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# Circular economy practices as a tool for sustainable development in the context of renewable energy: What are the opportunities for the EU?

**JEL Classification:** *Q50; Q29; F63*

**Keywords:** *circular economy; sustainable development; renewable energy*

**Abstract**

**Research background:** In order to tackle climate change and ensure Paris agreements are met, countries are forced to look for alternative ways of producing, consuming, and wasting and adopt a circular economy. Reduction of greenhouse gas emissions becomes one of the key elements. The demand for electricity is increasing, and most greenhouse gas emissions derive from the energy sector. Because of that, it is crucial to ensure the transition from fossil fuels to renewable energy. Renewable energy, as a part of the circular economy, also contributes to sustainable development. Only the efficient implementation of circular economy and renewable energy practices can ensure that sustainable development goals are achieved.

**Purpose of the article:** The study aims at determining the efficiency of European Union countries implementing circular economy practices through renewable energy to attain SDGs. The study focuses on the significance of renewable energy as a tool for the circular economy to achieve sustainable development and highlights the progress achieved in SDG through renewable energy in the EU.
**Methods:** For efficiency assessment of the circular economy represented by the renewable energy indicators, data envelopment analysis (DEA) was performed.
**Findings & value added:** This study presents a relation analysis of the circular economy and renewable energy and the importance of efficiency in achieving SDGs through a circular economy. The study helps to understand the circular economy represented by renewable energy and how it transforms into sustainable development and contributes to necessary actions needed for countries to improve. Based on the results, Sweden, Luxembourg, Ireland, Latvia, Estonia, Malta, the Netherlands and Bulgaria are considered the most efficient countries, while Austria is the least efficient. Unused solar and wind power potential can slow down sustainable development; however, EU programs and renewable energy strategies help countries move towards clean energy and ensure efficient implementation of sustainable development goals.

## Introduction

Nowadays, rapid climate change is becoming one of the hottest topics in most countries of the world. Most countries face degradation of the environment, a scarcity of natural resources, and even the unavailability of clean water. The continuous increase in greenhouse gas emissions is causing new challenges. According to (Güney, 2019; Østergaard *et al*., 2022) United Nations Environment Programme (2022), greenhouse gas emissions are growing each year, and most of the emissions are from the energy, industry and transport sectors since 1990. In 2020, more than one-third of emissions were generated from the energy sector. Reacting to these challenges, countries are switching from linear to alternative, low-carbon circular economies powered by renewable energy.

As stated by Mihai and Minea (2021), unsustainable mechanisms are the core of a linear economy. The extraction of raw materials and utilisation of fossil fuels for energy generation are the major barriers manifests. In the circular economy, the take-make-dispose model is taken over by the new economic system that is based on the reduction of raw material usage, promoting reusing and recycling in all product lifecycles — from designing and planning to producing, distributing and consuming (Škrinjarić, 2020). As stated by Alhawari *et al*. (2021), using a closed-loop circular economy minimises resource intake, generated waste, and carbon footprint, and all products are designed to provide maximum utility for consumers. The shift to a circular economy is closely linked to the transformation of the energy sector. Global energy sector development will shortly be based on green or renewable energy, which allows the reduction of emissions (Karaeva *et al*., 2022). Although the popularity of sustainable development and circular economy in scientific literature is steadily increasing, there is a lack of studies focusing on the efficiency of circular economy represented by renewable energy in the context of sustainable development. The efficiency of the circular economy is often measured in the context of waste. Banjerdpaiboon and Limleamthong (2023) measure the efficiency of EU countries in focus on waste, recycling and biowaste. Gatto (2023) focuses on Europe's transition to the circular economy, measuring management efficiency of energy recovery from waste, while Ji e*t al*. (2023) focus on solid waste and industrial wastewater to measure China's circular economy efficiency. Researchers in the field of sustainability examine the potential impact of circularity strategies on SDG (Garcia-Saravia Ortiz-de-Montellano *et al*., 2023).

However, there is a lack of studies assessing how efficiently EU countries are achieving sustainable development goals through circular economy practices within renewable energy. Circular economy practices should be implemented as soon as possible to lower the environmental, economic and social threads to manageable levels, and it is crucial to assess the efficiency. That also helps better understand the current level of progress towards SDGs and can contribute to necessary actions needed to achieve targets in certain areas. From the theoretical point of view, this paper examines renewable energy as an essential pillar of the circular economy and serves as a guideline to other researchers and policymakers to understand the role of renewable energy in the context of circular economy and sustainability. The selected methodology provides an innovative approach to evaluate effectiveness not just in circular economy or sustainability, but in social sciences in general. Effectiveness evaluation is especially important for policymakers of EU countries since all EU member countries are committed to developing sustainable development strategies and applying the best practices of other countries can lead to better results in the future.

The current study aims at determining the efficiency of European Union countries implementing circular economy practices through renewable energy to attain sustainable development goals. The study focuses on the significance of renewable energy as a tool for the circular economy to achieve sustainable development and highlights the progress achieved in

SDG through renewable energy in the EU. In order to reach the aim, the Data Envelopment Analysis approach has been selected. DEA is one of the most appropriate methods for efficiency assessment as it allows for identifying areas for improvement and benchmarking best practices within the given dataset.

This paper consists of an introduction and justification of the purpose of the study. Theoretical background examines the circular economy concept, research background and renewable energy production described, following the methodological part describing selected methods, the sample and data collection. The results, discussion, and conclusions of this study are presented after the methodology.

## Theoretical background

### *Circular economy concept and research background*

The circular economy is designed as a novel solution to the current linear economy, which means unsustainable consumption and production and finds its foundation in a take-make-dispose model (Sariatli, 2017). The growing need for raw materials and limited resources creates huge challenges, as well as climate change and other environmental issues. With the current situation, it should be ensured that a balance between the society, economy and environment is achieved (Kristensen & Mosgaard, 2020). In order to create economic wealth for now and the future and ensure social quality with the highest standards of environmental protection, a circular economy should be applied. Since resources are used for as long as possible in a circular economy, and value is created by minimised pollution and waste, it is crucial to ensure that a circular economy is powered by renewable energy sources such as wind or solar power for all production, distribution and consumption stages. A circular economy through renewable energy also helps to reduce the use of finite resources such as fossil fuels (Holechek *et al*., 2022).

In the circular economy, resource efficiency is cantered. To achieve a circular economy, products or product parts are made in a way that minimises waste and focuses on long-term value retention. As well as waste, raw material consumption is also minimised, promoting secondary material and establishing closed loops. That helps to achieve socio-economic benefits and ensure environmental protection (Morseletto, 2020).

As stated by Geissdoerfer *et al.* (2017), in a well-functioning circular economy, all products are made in a way that items can be repaired or reused or easily recycled at the end of the lifecycle, ensuring durability and ease of maintenance. In that way, the circular economy works as a regenerative system with minimal energy losses and carbon footprint, as well as minimalised resource intake and waste. This is achieved by slowing, closing and narrowing material and energy loops (Geissdoerfer e*t al*., 2017)

The circular economy concept is often implemented using different Rs framework, which refers to different waste management or production and consumption principles starting with the letter R: reduce, recover, recycle, recover, repair and many more. However, the fundamental principle of the circular economy is based on the 3R model: reduce, reuse and recycle (Gebhardt *et al*., 2022; Okorie *et al*., 2018; Prieto-Sandoval *et al*., 2018). A circular economy aims at keeping materials used as long as possible and minimising waste by designing products for reuse, repair, and recycling.

In the first phase, reduce refers to using fewer inputs of energy, raw material, and waste and saving natural resources (Morseletto, 2020). As stated by Kirchherr *et al*. (2017), reduction means increased efficiency in production and consumption by using fewer natural resources and materials. Renewable energy contributes to the circular economy and is highly related to one of the core circular economy principles — reduction.

The transition to a circular economy cannot be reached without renewable energy, which leads to reduced greenhouse gas emissions. The energy sector is one of the main pillars of the circular economy. Every single product or service cannot be considered independent from energy. The sustainability of energy production is essential for better performance of the circular economy (Yildizbasi, 2021). Renewable energy is a perfect solution for a circular economy since it prevents the extraction of limited resources and generates less waste (Majeed & Luni, 2020).

One of the most known agreements highly related to renewable energy and circular economy is the Paris Agreement, which was adopted in 2015 at the United Nations Climate Change Conference (COP21); it aims at reducing the risks and effects of climate change by limiting the temperature increase to 1.5°C above pre-industrial levels and keep the global average temperature increase below 2°C from pre-industrial levels (United Nations Framework Convention on Climate Change, 2015). One of the main pillars of this ambitious goal is the reduction of greenhouse gas emissions. In order to achieve this, greenhouse gas emissions should be cut by 45% by 2030, compared to the 2010 level (Intergovernmental Panel on Climate Change, 2018). Paris Agreement is inseparable from Sustainable Development Goals (SDG) was adopted by the United Nations in 2015. The definition of sustainable development was first introduced in the Brundtland Report named Our Common Future as a *development that meets the needs of the present without compromising the ability of future generations to meet their own needs* (Brundtland, 1987). Sustainable development goals refer to all three dimensions of sustainable development — the social, economic and environmental (United Nations General Assembly, 2015).

The circular economy is highly related to sustainable development. As stated by Kirchherr *et al.* (2017), by prioritising the reduction, reuse, recycling, and recovery of materials in all stages of production, distribution, and consumption, the circular economy model seeks to eliminate the notion of the "end-of-life" concept. The final aim of a circular economy is to achieve sustainable development, which encompasses environmental well-being, economic wealth, and social equity for both present and future generations.

*Energy production within the circular economy*

Merli *et al*. (2018) state that even though the circular economy is focused more on environmental and economic issues rather than social ones, it can promote sustainable development and contribute to sustainable development goals. Korhonen *et al.* (2018) agree that the successful adoption of circular economy principles contributes to all the sustainable development dimensions, including the social aspect. Korhonen *et al.* (2018) also highlight that renewable energy is one of the main pillars of the circular economy model, and it will create a fundamental transformation of economic activities, shifting away from the dependence on non-renewable and carbon-intensive energy sources on the way to more sustainable models of production and consumption power by green energy.

As stated by de Oliveira and Oliveira (2023), the circular economy is an instrument to attain sustainable development. The circular economy also contributes to various SDGs, including SDG7 — affordable and clean energy. Relation between sustainable development goals and the circular economy was examined by different authors. As Khan *et al*. (2022) state, renewable energy is crucial to meet rising energy demand and ensure environmental protection. Renewable energy is not only a tool to cope with the rising price of fossil fuels, but can also assist in achieving sustainable development. In addition to that, the transition to the circular economy can be sped up by promoting renewable energy, especially wind or solar. Circular economy as an economic system cannot be achieved without renewable energy (Palea *et al*., 2023). As stated by Desing *et al*. (2020), in a circular economy, all energy production should be from renewable energy, ensuring minimal raw material extraction and safe disposal of waste to protect the environment.

As stated by Wang *et al.* (2023), although renewable energy generation capacities or storage requires substantial investment and can become a challenge for developing countries, the contribution to economic sustainability and environmental as well as the 2030 UN Agenda is undoubted Khajuria *et al.* (2022) state that the circular economy plays a crucial role in sustainable development, and the benefits of the circular economy have been widely acknowledged by societies, governments, and stakeholders. The circular economy is a part of many goals and targets listed in the 2030 agenda for sustainable development goals (such as SDG 7, 8, 9, 12, 13). The adoption of renewable energy is a way to a more sustainable future. Knäble *et al.* (2022) state that sustainable development and a circular economy can only be achieved by promoting and adopting renewable energy since the economy relies on energy as a fundamental input for goods and services. Non-renewable energy sources are responsible for emitting an enormous amount of greenhouse gases, leading to global warming and without the adoption of renewable energy, sustainable development cannot be achieved. However, the achievement of sustainable development is vital as it is one of the top priorities not only for the European Union, but for the majority of the world moving towards UN sustainable development goals. It is crucial to evaluate how efficiently countries are implementing good practices and ensure that these goals can be met on time.

Despite the fact that renewable energy refers to the utilisation of natural resources that renew or regenerate at a pace surpassing their consumption rate and includes wind, geothermal, solar, hydropower, biomass and more, in this research, only wind and solar power were included. However, some scepticism regarding renewable energy exists, especially in the context of solar PV waste, due to some toxic or rare metals and chemicals that PV systems contain. De Sousa *et al.* (2023) state that end-of-life PV systems are not hazardous if treated right, and the value of generated solar power surpasses the possible environmental damage of properly disposed PV systems, which is minimised. Of course, in order to ensure proper utilisation of solar panels, technological solutions and processes should be developed, as well as political mechanisms and structures should be implemented. Aşkın *et al.* (2023) agree that technological progress in PV manufacturing, along with the imrovment of regulation and law and using circular economy practices, will minimise the possible environmental risks of utilising solar panels. Similar discussions exist about types of renewable energy, but the fact that renewable energy is the best option among all sources of energy is clear.

In order to assess the efficiency of the circular economy and its leading activities, different methodologies are applied. For example, stochastic frontier analysis is used for evaluating the efficiency of waste management (Agovino *et al.*, 2020), eco-efficiency of the waste sector (Molinos-Senante & Maziotis, 2021), energy efficiency gaps (Vasylieva *et al.*, 2021). Apart from that, there are scientists using a non-parametric method based on multidirectional efficiency analysis for computing the efficiency of circular economy in plastic waste (Robaina *et al.*, 2020a). Moreover, different econometric modelling techniques are used in order to assess the efficiency of the circular economy activities (Glavonjic *et al.*, 2019). The reviewed literature has explored a diverse array of empirical approaches in the field of efficiency analysis. These studies have employed various quantitative techniques, including stochastic frontier analysis, multidirectional efficiency analysis and different econometric modelling approaches. Notably, many of these methods share a common goal with Data Envelopment Analysis: assessing and benchmarking the efficiency of decision-making units (DMUs). While these previous methods have provided valuable insights into efficiency measurement, DEA stands out for its ability to handle multiple inputs and outputs simultaneously, offering a comprehensive and flexible framework for efficiency assessment. The following section delves into the methodology of DEA, highlighting its unique strengths.

## Method

For evaluating the efficiency of the circular economy represented by the determinant of renewable energy, Data Envelopment Analysis (DEA) was adopted. The research covered 27 EU countries. DEA is a quantitative procedure used for assessing the relative efficiency of units named decision-making units (DMUs) (Ahmed *et al*., 2019). In DEA, it is necessary to specify the inputs and outputs relevant to the evaluation. Inputs are the resources or factors used by the DMUs, while outputs are the products, services, or outcomes generated by the DMUs. Selected inputs and output for the current research with references to used databases are provided in Table 1. All the inputs represent renewable energy and cover almost all the possible factors for its measurement. All the quantitative information has been obtained from the statistical databases, and hence, the research could be replicable. The descriptive statistics of the used data are provided in Table 2.

DEA is indeed widely used in various research areas and industries to assess and measure relative efficiency. One of the fields where DEA is widely used in the assessment of bank efficiency (Nhan *et al*., 2021; Titko *et al*., 2014; Učkar & Petrović, 2021). Measuring bank efficiency is one of the most often used fields of DEA application in economics. However, there are works where DEA is used for other purposes, one of which is energy efficiency (Mohd Chachuli *et al*., 2021; Mushtaq *et al*., 2021; Rodríguez-Lozano & Cifuentes-Yate, 2021; Yang & Chen, 2021). By applying DEA to energy-related issues, scientists and practitioners could contribute to more sustainable and efficient energy systems. It provides a data-driven approach to optimising energy consumption and resource allocation, which is crucial for addressing contemporary challenges related to energy efficiency. The sustainability concept is also researched with DEA methodology (Galán-Martín *et al*., 2016; Tsaples & Papathanasiou, 2021; Yousefi *et al*., 2021). Based on that, it could be stated that there are some pieces of research investigating energy efficiency and sustainability issues; however, these studies are fragmented and still need further investigation. In other words, there are only a few articles examining renewable energy (as a part of the circular economy) with the DEA technique. In fact, the limited number of papers shows that the DEA application for the evaluation of the efficiency of circular economy is undervalued. Actually, DEA plays a vital role in evaluating the efficiency of circular economies and establishing benchmarks for improvement.

For applying the DEA technique, the inputs and outputs ought to be selected. In the present research, the input indicators are renewable energy factors representing the circular economy. The output is characterised by the Sustainable Development Goals Index (SDGI). The mentioned index was selected as an output, as scholars state that there is a relationship between the circular economy and sustainable development. For instance, Arauzo-Carod *et al*. (2022) claim that a circular economy could decrease the negative effects of climate change and, hence, contribute to sustainable development. Ünal and Sinha (2023) state that circular economy paradigms enable companies to rethink their resource management behaviour, which, in turn, could lead to more sustainable behaviour, which is part of a country's sustainable development. Bag *et al.* (2022) say that the circular economy contributes to the optimum utilisation of resources and, as a consequence, enhances sustainable development. In other words, there are articles analysing the link between circular economy and sustainable development; however, the number of research on how efficiently circular economy transforms into sustainable development is limited. In order to solve it, the current article employed the DEA method and found out how the circular economy, represented by renewable energy indicators, transforms into sustainable development.

The central principle of DEA is to evaluate and measure the relative efficiency of multiple DMUs in converting inputs into outputs. In this study, a model that operates under constant returns to scale (CRS) is utilised. The CRS model assumes that the scale of operations or production for each DMU under evaluation remains constant. In other words, it assumes that if the inputs and outputs of a DMU increase proportionally, its efficiency score remains the same.

The linear programming problem that needs to be addressed within the described approach incorporates a measure of return to scale represented on the variable axis as $c_k$ for country $k$ (see equations (1)-(3)).

$$\text{Maximise} \frac{\sum_{r=1}^{s} u_r y_{rk}}{\sum_{i=1}^{m} v_i x_{ik}} \tag{1}$$

$$\text{s.t.} \frac{\sum_{r=1}^{s} u_r y_{rj}}{\sum_{i=1}^{m} v_i x_{ij}} \leq 1, j = 1, \dots, n \tag{2}$$

$$u_r, v_i > 0, \forall r = 1, \dots, s; i = 1, \dots, m. \tag{3}$$

where

$y_{rk}$ quantity of output $r$ produced by country $k$;
$x_{ik}$ quantity of input $i$ covered by country $k$;
$u_r$ weights of output $r$;

$v_i$ weights of input *I;*
$n$ amount of countries to be assessed;
$s$ amount of outputs;
$m$ amount of inputs;

In DEA, there are both input-oriented and output-oriented models. In an input-oriented DEA model, the goal is to assess the efficiency of DMUs while keeping the level of outputs constant. In other words, it evaluates how efficiently a DMU uses its inputs to produce a fixed level of output. This is the model that was chosen for the study (see equations (4)-(6)):

$$\text{Maximise } \sum_{r=1}^{s} u_r y_{rk} \tag{4}$$

$$\text{s.t. } \sum_{i=1}^{m} v_i x_{ij} - \sum_{r=1}^{s} u_r y_{rj} \geq 0, j = 1, \ldots, n \tag{5}$$

$$\sum_{i=1}^{m} v_i x_{ik} = 1 \tag{6}$$

As was mentioned above, renewable energy indicators are used as inputs, and the SDGI values are used as output.

**Empirical findings**

In order to assess how efficiently the inputs represented by the renewable energy transform to the output represented by SDGI, DEA was performed, and the results are stated in Table 1. As shown in the table, Sweden, Luxembourg, Ireland, Latvia, Estonia, Malta, the Netherlands and Bulgaria are considered the most efficient countries with the highest ratio of outputs to inputs. Cyprus, Greece and Austria are the least efficient, according to the results.

For further evaluation, EU countries were divided into four regions of Europe using the United Nations geoscheme. Among eight countries that are considered efficient, Northern European countries represented by Sweden, Estonia, Latvia, and Ireland dominate, followed by Western European countries (the Netherlands and Luxembourg). One of the main factors why North European countries (especially Scandinavia) might be constantly significant investments in renewable energy, policy and taxation, as well as cultural differences and a strong connection to nature. Studies show that Scandinavian countries are moving towards sustainable economies with solid focuses on renewable energy reduction of greenhouse gas emissions. Investments in renewable energy also promote economic growth (Magazzino *et al*., 2022). However, Scandinavian countries have compared low energy intensity compared to, for example, comparing to industrialised countries like Germany.

Sweden is one of the leading countries in the SDGI. Sweden has the highest percentage of energy from renewable energy sources in the EU, with one of the lowest $CO_2$ emissions per capita. Energy productivity is also above the EU average in Sweden, and the country is among the leaders in wind power generation in the EU. These results ensure that Sweden is considered an efficient circular economy according to DEA results in this article. By 2040, Sweden's goal is to produce all of its electricity from renewable energy sources. The country's renewable energy policy is well developed, and it is likely that the country will remain in top positions implementing sustainable development and circular economy practices.

Although Finland has the highest SDGI, its energy productivity is comparatively low, and $CO_2$ emissions per capita are high, which makes this country less efficient in achieving sustainable development and is ranked in 15 places. Although renewable energy in Finland is developing fast, the potential in bioenergy, hydropower or wind power is not met, and a more vast portion of electricity is produced by nuclear power or other non-renewable sources. Kirikkaleli and Sowah (2023) states that improving energy productivity can lead to better environmental quality and lower emissions. Therefore, the Finnish authorities should introduce policies that can lead to an increase in energy productivity. These policy implementations can also increase the country's efficiency in achieving sustainable development through a circular economy represented by renewable energy. Murshed *et al*. (2022) agree that higher energy productivity can decrease $CO_2$ emissions. Energy productivity is also highly related to renewable energy, and the combination of these three dimensions is crucial to achieving sustainable development goals.

According to the European Commission (2009) report, southern European countries have the highest potential for solar electricity; only Malta is considered efficient according to this research's DEA results. However, in most countries, this potential is not used yet; countries lack national programs to promote renewable energy. Although Malta does not produce energy from wind, $CO_2$ emissions per capita in Malta are the lowest among all measured countries in this study. Although Malta is considered an efficient circular economy, it should continue to expand its renewable energy production capacities as a commitment to the Valletta Declaration that was signed in Malta's capital in 2017 by the EU Commission and 14 member states with island territories to reduce dependency on fossil fuel and non-renewable sources and promote energy self-reliance. Transitioning to renewable energy can not only further reduce $CO_2$ emissions and increase energy productivity but also promote Malta as a sustainable destination for tourists (Kotzebue & Weissenbacher, 2020). It can also be related to the small economy's effect, which is highly related to the smaller demand for energy, leading to lower investments needed to ensure energy production from renewable sources. Another example would be Luxembourg.

Even though Luxembourg currently has the lowest percentage of renewable energy in overall energy consumption, and its carbon footprint per capita is the highest in the EU, it is one of the leading countries in energy productivity in the EU. High energy productivity ensures that Luxembourg is efficiently using its energy resources to achieve sustainable development. It should be taken into account that Luxembourg is among the most developed economies in the EU, meaning that the country is capable of funding large-scale projects. Luxembourg should focus more on capacities of solar and wind energy to further increase its sustainable development; however, Luxembourg has very limited space for large-scale renewable energy projects.

The share of energy from renewable sources and energy productivity is slightly above the EU average, and $CO_2$ emissions per capita are slightly lower in Greece, but the country's SDGI is one of the lowest in the EU. Other countries that have similar results are more efficient in achieving sustainable development goals. The country should increase its share of renewable energy and produce more wind or solar energy since the country's geographical position is suitable for the expansion of renewable energy capacities, especially solar. Even though the share of energy from renewable sources in Austria is one of the highest in the EU, $CO_2$ emissions are high, and that leads to inefficient use of renewable energy for sustainable development.

According to the Eurostat (2023), the five most significant countries in the EU by sold industrial production were Germany, Italy, France, Spain and Poland, which generated 70% of the EU's value of sold production; these countries also have the biggest demand for electricity in EU (Ember, 2023). According to this research results, none of these countries are considered efficient. Ensuring that in such energy-intensive and industrialised countries, the majority of electricity demand comes from renewable energy might be challenging. One of the main challenges when it comes to renewable energy in highly industrialised countries is that some of the renewable energy sources, such as solar and wind, are intermittent, meaning that ensuring continuous power for industrial processes is difficult. Challenges are also related to the energy transition cost and needed upgrades to the grids to handle fluctuating inputs from renewable energy sources and efficiently distribute energy across regions. In order to handle these challenges, national-level changes should be introduced.

However, Germany recently introduced the biggest amendment to energy legislation in decades with the ambitious goal of increasing the share of the gross electricity consumption that comes from renewable energy to 80% by 2030. The new policy is mainly based on promoting wind, solar and green hydrogen as the main renewable energy sources. The expansion of renewable energy production in Germany is also crucial for its energy independence, which was a huge challenge for the country after the Russian invasion of Ukraine. However, even with new policies, there are lots of challenges related to regulations and bureaucracy (Pata *et al*., 2023). It is likely that these actions will increase the country's efficiency in seeking sustainable development goals.

As for Eastern European countries, most of them are considered inefficient, according to the DEA results, with the exception of Bulgaria. The reason for that could be the fact that most of these countries are compared to new and still developing economies. However, Bulgaria is among the most efficient countries in the EU. It is important to mention that it should be taken into account that Bulgaria's SDGI is the lowest in the European Union, but the share of energy from renewable sources is close to the EU average, $CO_2$ emissions are lower than the EU average, and solar energy is developed well within the country. That means that in relation to other countries, Bulgaria is making optimal use of its renewable energy resources to achieve sustainable development goals. In order to improve, Bulgaria should focus more on the improvement of energy productivity and reduction of $CO_2$ emissions, which can lead to a higher score of SDGI.

European Commission (2022) states that EU solar energy has significant potential and should be developed more in the whole EU and become a mainstream part of power. The EU has established several initiatives related to the expansion of renewable energy, including the REPowerEU plan, EU solar energy strategy and others. Bódis *et al*. (2019) state that Cyprus, Portugal, Italy, France, Spain and other South European countries have the highest potential for rooftop solar energy. It is likely that using this potential can lead to increased efficiency of the circular economy in terms of sustainable development in these countries. It is crucial that countries promote these large-scale EU programs within the country and ensure that people and businesses can move to clean and affordable energy and improve sustainable development. Besides the huge potential of solar power some countries also have a enormous potential for wind power generation. According to Ryberg *et al.* (2019), France has the most considerable potential for onshore wind energy, followed by Spain, Finland and some other countries. It is essential to mention that almost all EU countries can generate energy from onshore wind farms and reduce greenhouse gas emissions, ensure energy independence and promote sustainable development. It is imperative for countries that, according to this study, were identified as less efficient at transforming renewable energy into sustainable development to invest in renewable energy and promote local and EU-level programs for solar and wind energy development. Enevoldsen *et al.* (2019) suggest that for some countries, offshore wind farms are a better solution and confirm that with solar and offshore wind power potential Europe can move to green, 100% renewable energy generation even if we take into account increasing demant of electricity. Promoting clean energy is crucial for achieving sustainable development in the EU.

## Discussion

Giannakitsidou *et al.* (2020) measured EU countries' circular economy and environmental performance using the DEA method. In the research, municipal solid waste generation per capita and three dimensions of the Social Progress Index were used as inputs and circular material use rate, as well as the recycling rate of municipal solid waste as outputs. Castillo-Giménez *et al.* (2019) used DEA to measure the performance of the treatment of municipal waste in the EU. Municipal waste generation and treatment indicators were used as inputs and outputs of the research. Robaina *et al*. (2020) also analysed the efficiency of EU countries in the context of circular economy, more specifically in plastic waste. Banjerdpaiboon and Limleamthong (2023) used the super-efficiency dual DEA method to measure national circularity performance in EU countries in the context of waste and secondary raw materials. Although efficiency or performance measurement in the circular economy field on the EU level is not new, most of the research focuses on different kinds of waste or recycling. When it comes to sustainable development and sustainable development goals, research analysing relation between renewable energy and sustainable development goals (Chen *et al*., 2022) or sustainable development (Güney, 2019; Østergaard *et al*., 2022) exists, but efficiency evaluation of countries seeking sustainable development goals was not evaluated in any of these research.

In the present research, a different approach applying DEA is used to measure the efficiency of the circular economy and renewable energy as a pillar of the circular economy seeking sustainable development goals. Thus, the research representing the sustainable development measurement of circular economy practices through renewable energy is considered innovative, original and suitable to fill the identified research gap.

By recognising the most efficient countries, the results provide an opportunity for inefficient countries to apply the best practices of the efficient ones and improve not only renewable energy capacities but also achieve better results in the sustainable development of their countries and the entire EU. The gaps between efficiency and those that lag behind exist, indicating substantial room for improvement in the latter group. Consequently, less efficient countries have the potential for improvements in their policies and performance. Such enhancements include targets for renewable energy generation in consumption, for example, Sweden's target and action plan to produce all of its electricity from renewable energy sources by 2040 or promote funding to private individuals and businesses to build their own solar PV, etc. According to Kılıç and Kekezoğlu (2022), and Shao and Fang (2021), government subsidies for renewable energy are effective for renewable energy expansion and may help to achieve renewable energy goals faster.

It is essential to mention that the DEA does not provide information on the predicted potential country's maximum efficiency since efficiency scores are based on a specific database. Thus, even the countries that were considered as efficient have a potential for improvement. This fact is substantiated by nations such as Sweden, which, despite their remarkable achievements, are actively pursuing an ambitious policy enhancement in the realm of renewable energy. Their goal is to generate all their electricity exclusively from renewable energy sources by 2040.

Moreover, this research is relevant since, as stated in this study, it aims at determining the efficiency of European Union countries implementing circular economy practices through renewable energy to achieve sustainable development goals. An efficiency score was computed and supplied for each country, allowing for a comparison with other EU nations. These results are interpreted and easy to understand, even by non-experts. The chosen methodology is designed for the purpose of applying it to various countries or diverse contexts. This ensures that the methodology functions as a versatile instrument for evaluating the efficiency of individual countries in contrast to others. It also allows for identifying opportunities for future policy enhancements by drawing insights from the best practices of other countries.

## Conclusions

Challenges posed by climate change are leading to the need for a sustainable future. Transitioning to a circular economy powered by renewable energy becomes a crucial step towards sustainable development goals. Circular economy contributes to all three pillars of sustainable development: social, economic and environmental. Renewable energy is one of the key elements not only in circular economy, but also in sustainable development. Despite the fact that countries are moving towards a circular economy and promoting sustainable development, it is crucial to evaluate the efficiency of these changes. In order to measure the efficiency of the circular economy, represented by the determinant of renewable energy, Data Envelopment Analysis was adopted. Although DEA is popular among bank efficiency measurement research, the method is gaining popularity among researchers in sustainability, energy and circular economy. However, it could be stated that the DEA application for circular economy technical efficiency evaluation is underestimated. In this study, output was represented by the sustainable development goals index (SDGI), while inputs were represented by renewable energy factors that define the circular economy. According to the results, Sweden, Luxembourg, Ireland, Latvia, Estonia, Malta, the Netherlands and Bulgaria are considered the most efficient countries with the highest ratio of outputs to inputs. Cyprus, Greece and Austria are the least efficient, according to the results.

Lack of national and EU-level initiatives and regulations in circular economy represented by renewable energy and promoting sustainable development leads to lower efficiency in some countries. The European Union as a unit has introduced different initiatives and regulations related to the expansion of renewable energy, such as the REPowerEU plan, EU solar energy strategy, etc.; with these initiatives, countries can move towards green energy and can lead to the efficiency of achieving sustainable development goals. However, countries should promote national programs as well and encourage businesses to develop renewable energy projects. Based on geographical location, some countries can focus more on the wind while others focus on solar energy. EU countries located in Southern Europe have a higher potential for solar power, while countries located in Western Europe — in wind power.

Measuring the efficiency of achieving sustainable development goals is important because it allows policymakers, businesses and other stakeholders to identify areas for improvement and make informed decisions to create a more sustainable future. Efficiency can be considered one of the key elements moving towards sustainable development since the European Union and other countries should ensure that social, environmental and economic threads are manageable and sustainable development targets are met on time. Future studies on this topic should consider specific programs and regulations related to sustainable development goals and circular economy represented by renewable energy to highlight the best practices and provide detailed recommendations for less efficient countries.

The study was performed based on the European Union countries, and the result can be used only for the context of EU countries. It can be considered a limitation of this study. In order to determine the efficiency of non-EU countries (under the sustainable development goals agreement), data collection and study should be reperformed. Given variations in natural resource availability, levels of economic development, institutional capabilities, policy and regulations, it becomes apparent that this database and research alone cannot fully address all inquiries surrounding the implementation of circular economy principles within the renewable energy sector to achieve sustainable development. It is crucial to state that lack of data is also one of the limitations of this study. Since the circular economy and its evaluation is a relatively new topic, there is a gap in data for some circular economy and renewable energy indicators. One of the possibilities for future studies is to expand the number of selected indicators in the field of wind and solar energy or to include other means of renewable energy, such as biomass, geothermal and others.

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# Annex

**Table 1.** Indicators as inputs and outputs of DEA assessment

| **Input/ Output** | **Indicator** | **Type of measurement** | **Data source** |
|---|---|---|---|
| Output | SDG Index | Score | (Sachs *et al.*, 2023) |
| Input | Energy from renewable sources | % | (Eurostat, 2022b) |
| Input | Carbon dioxide emissions | Metric tons per capita | (Global Carbon Project, 2022) |
| Input | Energy productivity | GDP / gross available energy | (Eurostat, 2022a) |
| Input | Electricity generation from wind power | Terawatt hours | (EurObserv'ER, 2023b) |
| Input | Electricity generation from solar photovoltaic | Gigawatt hours | (EurObserv'ER, 2023a) |

**Table 2.** Descriptive statistics of the used data

| **Variable** | **Mean** | **Standard Deviation** | **Min** | **Max** |
|---|---|---|---|---|
| SDGI | 71.06 | 5.34 | 60.7 | 81.86 |
| Share of energy from renewable sources | 24.49 | 12.26 | 11.74 | 62.57 |
| Per capita carbon dioxide emissions worldwide | 6.22 | 2.18 | 3.27 | 13.07 |
| Energy productivity | 8.00 | 4.48 | 2.47 | 24.45 |
| Electricity generation from wind power in the European Union | 14.26 | 24.31 | 0 | 113.85 |
| Annual volume of electricity produced from solar photovoltaic in the European Union | 5833.70 | 11031.57 | 7 | 49992 |

**Table 3.** DEA efficiency results in EU

| DMU | rank | theta | | DMU | rank | theta | |
|---|---|---|---|---|---|---|---|
| Sweden | 1 | 1 | efficient | Finland | 15 | 0.890254 | inefficient |
| Luxembourg | 1 | 1 | efficient | Lithuania | 16 | 0.889156 | inefficient |
| Ireland | 1 | 1 | efficient | Portugal | 17 | 0.844728 | inefficient |
| Latvia | 1 | 1 | efficient | Romania | 18 | 0.784025 | inefficient |
| Estonia | 1 | 1 | efficient | France | 19 | 0.772424 | inefficient |
| Malta | 1 | 1 | efficient | Denmark | 20 | 0.758661 | inefficient |
| Netherlands | 1 | 1 | efficient | Slovenia | 21 | 0.757196 | inefficient |
| Bulgaria | 1 | 1 | efficient | Spain | 22 | 0.71321 | inefficient |
| Croatia | 9 | 0.994353 | inefficient | Germany | 23 | 0.705431 | inefficient |
| Belgium | 10 | 0.993767 | inefficient | Italy | 24 | 0.690068 | inefficient |
| Slovakia | 11 | 0.957531 | inefficient | Cyprus | 25 | 0.612528 | inefficient |
| Czechia | 12 | 0.952264 | inefficient | Greece | 26 | 0.611025 | inefficient |
| Hungary | 13 | 0.942255 | inefficient | Austria | 27 | 0.542266 | inefficient |
| Poland | 14 | 0.940561 | inefficient | | | | |