countries shaping both the old EU: DK, LU, and NL and the new EU: CY, LV, and MT (according to the EDAS ranking, occupying places 25-27) were distinguished by the lowest degree of implementation of regulations supporting the transition from a linear economy to a circular model.

Based on the pro-environmental transformation index, the diversity of this phenomenon was determined, and the countries with the greatest improvements in the production process were indicated, aimed at minimising the use of raw materials and waste generation. Countries with the lowest PETI index value were distinguished by the highest scope of the regenerative economy system, minimising materials, waste, emissions, and energy losses by slowing down, closing, and narrowing material and energy loops.

In 2010, the group of countries with a minimum PETI index value included 19 countries, including 11 from the old EU and Western Europe (FR, DE, ES, AT, LU, NL, BE), Northern Europe (SE, FI, DK) and Southern Europe (IT). The new EU was represented by 8 countries from Eastern Europe (PL, CZ, SK, HU), Northern Europe (EE, LT), and Southern Europe (MT, SI). In 2015, the number of countries with a low index increased to 23, adding to the above-mentioned countries IE located in Northern Europe, LV and HR in Southern Europe, BG in Eastern Europe, and CY in the Mediterranean Basin from the new EU. In 2022, the minimum index value was achieved by 22 countries, except FI and SI, which were joined by GR located in Southern Europe, from the old EU. The remaining EU countries had a high or zero PETI index value, which indicates low CE efficiency or inefficient use of resources and waste reduction.

The research results indicate that EU countries have not fully implemented CE solutions, and thus have not achieved the strategic goals of the CEAP1 and CEAP2 plans in the field of limiting the use of resources, green ICT technologies, and mitigating climate change through the processes of slowing down, closing and narrowing material and energy loops. Thus, the implementation of CE principles is insufficient and diverse.

In connection with the above, EU decision-makers should focus on intensifying activities aimed at implementing circular economy standards. Such projects should be implemented in particular in countries (PL, HR, EE) that have the lowest level of development of green technologies, while simultaneously strengthening the position of countries (DK, CY) that dominate as promoters of best practices. To achieve the goals set for waste reduction and efficient use of raw materials, EU managers should allocate significant financial resources for the development of integrated and additive technologies in EE, PT, and LT countries, characterised by less progress, using the experience of countries with significant achievements in the application of pro-environmental solutions. It is also recommended that an essential action should be to increase financial support for the implementation of "end-of-pipe" technologies in HR, SE, and EE, as well as intensive development of renewable energy sources in BG and GR. It is also recommended to develop coherent policies supporting environmental technologies that would take into account differences in the level of economic and technological development of the Member States. It should also be proposed to develop systems for monitoring and reporting results that will enable regular assessment of the effectiveness of actions and their adaptation to changing challenges. It would be desirable to increase funding for research and development of environmental technologies to support the exchange of knowledge and stimulate cooperation between Member States to enable the sharing of experiences resulting from the introduction of the principles of the circular economy. An approach of this type will accelerate the process of ecological transformation of EU countries.

The issues related to CE presented in the article do not exhaust the entirety of the issues related to the implementation of principles, solutions, and actions taken that affect the minimisation of material and energy consumption. The components that make up the CE concept, per the 5R assumption, should be supplemented with new actions aimed at slowing down, closing, and narrowing material and energy loops. For this reason, further research directions should focus on creating new indicators for assessing and monitoring the degree of circularity of the economy and searching for an optimal model of the closed-loop economy.

DOI: 10.34659/eis.2025.93.2.1004

The contribution of the authors

Conceptualisation, M.Sz.; literature review, M.Sz. and K.S.; methodology, M.Sz.; formal analysis, M.Sz.; writing, M.Sz. and K.S.; conclusions and discussion, M.Sz. and K.S.

The authors have read and agreed to the published version of the manuscript.

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Appendix 1. Cluster analysis

The methodology of grouping objects was preceded by the normalization of diagnostic variables, using the transformation of feature values to enable their comparability. Therefore, data standardization was applied according to the formula:

$$Z = \frac{X - E(X)}{D(X)}, \tag{3}$$

where:
X – standardized variable,
E(X) – expected value (arithmetic mean),
D(X) – standard deviation of the variable distribution.

Thus, the obtained variable has a distribution with an expected value $E(Z) = 0$ and variance D^2 (Z) =1. CA enables the formation of groups of highly homogeneous objects. The set of objects is considered from the perspective of an element of the multidimensional space of diagnostic variables:

$$x_i = [x_{i1}, \dots, x_{im}], \tag{4}$$

where:
m – number of variables.

The arrangement of objects into clusters was carried out by measuring the distance between individual elements and the distance between clusters. For this study, one of the taxonomic metrics called Euclidean distance was used to determine it, according to the following formula:

$$d\ (x_i, x_k) = \sqrt{\sum_{j=k}^{m} (x_{ij} - x_{jk})^2}, \tag{5}$$

where:
d – Euclidean metric between objects,
x_{ij} – the value of the *j*-th variable for the *i*-th object,
m – number of all diagnostic variables.

Then, in the procedure of grouping objects, the method of average connections (UPGMA – unweighted pair-group method using arithmetic averages) was used to shape the clusters. The choice of this type of methodology was determined by the configuration of the dendrogram per the iterative algorithm. The procedure used concerns determining the distance between two clusters using the arithmetic mean determined based on the sum of the distances of objects belonging to two divergent clusters based on the following formula (Jaeger & Banks, 2023):

$$d(C_i, C_j) = \frac{1}{n_{Ci} n_{Cj}} \sum_{i \in C_j} \sum_{j \in C_j} d(x_i, x_j), \quad (6)$$

where:
n_{ci}, n_{cj} – number of objects in the cluster C_i, C_j

Appendix 2. The procedure for selecting an average standard using the EDAS method

In the initial stage, a decision matrix is created (X):

$$X = [x_{ij}]_{n*m} = \begin{bmatrix} x_{11} x_{12} & \cdots & x_{1n} \\ \vdots & \vdots & \vdots \\ x_{m1} x_{m2} & \cdots & x_{nm} \end{bmatrix}, \quad (7)$$

where:
X_{ij} – value of the i-th alternative on the j-th criterion,
n – number of alternatives,
m – number of criteria.

Then, the average solution (AV – arithmetic mean) is determined for all criteria:

$$AV = [AV_j]_{1*m}, \quad (8)$$

where:

$$AV_j = \frac{\sum_{i=1}^{m} x_{ij}}{m}, \quad (9)$$

Next, the matrices for the positive distance from the mean (PDA) and the negative distance from the mean (NDA) are calculated.:

$$PDA = [PDA_{ij}]_{n*m} \; ; NDA = [NDA_{ij}]_{n*m}, \quad (10)$$

if the j-th criterion is favorable (stimulant):

$$PDA_{ij} = \frac{max(0, (X_{ij} - AV_j))}{AV_j}, \quad (11)$$

if the j-th criterion is unfavorable (destimulant):

$$NDA_{ij} = \frac{max(0, (AV_j - X_{ij}))}{AV_j}, \quad (12)$$

where: PDA_{ij} and NDA_{ij} denote the positive and negative distance of the i- h alternative from the average solution in terms of the j- h criterion, respectively.

In the next step, the weighted sums of PDA and NDA should be calculated for each scenario:

$$SP_i = \sum_{j=1}^{m} w_j PDA_{ij}, \quad (13)$$

$$SN_i = \sum_{j=1}^{m} w_j NDA_{ij}, \quad (14)$$

where:
w_j is the weight of the j-th criterion.

The next step concerns the normalization of the obtained SP and SN values. The obtained values should be added and a new NSP and NSN vector should be constructed based on them:

$$NSP_i = \frac{SP_i}{max_i(SP_i)}, \tag{15}$$

$$NSN_i = 1 - \frac{SN_i}{max_i(SN_i)}, \tag{16}$$

After performing the calculations, the AS was calculated for each alternative according to the formula:

$$AS_i = \frac{1}{2}(NSP_i + NSN_i). \tag{17}$$

where $0 \le ASi \le 1$.

The final step is to rank the values(ASi) in descending order. The alternative with the highest AS value is the best choice in the ranking.

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IMPLEMENTACJA ZASAD GOSPODARKI CYRKULARNEJ W ZAKRESIE UŻYTKOWANIA TECHNOLOGII ŚRODOWISKOWYCH I ŁAGODZENIA ZMIAN KLIMATU W PAŃSTWACH UE

STRESZCZENIE: Współcześnie nową tendencją zgodną z celami zrównoważonego rozwoju, której główne zamierzenie stanowi rozstrzygnięcie dylematów środowiskowych związanych z intensywnym wykorzystaniem zasobów naturalnych, wzrastającym poziomem emisji gazów cieplarnianych oraz nieracjonalnym użytkowaniem produktów jest gospodarka cyrkularna. Celem artykułu jest rozpoznanie działań podejmowanych przez państwa UE z perspektywy osiągnięcia zrównoważonego poziomu gospodarowania materiałami, produktami i surowcami na rzecz transformacji w kierunku gospodarki cyrkularnej. W trakcie procesu badawczego zestawiono dane z baz Eurostat, OECD, PORDATA. Badania realizowano z wykorzystaniem analizy skupień, metody EDAS oraz grupowania obiektów porządkowanych liniowo. Wyniki badań uwidaczniają, iż badane kraje Unii Europejskiej dotychczas nie zrealizowały celów strategicznych wyznaczonych w planach działania CEAP1 i 2. Ponadto określone zasady gospodarki cyrkularnej implementowane są w odmienny sposób. Rezultaty przeprowadzonych badań stanowią dla zarządzających gospodarkami państw podpowiedź w zakresie sposobu postępowania zmierzającego do kompletnego wdrożenia programów skutkujących redukcją ilości odpadów i wykorzystywanych surowców. Ponadto mogą one wpływać na decyzje modyfikacji przepisów dotyczących kreowania nowego modelu gospodarczego zgodnie z zasadą 5R.

SŁOWA KLUCZOWE: gospodarka o obiegu zamkniętym, technologie środowiskowe, zrównoważony rozwój, wskaźnik transformacji prośrodowiskowej, CEAP1 i 2

DOI: 10.34659/eis.2025.93.2.1004