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JOINT ANALYSIS OF NATIONAL ECO-EFFICIENCY, ECO-INNOVATION AND SDGS IN EUROPE: DEA APPROACH

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Abstract. The growing complexity and intertwining of different socio-economic issues both in individual countries and internationally mean that single-theme analyses do not consider all the relationships and thus have cognitive limitations. Therefore, studies that combine several research areas are increasingly common in the literature to clarify the connections and relationships. In this study, considering the sequential nature of the stages, a combined analysis of eco-efficiency, eco-innovation, and Sustainable Development Goals (SDGs) was performed. The analysis was carried out for 27 European Union countries in 2017–2019. Dynamic Network SBM and Dynamic Divisional Malmquist Index were used for the study. The research results show that the EU countries achieve relatively higher efficiency results in eco-innovation and SDG than eco-efficiency. The average overall efficiency level for all EU countries was only 0.63. The change in productivity was influenced by both the frontier shift and catch-up effect, but only with regard to eco-efficiency and eco-innovation. At the same time, the frontier-shift effect did not affect the change in SDG productivity.

Keywords: pro-environmental technologies, eco-innovation, sustainable development, SDGs, DEA, efficiency.

JEL Classification: C61, O44, Q01, Q55.

Introduction

The UN world representatives (United Nations [UN], 1992a, 1992b, 2015c), prompted by scientists, have warned the international community of the climate threats posed by global warming (caused by the emission of greenhouse gases) for almost three decades. Scientists have pointed to the anthropogenic threats to the natural environment caused by the economic growth model existing since the 1950s (Zalasiewicz et al., 2017).

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Currently, global actions aimed at limiting the negative consequences of global warming are formulated by the UN's plan to transform the world to meet the needs of the present generation in a sustainable manner, respecting the environment and taking into account future generations. It forms a resolution of the UN General Assembly signed in 2015 by the leaders of most countries entitled "Transforming our world: the 2030 Agenda for Sustainable Development" (UN, 2015a). The plan assumes the achievement of 17 Sustainable Development Goals (SDGs) and 169 targets, which need to be implemented by all participants of the international community.

Since the beginning of the implementation of the 2030 Agenda, the European Union warming has become the leader in the fight against global. The EU not only has undertaken to implement the provisions of this resolution, included in the Paris Agreement (UN, 2015b) signed by many countries but even accelerated the reduction of net emissions of greenhouse gases compared to those agreed on in the negotiations (Vanhercke et al., 2021). In 2019, the European Commission presented a document called "The European Green Deal", which comprises a part of the group's strategy to implement the UN resolution on sustainable development and achieve the goals described therein (European Commission [EC], 2019). The Green Deal is a plan that shows how the European Union will transform its economy towards reducing its impact on the natural environment, achieving climate neutrality by 2050, and creating conditions for a sustainable future (Vanhercke et al., 2021).

The transformation of the economy into a sustainable system occurs thanks to the introduction of eco-innovations (technical and non-technical ones) that reduce the negative impact of production on the environment, increase nature's resilience or optimize the use of natural resources (improve its efficiency). As Park et al. indicate (2017, p. 1), quoting Rennings's definition (Rennings, 2000), eco-innovations are "all efforts from relevant actors that introduce, develop, and apply new ideas, behaviors, products and processes and contribute to reducing environmental burdens or ecologically specified sustainability targets." Eco-innovation can also be treated as entrepreneurial behaviour. It consists in designing products in such a way (taking into account ecological problems) and managing them during their life cycle that contributes to pro-ecological modernization of the society of the industrial era. They are considered a tool for implementing the concept of sustainable development. Kemp et al. (2019) provide several definitions of eco-innovation that can be found in the documents of various international institutions and academic research. Among them is the following "Any form of innovation aiming at significant and demonstrable progress towards the goal of sustainable development. This can be achieved either by reducing the environmental impact or achieving more efficient and responsible use of resources" (p. 158).

Eco-innovations make it possible: to reduce the use of resources (including energy and water), to reduce environmental impacts, to prevent the anthropogenic burden on the environment, and to reduce waste generation and the effects of waste accumulation in the form of a limitation of per capita GHG emissions from the waste sector. This last aspect has been the subject of a comparative study of European Union countries by Pais-Magalhães et al. (2021).

Thinking about eco-innovation in this broad context is revealed by reviewing their definitions in the work of Carrillo-Hermosilla, del Río, and Könnölä (2010, p. 1074). They make it clear that eco-innovation can be seen in different dimensions. This is influenced by their nature (technological, product, service, organisational, social), the entity that creates and implements them (companies, households, politicians, NGOs) and their scope (they can cover only the boundaries of the organisation introducing the innovation or wider social systems). In the case of systemic impact, eco-innovations cause changes in the existing socio-cultural norms and institutional structures. This manifests itself, for example, in the networking activities of the organization creating new solutions with other entities to achieve the goal of sustainable development. As Leal Fihlo et al. (2021) point out, it is also possible to create and implement eco-innovation in a systemic dimension within the framework of the "quintuple helix" model. This model considers biological and ecological systems as an additional source of innovation besides government, private sector, research institutions and civil society (Carayannis et al., 2012). According to Kalra et al. (2021) eco-innovation should lead to the reduction of energy poverty and universal access to affordable energy, thus supporting the achievement of the Sustainable Development Goals. Moreover, Kemp et al. (2019) indicate that "Policies for the sustainable development goals (SDGs) need to be more concerned with eco-innovation than currently is the case. Conversely, the SDG framework could be a core target of eco-innovation for a green economy. Eco-innovation can contribute to at least nine of the SDGs on a global level if diffused and adopted effectively" (Kemp et al., 2019, p. 26). Obtaining social goals in addition to economic and environmental goals is nowadays recognized as the basis for a country to achieve a high level of sustainable development as measured by socio-economic efficiency (Stanković et al., 2021).

In the context of eco-innovation, it is also important to mention the concept of eco-efficiency, which emerged in the early 1990s. Eco-efficiency is a management strategy assuming that it is possible to create more goods and services using fewer resources and generating less waste and pollution (Glavi et al., 2012). Eco-efficiency enables the achievement of the intended goals of sustainable development (economic and social) in terms of managing natural resources. Experts from The World Business Council for Sustainable Development explained that "eco-efficiency is achieved by the delivery of competitively priced goods and services that satisfy human needs and bring the quality of life, while progressively reducing ecological impacts and resource intensity throughout the life-cycle to a level at least in line with the Earth's estimated carrying capacity" (World Business Council for Sustainable Development [WBCSD], 2006, p. 4). In this case, eco-efficiency is viewed at the organization, industry or sector level.

In contrast, eco-efficiency is looked at from a systemic (economy-wide) perspective by Moutinho and Madaleno (2021b), who undertook an assessment of the economic and environmental efficiency of economies in Asia and Africa. The authors recognize that eco-efficiency can be an indicator of sustainability when it can be used to shift the paradigm from unsustainable development to sustainable development. The concept of eco-efficiency is based on creating more products and services with fewer resources and less pollution. Moutinho and Madaleno (2021b) point out that accelerating the transition of economies to sustainable development principles can be achieved by increasing renewable energy generation and consumption.

Kuosmanen, on the other hand, in the context of its measurement, points out that "eco-efficiency means "doing more with less", or producing economic output with minimal natural resources and environmental degradation. Although the general idea of eco-efficiency is well established, there is no consensus about its precise definition or criteria. Usually, eco-efficiency is quantified as the ratio of economic value added to the environmental damage index" (Kuosmanen, 2005, p. 15). Although all three issues, i.e., eco-efficiency, eco-innovation, and sustainable development goals, create a coherent conceptual system, it has not been fully empirically investigated. Accordingly, it was decided to study these three topics together.

The aim of the research is a joint analysis of eco-efficiency, eco-innovation, and sustainable development goals and the assessment of the efficiency of European Union countries in this respect.

The added value of the paper is a combined analysis of three areas, i.e., eco-efficiency, eco-innovation, and SDGs, and the use of a more complex DEA model (Dynamic Network SBM – DNSBM) to measure the efficiency than the existing studies have done. Moreover, this value results from using the Dynamic Divisional Malmquist index, an approach that has not been used in the literature so far.

This article is organized as follows. Section 1 reviews the literature and presents the gaps found in previous research. The design of the empirical study is presented in Section 2. This section describes the variables adopted for the study, presents an original empirical analysis model, and selects the DEA model for the empirical study. The results of the empirical study are included in Section 3 and the discussion in Section 4. The last Section summarizes the research, points out the limitations of this study, and suggests directions for further research.

1. Literature review

The literature review revealed that the research conducted on the topic is very diverse in many respects. In general, it can be divided into (1) levels and structures of the units under study (e.g., sectors, countries), (2) areas of study (a selected feature of the phenomenon under study, industry or a comprehensive study of a sector, country), (3) research methodology (e.g., static vs. dynamic analysis), (4) research convention (selected area vs. several research areas). The authors of these studies used indicators proposed in the literature to evaluate specific areas of analysis (Miola & Schiltz, 2019). Selected scientific publications on eco-efficiency, eco-innovation, and SDGs are listed in Table A1 in Appendix. The literature includes both studies devoted to one research topic (Guo et al., 2017; Łozowicka, 2020) and several ones simultaneously (Kiani Mavi et al., 2019; Zhang et al., 2021; Madaleno et al., 2016). The literature review shows that more and more complex studies dealing not only with a single issue but even two or three issues simultaneously have appeared in recent years. However, they are still insufficient and have not sufficiently filled the research gaps (both in terms of content and research methodology) by means of the previous simple analyses – single-stage and monothematic (e.g. Moutinho, & Madaleno, 2021a).

An interesting study was conducted by Kiani Mavi et al. (2019), who analyzed eco-efficiency and eco-innovation using two stages. In the model they adopted, there were only input, intermediate, and output data. Li et al. (2021) conducted a more complex study, using a two-stage sequential model consisting of technological innovation in the first stage and eco-environment in the second one. However, unlike the study by Kiani Mavi et al. (2019), the authors (Li et al., 2021) additionally used data that were either inputs or outputs for only one stage. A different approach to the study was presented by Zhang et al. (2021). Although they used a two-stage model like the previous authors, they analyzed as many as three issues. The research consisted of two parallel scopes in the second stage (eco-technology innovation and eco-well-being performance) and only one in the first stage (eco-efficiency).

A complex study, both in terms of content and methodology of analysis, was proposed by Yu et al. (2020). The authors focused on three aspects of eco-efficiency (i.e., society, economy, and environment), constituting a separate subsystem affecting the other two subsystems. The connections between subsystems were both of input and output nature. The overall eco-efficiency index was the result of three subsystems. As a result, the overall eco-efficiency index and efficiency measures in the field of society, economy, and environment were obtained. Although the presented research is extremely interesting and inspiring, it concerns only the broadly understood eco-efficiency and eco-innovation. However, they do not consider the SDGs, which are currently the subject of numerous discussions (including the promoted EU development policy) and research in various contexts (Sompolska-Rzechula & Kurdyś-Kujawska, 2021; Cheba & Bąk, 2021). They are also a natural result of the two previous issues. Undoubtedly, eco-innovation influences the implementation of SDGs (Kemp et al., 2019). Therefore, future research needs to consider eco-efficiency, eco-innovation, and SDGs. It is worth noting that the authors (Łącka & Brzezicki, 2021) who study the efficiency of innovative systems in Europe explicitly stated that future research should analyze them in the broader context of the SDGs.

A systematic review of the literature in the areas of sustainable development, energy, and the environment shows that research is mainly carried out using several groups of DEA models and their extensions (Tsaples & Papathanasiou, 2021; Chachuli et al., 2020; Mardani et al., 2018; Zhou et al., 2021): Classic DEA (e.g., CCR, BCC, SBM), Extended DEA (e.g., super-efficiency, cross-efficiency), DEA with special data (fuzzy, negative data), Multi-stage and Network DEA (e.g., two or three-stage, Network SBM), Undesirable DEA (e.g., Undesirable SBM, DDF), Dynamic DEA (e.g., Dynamic SBM) and Malmquist index. The authors measuring eco-efficiency, eco-innovation, and SDGs using the DEA method use static models (single-period) with various features, e.g., CCR, BCC, SBM, Network DEA (Łozowicka, 2020; Moutinho & Madaleno, 2021a; Yu et al., 2020) and dynamic ones (Guo et al., 2017). However, there is an evident lack of studies utilizing a combination of two approaches (i.e., Network DEA with Dynamic DEA) and the properties of the Undesirable DEA model in one DEA model. The implementation of this proposal would be possible, for example, through Dynamic Network SBM (Tone & Tsutsui, 2014). It is also worth noting at this point that the Malmquist index (MI) is most often used only with static DEA models (Łozowicka, 2020) and exceptionally rarely with dynamic DEA models. There is an evident lack of such studies on the topic under discussion. Both approaches used separately (Dynamic DEA and Malmquist index – MI) have their advantages and disadvantages. However, using both in one study allows obtaining complementary results, as the "shortcomings" (e.g., MI: no inter-period variables) of one approach are the "advantages" of the other. Another research gap research is the failure of the Malmquist index to account for the structure of network linkages between production stages.

In the literature of many authors, apart from specifying the limitations of their research, future research directions are indicated. Zhang et al. (2021) indicate that future research should cover a period longer than one year. Moutinho and Madaleno (2021a) point out that new research needs to be developed to understand better the links between eco-efficiency and concepts such as sustainable development, environmental performance, and environmental performance indicators. In a similar vein, the directions of future research are indicated by Grochová and Litzman (2021), paying attention to the determinants of SDGs implementation and their interrelationships. The development of this concept is the research direction set by Łozowicka (2020), who specifies that it is necessary to analyze the efficiency of implementing the sustainable development policy in the economic and socio-cultural dimensions. Therefore, considering the gaps found in the literature and the indicated directions for future research in the existing analyses, it was decided to carry out this study. Based on the results of studies undertaken in the literature, it was decided to formulate the following research hypotheses: (1) the countries admitted to the European Union after 2004 achieve relatively higher efficiency measures than the old Union countries, and those admitted before 2004, (2) the analyzed countries obtain relatively higher efficiency measures in terms of eco-innovation and SDGs than eco-efficiency.

2. Materials and methods

The research procedure was divided into five successive stages that differed in nature, purpose, and scope. The research procedure is presented in Figure 1.

In the first stage ("Recognize"), the main research area was selected (in line with, i.a., the profile of the journal), a literature review was carried out (both own search in databases and other sources, and using review articles of other authors), the gaps in previous research were identified. Then the topic of original research focused on the issues of eco-efficiency, eco-innovation, and SDGs was specified.

In the second stage ("Data"), based on a literature review and own experiences, the authors identified data sources that pertained to the research topic, then selected individual variables from relevant databases (Eurostat, OECD, Sustainable Development Report, Eco-Innovation Scoreboard) and extracted the necessary data, considering their uniform period – scheduled for the entire study. The literature review shows that some variables are more often used in research than others, including labor force, energy consumption, capital stock, GDP, and CO_2 emissions (Table A2 in Appendix). However, it should be noted that there is no universal set of variables considered a standard, as each study has a different nature, purpose, and scope of the analysis. The data adopted for the empirical study are presented in Table A3 in Appendix. Their choice was guided by the purpose of this analysis and literature studies. The authors made the preliminary assumption that the data should be the most recent but not from the pandemic period, which could have disrupted the overall trend of a given phenomenon over a more extended period. Therefore, considering the above initial assumption and data time uniformity to maintain the consistency of the analysis, the authors adopted the 2017–2019 period for the study. Therefore, based on data for this short period, it is impossible to make conclusions about long-term trends in the countries studied. Since

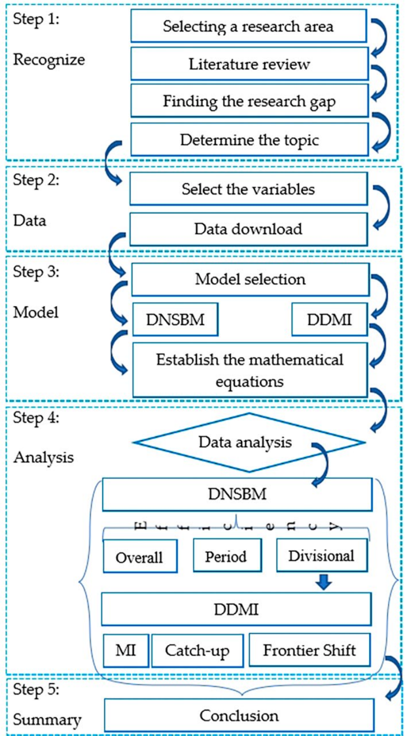


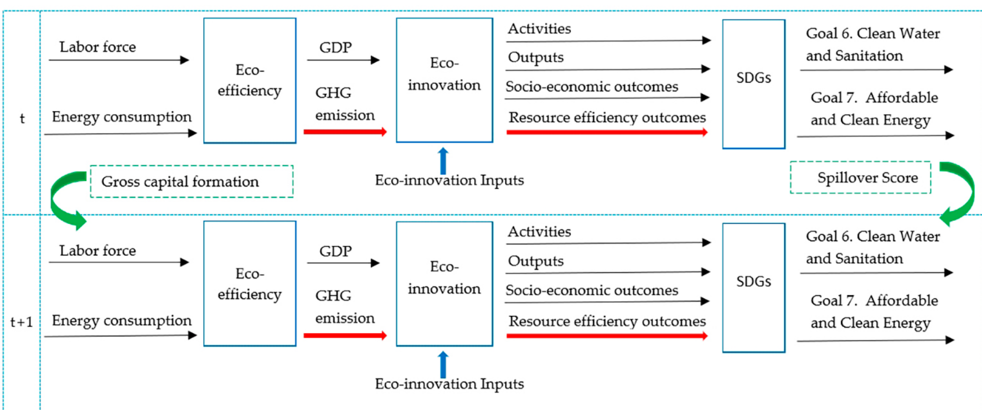
Figure 1. Research procedure

the data for two aspects of the study, i.e., eco-innovation and SDGs, were indicators, the authors decided that for the third issue (eco-efficiency), the data should also be expressed as indicators. In this way, a uniform research approach was achieved, which in turn will enable the application of appropriate assumptions in DEA models. It was also at this stage that the countries were selected for the research. The inclusion in the sample was determined by the availability of data and the adopted aim of the research. Consequently, the authors finally selected 27 countries of the European Union for the research sample. The choice of the 27 countries that currently make up the European Union and the omission of other OECD countries was dictated by the following factors. The present research was intended to allow an assessment of whether the current members of the EU, are advanced in the implementation of the Sustainable Development Goals. Following the announcement of the European Green Deal strategy in December 2019, member states were required to implement it. Therefore, it was decided to make an indirect assessment of the preparedness of the EU countries for the grouping's ambitious plans for the European Green Deal goals.

In the third stage ("Model"), based on the nature of the subject and the identification of gaps and suggestions for further research presented in previous analyses, the authors created their research concept (Figure 2). It was assumed that the system covered by the study would be sequential and would include a succession of stages, the first dealing with eco-efficiency, the second with eco-innovation, and the last with SDGs. It is worth noting that the sequential approach was most widely used in the literature. The authors assumed that the goal of each country, in the first place, is to achieve the highest level of GDP from its resources while at the same time the lowest value of greenhouse gas (GHG) emissions. Then, the mechanisms related to eco-innovation are implemented to reduce the negative effects on the environment, society, and, consequently, the economic system. As a result, it is possible to obtain the highest measures of SDGs. Subsequently, it was assumed that the individual stages of the research are connected in terms of both benefits (expected values) and negative effects (undesirable values, which are side effects of human activity). The authors also concluded that the complexity of the processes of the three elements adopted for the study and the interrelationship among many sectors required the evaluation of the entire system and its individual stages over a longer period. It will allow them to capture changes that may occur unevenly at each stage and period, thus affecting the entire system.

In order to conduct the research according to the original concept, the authors chose the DEA model: Dynamic Network SBM – DNSBM (Tone & Tsutsui, 2014), as it was best suited to the study.

The Data Envelopment Analysis (DEA) method, presented in 1978 (Charnes et al., 1978), was created to measure the efficiency of decision-making units (DMU) while considering many inputs and outputs. The obtained efficiency measures fall within the range (0.1), where the value of 1 means a 100% efficient unit. Initially, the DEA method had many shortcomings (deviating from real economic situations), which have been removed over the years by adopting additional assumptions and implementing new research concepts within the DEA methodology. The first two DEA models, i.e., CCR (Charnes et al., 1978) and BCC (Banker et al., 1984) with constants (CRS) and variable returns to scale (VRS), were based on radial efficiency. It assumes, depending on the orientation of the model, either a proportional reduction of all inputs (orientation to inputs) or a proportional increase of all outputs (orientation to outputs). Due to the imperfections of radial efficiency, Färe and Lovell (1978) presented non-radial efficiency (also called Russell efficiency), in which individual inputs



Note: red line – undesirable (bad) outputs; blue line – input for one stage, green line – carry-over link between periods.

Figure 2. Scheme of the adopted empirical model

or outputs are assumed to have varied effects on the level of efficiency. Consequently, Tone (2001) proposed a new DEA model, referred to in the literature as SBM (Slack Based Measure), based on the non-radial efficiency and the slack that arises during the optimization of the objective function. It is worth noting that the non-radial SBM model and the radial CCR and BCC models belong to the canon of the main DEA models based on which subsequent modifications and additions are created.

Classic DEA models assume that all outputs are desired. However, in economic practice, the above assumption is not always correct, especially in areas such as industrial production or power generation, where negative by-products (effects) are created that affect, among others, the environment. In response to this problem, Färe et al. (1989) developed a non-linear DEA program with desirable and undesirable outputs. In the presented model, the desired outputs are increased, and the undesirable outputs are decreased. The idea proposed by Färe et al. (1989) has been successfully implemented in the SBM model, which in the literature is called SBM with Undesirable Outputs (Cooper et al., 2007).

Initially, the DEA method could not measure the efficiency of economic actors taking into account their complex and networked production structure. The situation changed when Färe and Grosskopf (2000) presented Network DEA, which made it possible to include production steps (sub-processes) in different production structure (Koronakos, 2019). According to Kao's (2014) review of the literature on Network DEA models, it can be seen that there are many variations. However, the most popular, general form of the Network DEA model is the sequential production process consisting of consecutive stages linked together by intermediate variables (links). These intermediate variables are both the output of the previous production stage and the input of the next stage. Depending on the nomenclature adopted by the Network DEA model, smaller units within a given DMU are called sub-units, also known as stages, divisions, sub-DMUs, subsystems, sub-processes (Koronakos, 2019). The main advantage of Network DEA models is to model the processes inside the unit that affect the overall efficiency. Therefore, it allows measuring the efficiency of individual production stages and the overall efficiency of the DMU.

Färe and Grosskopf (1996) also presented a dynamic DEA methodology that allows the performance of a DMU entity to be measured over more than one period. Undoubtedly, it is particularly useful in the case of complex and, therefore, long-term projects or undertakings, which the classic DEA models cannot capture because they measure efficiency in only one period (i.e., they have a static and not dynamic character). Whereas the connections between periods are established through inter-period variables, also known as carry-overs. Dynamic DEA models can be used to measure not only overall efficiency over the entire study period but also over particular periods. A review by Mariz et al. (2018) shows that dynamic modeling in DEA contemplates different configurations and structures. The most used structure is the type of the series structure.

It is worth noting that Färe and Grosskopf (1996) indicate a close relationship between dynamic models and network DEA models. The dependence mentioned above prompted Tone and Tsutsui (2014) combined their previously proposed models, i.e., Network SBM (Tone & Tsutsui, 2009) with Dynamic SBM (Tone & Tsutsui, 2010), into a single structure, calling the new model Dynamic Network SBM (DNSBM). Mariz et al. (2018), based on the works of Tone and Tsutsui (2010, 2014), indicate that many dynamic models do not distinguish between the types of carry-overs between periods. Only some authors allow the desirable and undesirable elements in the model structure. In the Tone and Tsutsui models (2010, 2014), the authors presented four types of links between divisions (Tone & Tsutsui, 2014). However, only two of them were used for the empirical study in the following part of the article:

- "as-input" link value – linking activities are treated as input to the succeeding division, and excesses are accounted for in the input inefficiency. Otherwise, they can be called a "bad (undesirable) link",
- "as-output" link value case – linking activities are treated as output from the preceding division, and shortages are accounted for in the output inefficiency. Otherwise, they can be called a "good (desirable) link",

as well as one type of carry-over between periods (Tone & Tsutsui, 2014):

- desirable (good) carry-over case (e.g., profit carried forward and net earned surplus carried to the next period). In the model, desirable carry-overs are treated as outputs, and their values are restricted to be not less than the observed ones.

Due to the above types of links and carry-overs, it is important to emphasize that the Tone and Tsutsui models (2010, 2014) have far greater ability to model the production structure, and thus broade analytical capabilities than the other Network and Dynamic DEA models.

The adopted research concept clearly shows that the analysis aims to maximize the outputs of eco-efficiency, eco-innovation, and SDGs (including the assumption of undesirable outputs) rather than minimize resources. Therefore, the DEA model is oriented towards outputs. Given that indicator data – with slight variation between countries - was used to examine eco-efficiency, eco-innovation, and SDGs, the authors decided to apply constants returns to scale in the DNSBM model. The literature indicates that "if the data set consists of normalized numbers, e.g., per capita, the CRS model might be an appropriate candidate" (Cooper et al., 2007, p. 344). It is worth noting that the CRS models have an advantage over the VRS models, as feasible solutions are not missing therein, as is the case of the latter, particularly while calculating the Malmquist index (Cooper et al., 2007).

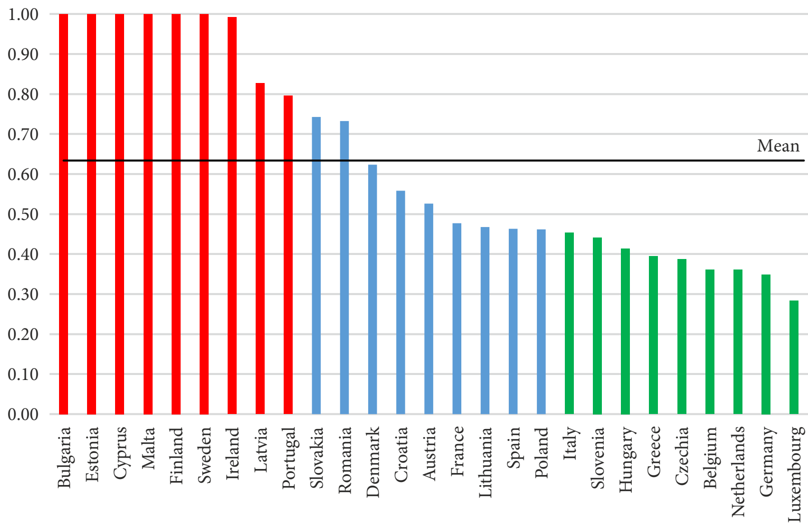
The DNSBM model above can measure efficiency in three sections (Tone & Tsutsui, 2017), i.e., estimate: (1) overall efficiency in the entire observed period, (2) efficiency in particular periods, (3) efficiency in individual division (stage). The overall performance is measured based on the main program of DNSBM, along with three groups of conditions in terms of inputs/outputs (1), "link" between divisions (2), and "carry-overs" between periods (3). Although the purpose of the research is a combined measurement of three thematic areas, it was decided to prioritize the issues in the main program DNSBM using division and period weights. Since recent literature emphasizes the importance of SDGs as a necessary direction of development, it was assigned the highest weight in the main program DNSBM. Achieving the SDGs targets should not reduce the economic development of countries. Therefore, medium weight was assigned to eco-efficiency and the lowest one to eco-innovation. Changes in the previous two issues (SDGs and eco-efficiency) can occur through eco-innovation and structural changes. A similar approach was adopted when determining the weights for each year. It was assumed that the most recent data is the most important. Therefore, the highest weight was assigned for 2019 and the lowest for 2017.

However, as Tone and Tsutsui explicitly states (2017, p. 82): "The period-divisional efficiencies in the dynamic network DEA model are measured relatively based on the frontier in each period for each division, and do not take the frontier shift during the study periods into account. Therefore, even if the period divisional efficiency of division k of DMU increases period by period, the absolute productivity of the DMU may not increase because of regress of the frontier for division k. In order to capture the absolute productivity change of DMUs in the dynamic network DEA model, we can use the Malmquist index". Färe et al. (1994) first presented the Malmquist productivity index (MI) using the radial DEA model to measure changes in productivity between two periods. Färe et al. (1994) also decomposed MI into two elements: efficiency change (EC) or "catch-up" effect and technical change (TC) or "frontier shift" effect. Then Tone (2004) presented a non-radial Malmquist index based on the SBM model. Tone and Tsutsui (2017), based on period-divisional efficiency in DNSBM and assumptions non-radial Malmquist index (Tone, 2004), proposed the Dynamic Divisional Malmquist Index (DDMI). However, DDMI can be decomposed into two elements: the Dynamic Divisional Catch-up Index (DDCU) and the Dynamic Divisional Frontier Shift Effect (DDFS). The boundary value for DDMI, DDCU, and DDFS is one. If the value is less than, equal to, or greater than this value, there is a regress, no change (status quo), and progress, respectively. The presented research scheme shows that DNSBM was used to estimate the efficiency in various cross-sections, and the DDMI was used to explain the productivity changes in divisions. In order to maintain research consistency, both approaches (DNSBM and DDMI) used constants returns to scale and orientation towards outputs.

3. Results

The average value of the overall efficiency for the 27 EU countries was only 0.63. It is worth noting that six countries achieved total efficiency (1.00), and eleven had a value above the EU average. In order to group the countries, it was decided to use the convention of dividing them int three groups used to assess eco-innovation in the EU (Sustainable Development Solutions Network [SDSN], 2021). The leading countries are ranked from 1st to 9th. The 10th to 18th places belong to the group of countries with average results. In contrast, places from 19th to 27th belong to the group of catching-up countries. Figure 3 presents the ranking of countries and their division into three groups in terms of overall efficiency.

Based on the ranking, it is impossible to observe the spatial variation of the efficiency indicators in different European regions, so it was decided to present the overall efficiency results in Figure 4 spatially. Efforts were made to check whether the location of a given country in a particular region of Europe or the proximity of other specific countries may affect the results of individual countries. Based on the map, two phenomena were observed. Firstly, the countries in the northern part of Europe immediately bordering each other (including two Scandinavian countries) achieved the highest and high-efficiency scores. A similar phenomenon was recorded among the following countries: Slovakia, Romania, and Bulgaria, but with much less intensity. Secondly, the countries with the highest efficiency indicators were mainly located in the periphery of Europe (e.g., Sweden, Finland, Estonia, Bulgaria, Cyprus, Malta, Ireland, and Portugal), not in its central part.



Note: Detailed results for each country are presented in Table A4 in the Appendix.

Figure 3. Ranking of overall efficiency

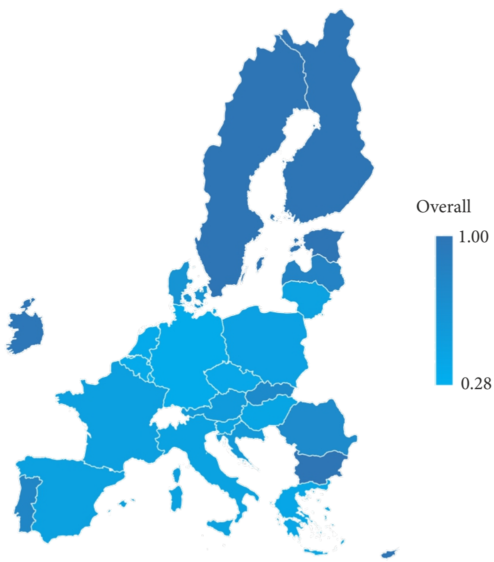


Figure 4. Geographical distribution of overall efficiency

The performance of some countries may have been influenced by historical aspects (e.g., the geopolitical situation after World War II, including membership in the so-called "Eastern Bloc"), the effects of which are still noticeable despite joining the European Union. It was decided to divide the member states into two groups regarding the period of integration with the EU to address these doubts. The new group included those countries that joined the EU after 2004 (including post-communist ones), and the old group included the remaining ones.

For the sake of comparison between the groups, the results for the EU as a whole are also presented. Figure 5 presents the overall and period efficiency by country group.

The division of countries into two groups revealed slight differences in overall efficiency, reaching 11 percentage points. Slightly higher differences between the groups of countries were observed in terms of period efficiency (2017: 15 p.p., 2018: 14 p.p., 2019: 9 p.p.). On the other hand, the average values of period efficiency for the entire EU in the analyzed period were above 0.60. However, it should be remembered that the overall and periodic efficiency result is influenced by individual aspects of the studied system (eco-efficiency, eco-innovation, and SDGs), which may be different in individual countries. Therefore, Figure 6 presents the average values of the efficiency of individual division.

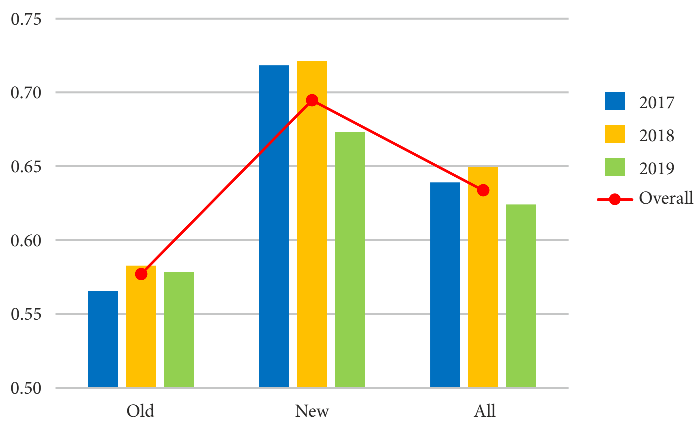


Figure 5. Overall and period efficiency by old, new, and all EU members

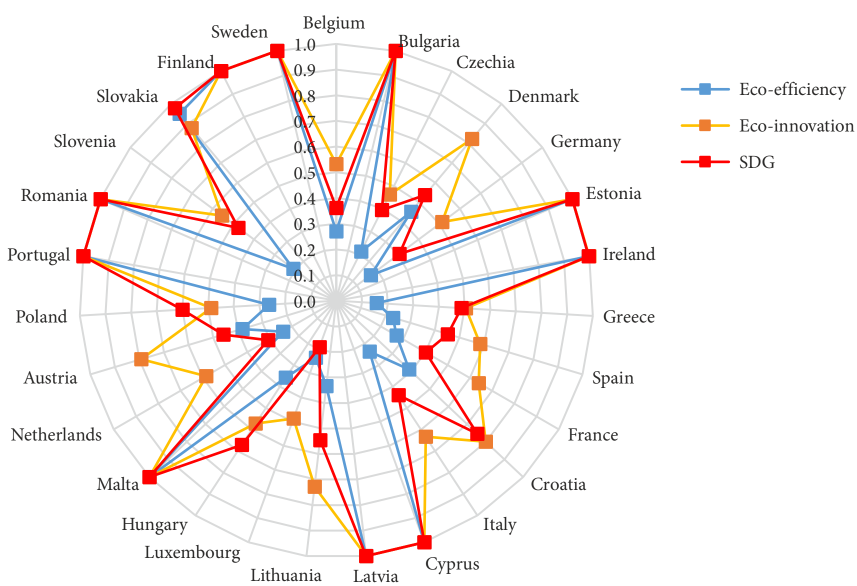


Figure 6. Average divisional efficiency in EU countries

Graphical analysis has shown that some countries focus almost equally on three aspects of the system, achieving similar efficiency values. On the other hand, the other part of the countries focuses on a selected area (chooses the most important task of their country's development policy), obtaining much higher efficiency measures in one or two issues than in the remaining ones. The countries that obtained the highest and high overall efficiency measures were usually highly ranked in three divisions of the analyzed system (divisional efficiency). It is worth noting that countries that did not focus equally on the three aspects of the system, by far more often obtained higher measures in terms of eco-innovation and SDGs (or one or both of them at the same time) than eco-efficiency.

Regarding the above observations, it was decided to check whether the differences mentioned above are also between the two groups of EU countries (Figure 7). Previous observations confirmed that regardless of the group of countries studied, eco-efficiency obtains a lower value than the other two issues. It was also observed that two groups of member countries approach eco-innovation and SDGs differently. The old group countries pay more attention to eco-innovation, achieving much higher efficiency measures than in the scope of SDGs. On the other hand, the group of new countries is almost as much oriented towards eco-innovation (0.81) as towards SDG (0.80).

The observed differences between the two groups of EU countries do not cover the analyzed topics entirely because it is also necessary to check how the efficiency of the studied phenomena has changed over the years, thus influencing the efficiency of individual divisions. The efficiency of individual aspects of the entire system changed in the subsequent years (Figure 9). The smallest variation of the efficiency indicators in the following years was observed in eco-efficiency and SDGs. However, in the case of the first issue, there were abrupt, alternating changes with a small amplitude of fluctuations. On the other hand, the change in the efficiency of SDGs was slightly increasing in subsequent years. The largest disproportions of efficiency indicators between particular years were observed in the field of eco-innovation. The obtained results may prove that the most dynamic and, at the same time, the fastest changes may occur first in activities related to eco-innovation and then in activities aimed at achieving sustainable development goals.

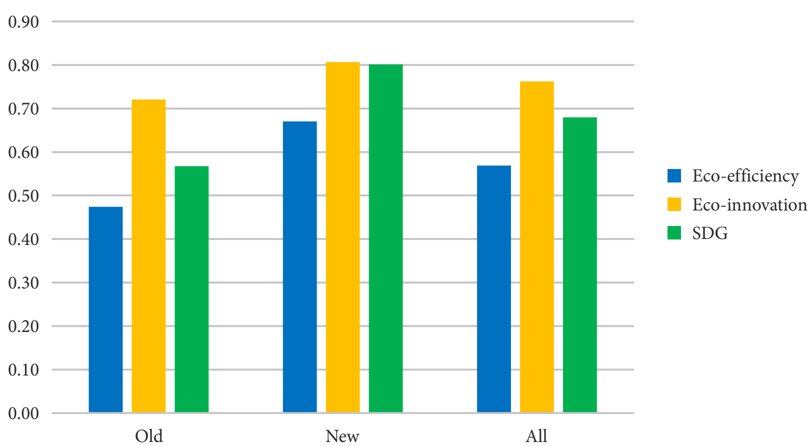
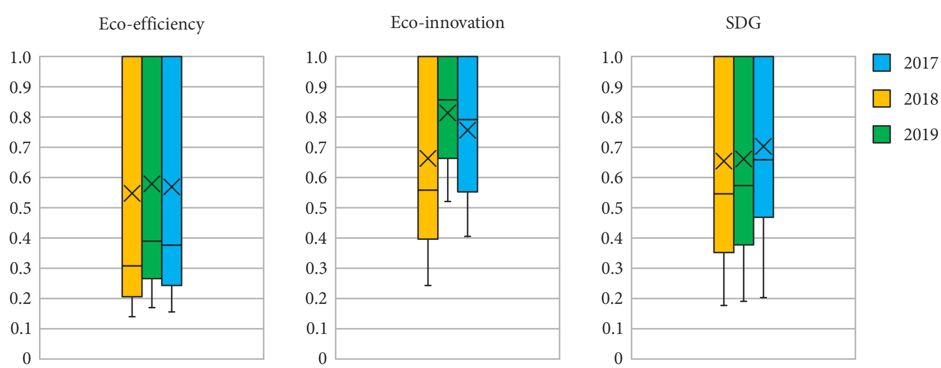


Figure 7. Mean divisional efficiency of eco-efficiency, eco-innovation, and SDGs, by old, new, and all EU members

Although Figure 8 shows changes in period-divisional efficiencies in the DNSBM in subsequent years, it is not known whether there has been a change in absolute productivity. Therefore, Figure 9 presents the results of the DDMI, DDCU, and DDFS calculations. For all EU countries, higher productivity growth in the period 2018–2019 than 2017–2018 was observed for eco-efficiency and SDGs, and the opposite was true for eco-innovation. Differences in productivity changes also occurred between old and new EU countries. However, these are dependent on the study period and the issue in question. Although there was an increase in eco-efficiency productivity for both groups, the new group of countries achieved a higher rate in 2018–2019 than in 2017–2018. Interestingly, in the case of the old group, the result was the same in both periods.

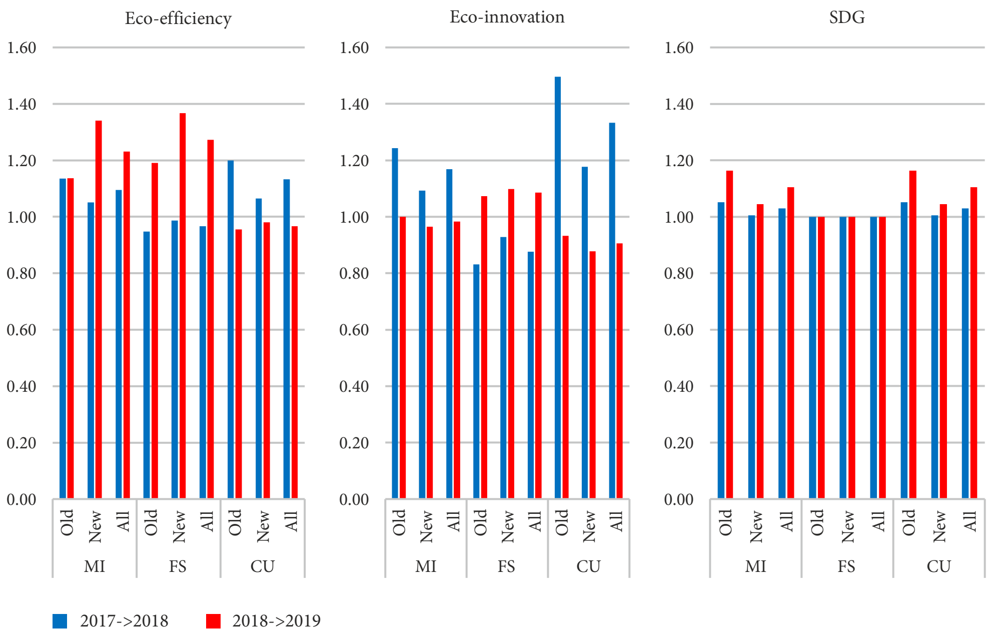
In the first period (2017–2018), there was an increase in productivity in both groups of countries. However, in the second period (2018–2019), a slight decrease of the indicator was observed for the new countries, and the situation remained unchanged for the old countries. On the other hand, in terms of SDGs, as in the case of eco-efficiency, there was an increase in productivity in both groups of countries in both periods. However, higher increases were recorded in the second (2018–2019) than in the first (2017–2018) period (Figure 9).

The catch-up and the frontier-shift effect had a diversified impact on the level of changes in productivity, depending on the research period. The increase in eco-efficiency productivity in 2017–2018 was driven by the catch-up effect increase and the 2018–2019 frontier-shift effect. The opposite situation occurred concerning changes in eco-innovation productivity. A significantly larger increase in the catch-up effect over the 2017–2018 period than a decrease in the frontier-shift effect over the same period resulted in increased productivity for all EU countries. On the other hand, the decrease in the catch-up effect in 2018–2019 was not mitigated significantly by the increase in the frontier-shift effect. Ultimately, a slight decrease in eco-innovation productivity was observed. Interesting results were obtained for the productivity growth of SDGs because for both groups of countries, in two study periods, this increase was not influenced by the frontier-shift effect but only by the catch-up effect.



Note: X – mean.

Figure 8. Boxplot divisional efficiency by the year



Note: MI – Malmquist index, FS – Frontier-shift effect, CU – Catch-up effect. Detailed results for each country are presented in Table A5 in the Appendix.

Figure 9. Dynamic divisional Malmquist index, Frontier-shift and Catch-up effect, by old, new and all EU members

4. Discussion

The obtained research results on the overall efficiency of the European Union member states indicate a relatively low level of the overall efficiency of all member states. However, it can be seen that nine countries are leaders who have achieved full and very high efficiency. It was distinctive that all the countries with such high overall efficiency scores were located at the continental margins. At the same time, it can be noticed that the leading countries in terms of overall efficiency were located in close proximity. It can be observed in the case of countries in northern Europe and some Central and Eastern European countries. The authors asked themselves what could be the reason for this?

High results of the overall efficiency of countries located on the outer edges of the continent and being neighbors, including those in the northern part (Sweden, Finland, Estonia, Latvia) but also Ireland and some southern and central countries (Bulgaria, Slovakia, Romania, Cyprus, Malta, Portugal), may result from such a location (limited neighborhood). Countries located in the central part of the continent have a more complicated geographical situation, as their decisions resulting from national policies to increase overall efficiency may negatively affect neighboring countries. According to the authors, the differences in overall efficiency between the countries of Northern Europe and the other EU member states may be due to the earlier preparation of the economy for environmental challenges by the Scandinavian countries (using renewable energy sources for a long time and reducing GHG emissions). Many countries of the Community have taken action in accordance with the Agenda 2030 after the UN introduced the guidelines for sustainable development. On this basis, the European Union has prepared the principles of the Green Deal policy. It now sets the direction for the transformation of the economy and society in member countries until 2050. Thus, they are even less advanced in achieving high overall efficiency measures.

The research also revealed disparities in the overall and periodic efficiency between the old EU countries and its new members (admitted after May 1, 2004). The results confirmed the first hypothesis that the new Member States obtain relatively higher efficiency measures than the previously integrated ones. In the entire research period, the differences were not significant, as they reached 11 percentage points. However, in the case of periodic analyses, the differences increased and amounted to 14–15 percentage points.

The authors also wanted to verify the second hypothesis: the countries belonging to the new EU member states compared to the old EU countries achieve higher scores in eco-innovation and the implementation of SDGs than eco-efficiency. This hypothesis was positively verified. Naturally, this required determining the size of the efficiency achieved by individual countries in the three areas and then arranging these data into two groups of Member States. The research shows that countries with the highest and high overall efficiency scores most often also obtained high results in individual partial areas of efficiency (eco-efficiency, eco-innovation, and SDGs). The results indicate that some community countries strongly focus on all aspects of the system and that each of these areas has been adopted as an important area of government policy. Probably each of these areas is considered an essential element of development policy. It is consistent with the assumptions of the 2030 Agenda, the provisions of the European Green Deal, but also with the economic possibilities of a given country (GDP level, current use of renewable energy resources, economic policy priorities, innovative potential). Sweden is an example of such a country. As indicated by Somolska-Rzechuła and Kuryś-Kujawska (2021, p. 13), "This is due to the fact that this country has adopted ambitious and stable environmental policies that are characterized by broad social and political acceptance, long-term horizons and a fairly high degree of environmental integration or environmental policy in other policy areas".

However, other countries choose a specific strategy while striving to achieve the highest possible economic growth rate and to respect the requirements established within the group to reduce the pressure on the environment (e.g., reducing GHG) or other SDGs. Such a conclusion was also reached by Cheba and Bąk (2021), although their research covered a slightly different scope and used a different methodology. The pursuit of trade-offs characterizes the actions of the authorities of such countries. Implementing non-environmental goals (e.g., social ones) sometimes forces a slowdown in efforts to reduce pressure on the environment, resulting in smaller eco-efficiency measures and overall efficiency. The authors confirm these findings. They found that the EU member states that did not focus equally on all efficiency areas were more likely to achieve higher eco-innovation measures and SDGs (sometimes in both areas simultaneously or in either area) with lower levels of eco-efficiency. At the same time, the authors noticed that the new member states were more focused on achieving higher eco-innovation measures and SDGs than the old ones. Thus, this indicates their choice of specific economic policy priorities.

The above results can also be justified by the efforts of the new EU countries to eliminate the distance from highly developed countries (belonging to the old group) in various aspects, e.g., institutional, the size of GDP per capita, consumption structure (Jankiewicz & Pietrzak, 2020) and catch up in terms of pro-environmental technologies and products (catch-up effect). Therefore, they make short-term and medium-term changes in the field of infrastructure, which increases eco-innovation. The need for their introduction stems not only from the need to respect the EU Green Deal policy. They also constitute an opportunity to improve the competitiveness of the economy and its entities. The old countries of the Community are less forced to change in terms of pro-environmental infrastructure, so they focus on changes in the area of society (as part of the implementation of SDGs). They focus, for example, on issues such as human and social capital, equal opportunities, reducing discrimination, promoting healthy living and prosperity. Such attitudes are associated with long-term activities, which also applies to the emergence of effects in reducing the environmental pressure (eco-efficiency). From the point of view of the new countries, such a policy does not bring about as visible results in the short and medium-term as investments in innovative products and technologies (eco-innovation).

Although according to Kemp et al. (2019), eco-innovation affects at least nine SDGs, only two related ones (SDGs 6 and 7) were incorporated in this study. The authors share the view presented by Allen et al. (2018, 2019) that the implementation of a larger number of SDGs or a systemic approach to their implementation causes the problem of establishing compromises between them because their implementation depends, among other things, on the priorities of the implemented policy (their urgency), the impact on the entire system of a given country, or the political will (as it is at a given moment). Therefore, countries that are inefficient in SDGs 6 and 7 may be more efficient in other goals, which they have deemed more important.

The results of the authors' research also allow for the formulation of specific recommendations for the Community's policy in the field of the European Green Deal and the implementation of the provisions of the UN resolution on sustainable development in the coming years. The results revealed significant disparities in the effectiveness and directions of their implementation. They suggest that, for various reasons, individual countries belonging to the group of the old or the new member states are implementing the requirements formulated by the EU at a different pace and to a different extent. As a result, there are countries in the European Union that are "at different speeds" in their efforts to achieve the climate neutrality of their economies and meet the requirements of the sustainable system in many respects (social, economic, and ecological ones). There is a situation in which some countries (previously advanced in the processes of reducing pressure on the natural environment and aiming to ensure broadly understood welfare to citizens) have followed this path regardless of the European Union's policy. At the same time, some countries cannot meet high requirements in meeting climate goals and SDGs within the Community. They choose from those they can achieve relatively quickly, allowing the countries to achieve a satisfactory economic growth rate. The authors recognize that some countries show poor responsiveness to changes in the overall EU policy, which influences the formation of necessary actions and policies at the member state level. As it stands, these are supposed to be of unified nature, although the results of this research and the work of other authors indicate that it is impossible to achieve the same results by all EU members. This problem has intensified recently with the impact of the COVID-19 pandemic and the emergence of health, social and economic problems that are difficult to solve by EU governments. Therefore, the authors recommend introducing a more diversified, flexible policy to implement the European Green Deal and SDGs. It should be adjusted to the socio-economic situation of a given country, the rate of economic growth, the state of development of the country, and its production potential.

The authors' research and the results of other studies show that the use of a comprehensive, interactive tool for monitoring different but interrelated thematic areas (e.g., eco-innovation, eco-efficiency, SDGs) allows conducting more complex and multi-faceted analyzes. They also allow to identify cause-effect relationships, to indicate the causes and effects of the impact of specific phenomena on individual elements of a complex system. They reveal a more detailed picture of economic phenomena that are becoming increasingly complex and multi-threaded. The results of such complex research shall enable the creation and implementation of appropriate policies (e.g. for sustainable development). As pointed out by Allen et al. (2018, 2019), to effectively implement the relevant policies in a given area, proper monitoring is necessary, which in turn benefits the implementation and functioning of evaluation both in individual countries and at the community level.

Conclusions

The above research aimed to establish how the EU and its member states effectively achieve selected declared objectives. The prepared study presents an innovative research approach to the issues mentioned above and fills the current research gap.

In this study, a complex analysis of the efficiency of the entire system consisting of eco-efficiency, eco-innovation, and SGDs of each EU member state was performed. The results revealed a relatively low level of the overall efficiency of the entire European Union and significant differences between individual countries. There were also differences in selecting priorities for implementation (in response to the commitments resulting from the 2030 Agenda and the European Green Deal) regarding the old and the new member states. The research allowed the authors to confirm both hypotheses put forward in the paper and explain the obtained results.

The main limitation of the efficiency measurement of the DNSBM model or other DEA models is that only past analysis is conducted based on historical data. Therefore, in the future, the use technology forecasting with data envelopment analysis (TFDEA) needs to be considered to forecast the system performance in the discussed subject in the future, not only in the past periods. Also noteworthy is the research approach that considers various scenarios of undertaken activities that may affect efficiency. In order to implement this assumption, the Nested Dynamic Network SBM (NDNSBM) model (Chang et al., 2021) can be used. Assessing the efficiency in different scenarios seems particularly useful in terms of individual countries and the whole Community. Another interesting issue to consider in the future may also be the analysis of the three areas indicated in this article in the broader context of the circular economy system using, for example, Circular Economy Indicators (European Commission, 2020), as well as the implementation of game theory within the DEA methodology (Ding et al., 2020). That would extend the existing research.

Although this study filled the established literature gap, it also has substantive limitations. Firstly, only Goal 6 and 7 were used to evaluate the SDGs. Therefore, it is proposed to extend the research to all SDGs in the future. Secondly, only a single data source was used to measure eco-innovation (European Commission, 2021). Therefore, other sources ought to be used in future research, for example, the Global Cleantech Innovation Index (Cleantech Group, 2017), ASEM Eco-innovation Index (ASEM SMEs Eco-innovation Center [ASEIC], 2018), or OECD Green Growth Indicators (2017). This approach will enable the analysis of the issues mentioned above from various perspectives. Thirdly, the study was conducted only on a group of 27 EU countries in the short term. Therefore, future research should investigate a longer period of analysis and include OECD countries.

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Author contributions

Conceptualization, I.Ł. and Ł.B.; methodology, Ł.B.; software, Ł.B.; validation, I.Ł. and Ł.B.; formal analysis, I.Ł. and Ł.B.; investigation, I.Ł. and Ł.B.; resources, I.Ł. and Ł.B.; data curation, I.Ł. and Ł.B.; writing – original draft preparation, I.Ł. and Ł.B.; writing – review and editing, I.Ł. and Ł.B.; visualization, Ł.B.; supervision, I.Ł.; project administration, I.Ł.; funding acquisition, I.Ł. Both authors have read and agreed to the published version of the manuscript.

Disclosure statement

The authors declare that they have any competing financial, professional, or personal interests from other parties.

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APPENDIX

Table A1. Summary of previous studies on analysis topic

Authors	Context	Methods	Variables
Guo et al. (2017)	Energy	DSBM	I: Land area, population, and energy use O: CO_2 emission and GDP C-O: energy stock
Kiani Mavi et al. (2019)	Eco-efficiency, eco-innovation	Two-stage DEA	I: Labor force, Energy consumption, Land area O: Researchers in R&D, High technology export, ISO 14001 certificates, Electricity production Intermediate I/O: GDP, GHG emission
Łozowicka (2020)	Sustainable Development	Super-SBM, Malmquist	I: Non-renewable energy consumption in gross final energy consumption, population that is not connected wastewater treatment systems, Level of 'non-afforestation, Unprotected area O: Biochemical oxygen demand, Balance of nutrients (phosphorus) in agricultural land, Index of clean energy, Mean population exposure to air pollutant PM2.5
Yang et al. (2021)	Environmental	Meta-Malmquist	I: Labor force, Energy consumption, Capital stock O: GDP, CO_2 emissions
Moutinho and Madaleno (2021a)	Eco-Efficiency	CCR, BCC, Regression	I: Gross fixed capital formation, Labor per capita, Energy use/area, Deviations temp O: GDP pc/(GHG/area)
Zhang et al. (2021)	Eco-efficiency, eco-technology innovation, eco-well-being performance	Two-stage Super-SBM	I: Land area, Energy use, Labor force O: High-tech exports, Scientific articles, Patent applications, Life expectancy, Mean years of schooling, Income index Inter. I/O: GDP, CO_2 emissions, PM2.5 emissions
Li et al. (2021)	Technology innovation, Eco-environment	Two-stage DEA	I: R&D full-time equivalent, R&D expenditure, New fixed assets, Labor, Energy consumption, Capital stock O: CO_2 emission, Sulphur dioxide, Total water discharged, Common industrial solid wastes produced, GDP Inter. I/O: Number of patent application authorizations, Trading volume of the technology market, Number of new product development items
Grochová and Litzman (2021)	Sustainable Development	BCC	I: selected variable SGD (3,5,6,11) O: selected variable SDG (1,3,7,8,9,12,15, 17)

Notes: I: input, O: outputs, C-O: carry-over links, Inter. I/O: Intermediate inputs/outputs.

Table A2. Variables adopted in the study, used in the literature

Variable	Reference
Labor force	Kiani Mavi et al. (2019), Yang et al. (2021), Moutinho and Madaleno (2021a), Zhang et al. (2021), Li et al. (2021)
Energy consumption	Guo et al. (2017), Kiani Mavi et al. (2019), Łozowicka (2020), Yang et al. (2021), Li et al. (2021)
Indicators of Eco-innovation	Park et al. (2017), Kiani Mavi and Kiani Mavi (2021)
SDG	Grochová and Litzman (2021), Miola and Schiltz (2019), Sompolska-Rzechula and Kurdyś-Kujawska (2021), Cheba and Bąk (2021)
GDP	Guo et al. (2017), Kiani Mavi et al. (2019), Yang et al. (2021), Moutinho and Madaleno (2021a), Zhang et al. (2021), Li et al. (2021)
GHG emission	Guo et al. (2017), Kiani Mavi et al. (2019), Yang et al. (2021), Zhang et al. (2021), Li et al. (2021)
Gross capital formation	Yang et al. (2021), Moutinho and Madaleno (2021a)

Table A3. Variables adopted for the empirical study

Variable name	Description	Variable type		Stage / Period	Source
Labor force	Total employment of total population (%)	I	X_1	1	(Eurostat, 2021)
Energy consumption	Final energy consumption is the total energy consumed by end-users, such as households, industry, and agriculture. It is the energy that reaches the final consumer's door. It excludes the energy used by the energy sector itself. Final energy consumption per capita	I	X_2	1	(Eurostat, 2021)
Eco-innovation input	The indicators include: Governments environmental and energy R&D appropriations and outlays, Total R&D personnel and researchers, Total value of green early-stage investments	I	X_3	2	(EC, 2021)
Goal 6 SDG	Ensure availability and sustainable management of water and sanitation for all	O	Y_1	3	(SDSN, 2021)
Goal 7 SDG	Ensure access to affordable, reliable, sustainable, and modern energy for all	O	Y_2	3	(SDSN, 2021)
GDP	Gross domestic product (GDP) per head, current prices, current PPPs	LG	L_1	1 => 2	(OECD, 2021)/ (Eurostat, 2021)
GHG emission	Greenhouse gas emissions: the indicator measures total national emissions including international aviation of the so-called 'Kyoto basket' of greenhouse gases, including CO_2, CH_4, N_2O, and others GHG per capita	LB	L_2	1 => 2	(Eurostat, 2021)

End of Table A3

Variable name	Description	Variable type		Stage / Period	Source
Activities Eco-innovation (E-I)	The indicators include: Implementation of sustainable products and resource efficiency actions among SMEs, Number of ISO 14001 certificates	LG	L_3	2 => 3	(EC, 2021)
Outputs (E-I)	The indicators include: E-I related patents, E-I related academic publications, E-I related media coverage	LG	L_4	2 => 3	(EC, 2021)
Socio-economic outcomes (E-I)	The indicators include: Exports of products from eco-industries, Employment, and Added Value in environmental protection and resource management activities	LG	L_5	2 => 3	(EC, 2021)
Resource efficiency outcomes (E-I)	The indicators include: Material, Water and Energy productivity, and GHG emissions intensity	LB	L_6	2 => 3	(EC, 2021)
Gross capital formation	Gross capital formation (formerly gross domestic investment) consists of outlays on additions to the fixed assets of the economy plus net changes in the level of inventories. GCF (% of GDP)/per person	C-O	C_1	t => t + 1	(World Bank [WB], 2021)/ (Eurostat, 2021)
Spillover Score SDGs	The Spillover Index assesses such spillovers along three dimensions: environmental & social impacts embodied into trade, economy & finance, and security. A higher score means that a country causes more positive and fewer negative spillover effects	C-O	C_2	t => t + 1	(SDSN, 2021)

Note: Variable type: I: input, O: outputs, LG: link good, LB: link bad, C-O: carry-over links (good). Stage (1, 2, 3) / Period (t, t + 1).

Table A4. Overall, term and divisional efficiency for each country (Model DNSBM)

		Overall	Term Efficiency			Divisional Efficiency											
						Eco-efficiency				Eco-innovation				SDG			
No.	DMU	Score	2017	2018	2019	2017	2018	2019	Mean	2017	2018	2019	Mean	2017	2018	2019	Mean
1	Belgium	0.36	0.33	0.35	0.38	0.23	0.30	0.26	0.27	0.41	0.60	0.53	0.53	0.29	0.30	0.43	0.36
2	Bulgaria	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
3	Czechia	0.39	0.39	0.39	0.38	0.18	0.22	0.22	0.22	0.38	0.59	0.41	0.46	0.35	0.36	0.43	0.39
4	Denmark	0.62	0.57	0.59	0.67	0.31	0.45	0.50	0.45	0.59	0.85	0.88	0.82	0.42	0.43	0.65	0.54
5	Germany	0.35	0.33	0.35	0.36	0.14	0.18	0.17	0.17	0.25	0.52	0.60	0.51	0.24	0.28	0.35	0.31
6	Estonia	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
7	Ireland	0.99	1.00	1.00	0.98	1.00	1.00	0.99	1.00	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00
8	Greece	0.39	0.41	0.42	0.37	0.14	0.17	0.16	0.16	0.40	0.69	0.42	0.50	0.44	0.45	0.53	0.49
9	Spain	0.46	0.44	0.47	0.46	0.19	0.28	0.21	0.23	0.40	0.64	0.61	0.58	0.36	0.42	0.50	0.45
10	France	0.48	0.45	0.47	0.49	0.23	0.31	0.25	0.27	0.38	0.72	0.68	0.64	0.35	0.37	0.44	0.40
11	Croatia	0.56	0.61	0.63	0.50	0.49	0.49	0.29	0.39	0.56	0.93	0.79	0.80	0.79	0.76	0.74	0.75
12	Italy	0.45	0.45	0.48	0.44	0.22	0.28	0.21	0.24	0.40	0.71	0.66	0.63	0.39	0.43	0.47	0.44
13	Cyprus	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
14	Latvia	0.83	0.84	0.90	0.78	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
15	Lithuania	0.47	0.49	0.53	0.43	0.27	0.30	0.38	0.33	0.52	0.91	0.68	0.73	0.52	0.57	0.54	0.55
16	Luxembourg	0.28	0.27	0.28	0.29	0.19	0.19	0.28	0.24	0.30	0.56	0.50	0.49	0.17	0.19	0.20	0.19
17	Hungary	0.41	0.50	0.40	0.40	0.31	0.36	0.38	0.36	0.62	0.64	0.51	0.57	0.62	0.60	0.73	0.67
18	Malta	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
19	Netherlands	0.36	0.37	0.37	0.35	0.22	0.26	0.23	0.24	0.33	0.72	0.58	0.59	0.29	0.30	0.32	0.31
20	Austria	0.53	0.49	0.51	0.55	0.27	0.39	0.41	0.38	0.51	0.86	0.84	0.79	0.35	0.36	0.56	0.46
21	Poland	0.46	0.46	0.47	0.46	0.20	0.21	0.32	0.26	0.55	0.56	0.42	0.49	0.54	0.54	0.66	0.60
22	Portugal	0.80	0.81	0.86	0.75	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
23	Romania	0.73	0.75	0.79	0.69	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
24	Slovenia	0.44	0.44	0.46	0.43	0.19	0.26	0.18	0.21	0.38	0.69	0.53	0.56	0.44	0.44	0.51	0.48
25	Slovakia	0.74	0.85	0.80	0.68	1.00	0.97	0.92	0.95	0.96	0.91	0.83	0.88	1.00	1.00	0.96	0.98
26	Finland	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
27	Sweden	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	Mean	0.63	0.64	0.65	0.62	0.55	0.58	0.57	0.57	0.66	0.82	0.76	0.76	0.65	0.66	0.70	0.68

Table A5. Malmquist index, frontier-shift and catch-up effect scores by country (DDMI)

		Eco-efficiency						Eco-innovation						SDG					
		MI		FS		CU		MI		FS		CU		MI		FS		CU	
No.	DMU	7>8	8>9	7>8	8>9	7>8	8>9	7>8	8>9	7>8	8>9	7>8	8>9	7>8	8>9	7>8	8>9	7>8	8>9
1	Belgium	1.14	1.11	0.88	1.30	1.30	0.86	1.26	0.91	0.85	1.04	1.48	0.88	1.04	1.45	1.00	1.00	1.04	1.45
2	Bulgaria	1.00	1.42	1.00	1.42	1.00	1.00	1.01	1.01	1.01	1.01	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
3	Czechia	1.18	1.63	0.95	1.62	1.23	1.01	1.24	0.86	0.80	1.23	1.56	0.70	1.04	1.20	1.00	1.00	1.04	1.20
4	Denmark	1.27	1.25	0.88	1.13	1.44	1.11	1.22	1.06	0.84	1.03	1.44	1.03	1.03	1.49	1.00	1.00	1.03	1.49
5	Germany	1.20	1.34	0.93	1.45	1.29	0.92	1.35	1.11	0.64	0.96	2.10	1.15	1.14	1.25	1.00	1.00	1.14	1.25
6	Estonia	1.01	1.56	1.01	1.56	1.00	1.00	1.05	1.35	1.05	1.35	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
7	Ireland	1.02	1.15	1.02	1.15	1.00	0.99	1.17	1.04	1.16	1.04	1.01	1.00	1.00	1.00	1.00	1.00	1.00	1.00
8	Greece	1.15	0.96	0.94	1.04	1.23	0.93	1.18	0.86	0.68	1.43	1.74	0.60	1.02	1.17	1.00	1.00	1.02	1.17
9	Spain	1.19	0.99	0.83	1.29	1.44	0.77	1.25	1.01	0.78	1.05	1.60	0.95	1.15	1.20	1.00	1.00	1.15	1.20
10	France	1.23	0.93	0.92	1.16	1.34	0.80	1.36	1.01	0.72	1.07	1.88	0.95	1.07	1.17	1.00	1.00	1.07	1.17
11	Croatia	1.00	0.75	1.00	1.27	1.01	0.59	1.30	0.94	0.78	1.11	1.67	0.85	0.96	0.97	1.00	1.00	0.96	0.97
12	Italy	1.16	0.88	0.89	1.16	1.31	0.76	1.36	0.93	0.77	1.00	1.76	0.94	1.10	1.09	1.00	1.00	1.10	1.09
13	Cyprus	0.96	1.60	0.96	1.60	1.00	1.00	0.92	1.11	0.92	1.11	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
14	Latvia	1.01	1.28	1.01	1.28	1.00	1.00	0.97	1.05	0.97	1.05	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
15	Lithuania	1.12	1.70	1.01	1.36	1.11	1.25	1.29	0.91	0.74	1.22	1.74	0.75	1.09	0.94	1.00	1.00	1.09	0.94
16	Luxembourg	1.03	1.22	1.00	0.84	1.04	1.45	1.59	1.07	0.87	1.18	1.83	0.91	1.08	1.06	1.00	1.00	1.08	1.06
17	Hungary	1.15	1.32	1.00	1.25	1.15	1.05	0.70	0.94	0.67	1.18	1.04	0.79	0.97	1.22	1.00	1.00	0.97	1.22
18	Malta	1.02	1.01	1.02	1.01	1.00	1.00	1.51	0.83	1.51	0.83	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
19	Netherlands	1.14	1.33	0.98	1.47	1.16	0.90	1.46	0.87	0.67	1.09	2.20	0.80	1.06	1.04	1.00	1.00	1.06	1.04
20	Austria	1.26	1.26	0.89	1.18	1.43	1.06	1.32	1.06	0.79	1.07	1.67	0.99	1.05	1.55	1.00	1.00	1.05	1.55
21	Poland	1.03	2.12	0.96	1.43	1.07	1.48	1.07	0.89	1.04	1.20	1.03	0.74	1.00	1.20	1.00	1.00	1.00	1.20
22	Portugal	1.00	1.32	1.00	1.32	1.00	1.00	1.01	1.06	1.01	1.06	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
23	Romania	1.00	1.01	1.00	1.01	1.00	1.00	1.05	0.96	1.05	0.96	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
24	Slovenia	1.22	1.24	0.89	1.76	1.37	0.71	1.39	0.90	0.76	1.17	1.83	0.77	1.02	1.16	1.00	1.00	1.02	1.16
25	Slovakia	1.00	1.35	1.03	1.43	0.97	0.94	0.98	0.89	1.03	0.98	0.95	0.92	1.00	0.96	1.00	1.00	1.00	0.96
26	Finland	1.02	1.30	1.02	1.30	1.00	1.00	1.01	1.03	1.01	1.03	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
27	Sweden	1.13	1.05	1.13	1.05	1.00	1.00	1.02	1.02	1.02	1.02	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	G. m.	1.09	1.23	0.97	1.27	1.13	0.97	1.17	0.98	0.88	1.09	1.33	0.91	1.03	1.10	1.00	1.00	1.03	1.10

Note: MI – Malmquist Index; FS – Frontier-shift effect; CU – Catch-up effect; G. m. – Geometric mean; 7 > 8 – 2017–>2018; 8 > 9 – 2018–>2019.