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Role of Renewable Energy in Carbon Emission Reduction in European Union Member States

Znaczenie odnawialnych źródeł energii w obszarze redukcji emisji CO₂ w krajach członkowskich Unii Europejskiej

Abstract

The study aims to compare European Union Member States in terms of the pace of CO₂ emission reduction and renewable energy growth. We present a hypothesis that EU Member States with a substantial share of renewable energy in their energy mixes reduce carbon emissions faster than countries with less renewable energy. The statistical input for the comparative analysis spanning 2000 to 2023 is sourced from the electronic publication *Our World in Data*. The methodological framework comprises a correlation analysis and a non-parametric Kruskal-Wallis test. The results indicate that an increase in renewable energy leads to reduced carbon emissions on an annual time scale. The magnitude of the effect varies across the community. The research hypothesis that EU Member States with a substantial share of renewable energy in their mixes exhibit a greater decline in carbon emissions than countries with a lower renewable energy percentage has been confirmed. The results demonstrate that improved carbon footprint reduction rates require a specific threshold of renewable energy in the mix to be exceeded.

Keywords: European Union, Carbon Dioxide Emissions, Renewable Energy Sources.

JEL: O52, Q42, Q58

Streszczenie

Celem niniejszego badania jest dokonanie analizy porównawczej krajów Unii Europejskiej pod względem tempa redukcji emisji CO₂ i wzrostu udziału OZE. W ramach postawionej hipotezy badawczej przyjęto, że kraje UE ze znaczącym udziałem OZE w strukturze energetycznej notują większe tempo spadku emisji CO₂ niż kraje o niższym udziale. W badaniu wykorzystano zasoby danych statystycznych elektronicznej publikacji naukowej „Our World in Data”, gdzie za okres badań przyjęto lata 2000–2023. W procesie badawczym zastosowano metodę analizy korelacji oraz nieparametryczny test Kruskala-Wallisa. W badaniach dowiedziono, że w ujęciu rocznym wzrost udziału OZE determinuje redukcję emisji CO₂. Niemniej jednak stopień tego oddziaływania jest zróżnicowany w zależności od kraju. Hipoteza badawcza głosząca, że kraje członkowskie ze znaczącym udziałem OZE notują większe tempo spadku emisji CO₂, niż kraje o niższym ich udziale w strukturze energetycznej, została zweryfikowana pozytywnie. Rezultaty badań wskazują, że uzyskanie silniejszego efektu w zakresie ograniczenia emisji CO₂ wymaga przekroczenia pewnego progu udziału OZE w strukturze energetycznej.

Słowa kluczowe: Unia Europejska, emisje dwutlenku węgla, odnawialne źródła energii.

JEL: O52, Q42, Q58



1. Introduction

Energy is a *sine qua non* for fulfilling the needs of the economy and the public. As such, it has to be constantly available (Sen & Ganguly, 2017). The rapid global population growth and progress have resulted in an exponential increase in energy demand (Olabi & Abdelkareem, 2022). Energy generation from coal is detrimental to the environment at the local and regional levels. It causes greenhouse gas (GHG) emissions and exacerbates climate change. Therefore, it is imperative that energy security be improved and GHG emissions reduced (Tripathi et al., 2016). Limited and dwindling fossil fuels, security issues associated with their supply, and their harmful climate effects have prompted a transition towards renewable energy sources (Moriarty & Honnery, 2016). In comparison to fossil fuels, renewable energy offers numerous benefits by improving energy security and fuelling sustainable economic growth (Can Şener et al., 2018). Renewable energy is perceived as an opportunity to limit GHG emissions and address the problem of global warming (Panwar et al. 2011), which helps to control the risk of an environmental disaster (DeCanio, 2009).

The topic of global warming and climate change is a crucial aspect of the international academic and political discourse. These environmental concerns necessitate global action to reduce carbon emissions to the atmosphere. Despite this, the efforts so far have been largely ineffective. For example, the *Kyoto Protocol* (United Nations Framework Convention on Climate Change, 1998) is not binding on the signatories (Pilatowska & Geise, 2021). The current international climate treaty, the *Paris Agreement* (United Nations Framework Convention on Climate Change, 2015), aims for a reduction in GHG emissions and the continuous monitoring of progress by the parties (King & Karoly, 2017). Its primary objective is to reduce global warming to a level substantially below 2°C relative to the pre-industrial era, while keeping the temperature increase below 1.5°C.

In response to the global efforts, the European Union (EU) has drafted its energy transition plan to phase out fossil fuels, the *European Green Deal* (European Commission, 2019). The strategy aims for complete climate neutrality in Europe by 2050, which means its economy should emit the same amount of GHG as it can absorb. It should also strive for sustainable resource management, circular frameworks, and low emissions. GHG emissions are expected to be reduced by at least 55% by 2030 compared to the 1990 levels. This ambitious goal is supported by the *Fit for 55* package (European Commission, 2021), which involves reforms to the *European Union Emissions Trading System* (EU ETS) and the introduction of new energy efficiency standards, as well as the expansion of renewable energy. Additionally, in 2024, the European Commission set an intermediary goal of a 90% reduction in total GHG emissions by 2040 compared to the 1990 level (European Commission, 2024). Renewable energy is to play a special role in reaching these targets, which are integral to the EU's energy policy (Firlej & Stanuch, 2023). The amended version of Renewable Energy Directive III requires EU Member States to achieve at least 42.5%, and preferably 45%, of renewable energy in their gross final energy consumption by 2030 (Directive (EU) 2023/2413).

A review of the subject literature indicates the existence of a relationship between the development of renewable energy sources and the reduction of CO₂ emissions in the Member States of the European Union. Nevertheless, an in-depth analysis of previous studies has made it possible to identify a research gap. This gap relates to the limited number of studies analysing EU Member States in terms of the rate of CO₂ emission reduction resulting from the achieved shares of renewable energy sources in the energy mix. Existing research largely focuses on average effects, while to a lesser extent addressing the structural heterogeneity of individual EU economies.

The research issue addressed in this article concerns whether European Union Member States which have a significant share of renewable energy sources in their energy mix achieve a faster rate of CO₂ emission reduction than countries with a low share of renewables. The research hypothesis assumes that EU Member States with a substantial share of renewable energy in their energy structure experience a higher rate of CO₂ emission decline than countries with lower renewable energy shares. The contribution of this article to the literature lies in a comparative analysis of EU Member States with regard to the rate of CO₂ emission reduction resulting from differentiated levels of renewable energy penetration in the energy mix.

The empirical analysis presented in this article covers the period 2000–2023, and is based on statistical data obtained from the *Our World in Data* database. The study employs correlation analysis and the non-parametric Kruskal-Wallis test. The adopted research approach enabled the identification of statistically significant differences in CO₂ emission levels between groups of countries with varying shares of renewable energy sources.

This article is organised into five sections. The paper begins with an introduction, followed by a review of the relevant literature. The subsequent section presents the research framework and describes the applied research methods. The results and discussion section reports the findings of the empirical analysis and compares them with the results of previous studies. The final section concludes the article by presenting conclusions drawn from the empirical analysis, policy recommendations, and directions for future research.

2. Literature review

The literature on environmental economics and energy economics comprises a substantial body of research addressing the relationship between the development of renewable energy sources and CO₂ emissions. The results of existing empirical studies largely indicate that an increasing share of renewable energy in the energy mix is a key determinant of CO₂ emission reductions. Nevertheless, the magnitude and nature of this impact vary and are conditioned by multiple determinants, including institutional factors, the economic structure, and the level of technological development of individual countries.

The analysed relationship is strongly embedded in the theory of energy transition, according to which the positive effects of renewable energy development on environmental well-being do not materialise immediately but rather require time

and depend on the aforementioned determinants. This leads to the conclusion that the relationship between renewable energy development and CO₂ emission reduction may be non-linear in nature and may be subject to a certain threshold of renewable energy penetration in the energy mix.

In the energy transition theory, particular importance is attributed to the *de-coupling* hypothesis, which says that economic growth may be achieved while simultaneously and progressively reducing the adverse impact on environmental well-being, for instance through changes in the structure of energy production.

Considering the objective, hypothesis, and the necessity to ensure comparability with existing econometric studies, we intentionally focus on analyses that involve the entire EU or selected Member States.

2.1. Empirical Studies for the EU: Classical Approaches and Long-Term Relationships

A characteristic feature of early empirical studies examining the relationship between renewable energy development and CO₂ emissions is their focus on identifying long-term relationships. Dogan and Seker (2016) analysed the impact of renewable energy and other selected factors on EU carbon emissions from 1980 to 2012. The research yielded a reciprocal link between renewable energy consumption and carbon emissions. In other words, changes in renewable energy consumption determine the scale of carbon emissions, and carbon emissions, in turn, affect the consumption of renewable energy. Leitao and Lorente (2020) arrived at similar conclusions regarding the relationship between such factors as renewable energy and carbon emissions in the EU between 1995 and 2014. The link between renewable energy and carbon emissions they demonstrated was mutual in the long term. The obtained results indicate mutual interactions between climate policy, the development of renewable energy, and emission levels, thereby challenging the simplified view of a unidirectional impact of energy on environmental well-being. The observed impact of one country's energy policy on another reinforces the rationale for pursuing coordinated actions in this area at EU level. Busu et al. (2021) estimated the impact of renewable energy and other selected factors on EU carbon emissions from 2000 to 2019. The authors emphasised the beneficial role of biofuels, bioenergy, and renewable energy consumption, as well as their contribution to carbon footprint reduction.

2.2. Direction of Relationships, Spatial Effects, and Cross-Country Heterogeneity

The topic of the interrelationships between economic growth, carbon emissions, and renewable energy consumption in the EU from 1995 to 2014 was discussed by Radmehr et al. (2021). Their results show a unidirectional relationship between increased renewable energy consumption and reduced carbon emissions. Moreover, these authors have proven spatial correlations among countries. Carbon emissions in one country can affect its neighbours. This demonstrates the importance of cross-border policy, as instruments employed in this policy can effectively guide carbon

emissions reduction using renewable energy sources. This observation regarding the cross-border effects of national energy policies strengthens the justification for implementing coordinated actions in this area across the EU. Jianu et al. (2022) presented an assessment of the effect of selected factors on GHG emissions in the EU-27 from 2010 to 2019. Their results indicated a moderate impact of a growing share of renewable energy in gross final consumption of energy on reduced GHG emissions. This was slightly lower than for the other investigated factors. The authors emphasised the importance of renewable energy in limiting harmful GHG emissions while pointing out limited capabilities in this regard until households embraced renewable sources.

2.3. The Role of Intermediating Factors and Technological Progress

Dimian et al. (2025) attempted to determine the impact of digitalisation on GHG emissions, taking into account renewable energy consumption as an intermediate variable in the EU 27 between 2000 and 2021. Their results demonstrate that renewable energy consumption reinforces the relationship between digitalisation and GHG emissions. This is because digitalisation boosts renewable energy consumption, which causes tangible reductions in emissions. The scope of the impact can vary due to economic differences or the specifics of the digitalisation process.

2.4. Empirical Studies for Selected EU Member States: Long-Term Relationships

Piłatowska & Geise (2021) analysed the effect of clean and fossil energy consumption on carbon emissions and economic growth in two phases (formation and expansion) of the renewable energy deployment in France, Spain, and Sweden from 1965 to 2019. Their results show that increased consumption of renewable energy in Spain and France reduces carbon emissions, especially in the expansion phase. A similar and even more pronounced tendency was found for Sweden. Despite this, to significantly curb emissions on a global scale, the renewable energy share in the mix would have to grow even further, especially in transport and heating. An article by Petruška et al. (2022) offers an analysis of the link between carbon emissions and energy from renewable sources in 22 European countries from 1992 to 2019. The authors revealed that a growing share of renewable energy led to a statistically significant reduction in carbon emissions per capita in most of the countries they investigated. The only exception was Germany, where an increase in renewable energy sources was correlated with more carbon emissions, which the authors may explore in the future. They also demonstrated that the relationship does not emerge in the short term, which may suggest that it develops over time.

2.5. Technological Disparities and the Non-Linear Nature of Effects

The problem of the effects of renewable energy production on environmental well-being in the ten European countries with the highest carbon emissions (Germany, the UK, Italy, France, Spain, Belgium, Czechia, Romania, Austria, and Bulgaria)

for 2019–2023 is investigated in a paper by Kartal et al. (2024). Their results show that renewable energy production curbs carbon emissions. Despite this, the effects vary depending on the energy source, country, and scale of the emissions. Carbon emissions in Germany, Belgium, and Austria have declined mostly due to hydropower. The driving factor in Italy, Spain, Romania, and Austria is solar energy. All of the investigated countries, except for Bulgaria, profited from wind energy. The results suggest that the type of renewable energy source used should be that that best matches local constraints, such as hydropower in Germany, solar energy in Italy and Austria, and wind energy in other countries, except for Bulgaria.

2.6. Research Gap and the Positioning of the Present Study

Research on the relationship between renewable energy development and CO₂ emissions is extensive and characterised by attempts to encapsulate this relationship using diverse methodological approaches. Nevertheless, a noticeable gap remains in studies offering comparative analyses of differences in the dynamics of CO₂ emission reductions among groups of countries with varying shares of renewable energy in their energy mix from a long-term perspective. Moreover, limited attention has been paid in literature to identifying practical thresholds of renewable energy penetration beyond which CO₂ emission reductions become statistically significant.

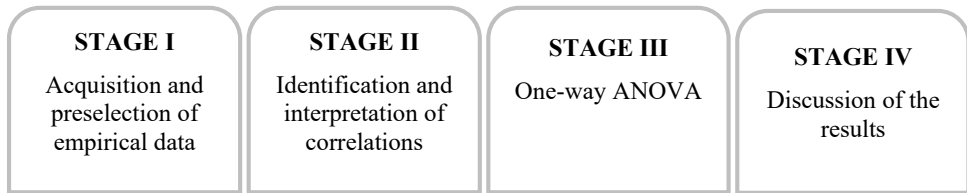
The research presented in this article seeks to address this gap through a comparative analysis of EU Member States over the period 2000–2023, employing correlation analysis and the non-parametric Kruskal-Wallis test. The adopted research perspective helps to identify statistically significant differences between groups of countries with different levels of renewable energy shares in their energy structure.

3. Methodology

The study aims to compare EU Member States in terms of the pace of CO₂ emission reduction and renewable energy growth. We present a hypothesis that EU Member States with a substantial share of renewable energy in their energy mixes reduce carbon emissions faster than countries with less renewable energy. Statistical data for the comparative analysis covering the years 2000–2023 were obtained from the *Our World in Data* database in their raw form, and the variables were not scaled, as they are already expressed in appropriate units (CO₂ emissions per capita in tonnes and the share of renewable energy as a percentage). Malta was removed from the sample because complete time series for the analysed period were not available, which made it impossible to include this country in the analysis. For the remaining countries, no missing observations or episodic deviations resulting from reporting errors were identified. This specific study period was selected for several reasons. In the early twenty-first century, the global debate on climate change intensified, and the EU became even more committed to environmental protection. One sign of this interest was the European Commission's release of the Green Paper on a GHG emissions trade system for the EU. It analyses the critical problems related

to establishing the EU ETS (Klimko & Hasprová, 2025). Moreover, the investigated period exhibits rapid technological progress in renewable energy sources, which has substantially transformed the energy mixes of EU Member States (Igliński et al., 2024). The analysis does not extend beyond 2023, because the most valid and complete data were available up to that year at the time of writing the paper. The choice of the years 2000, 2010 and 2023 reflects key turning points in EU climate and energy policy, but does not encapsulate the full year-to-year dynamics between these points. The authors are aware that short-term shocks (such as the crises in 2008 and 2020) may have occurred within the selected period; however, these were treated as genuine observations reflecting true economic changes rather than outliers requiring correction. The study design is illustrated in figure 1.

Figure 1.
Study design diagram



Source: original work

The first stage involved the acquisition and preselection of quantitative data necessary to analyse the impact of renewable energy on carbon emissions. The empirical data were sourced from *Our World in Data*, an electronic publication collaboratively developed by Oxford University. We acquired data on annual CO₂ emissions per capita and the percentage of renewable energy consumption in the primary energy structure. In this study, priority was given to examining the direct relationship between renewable energy and CO₂ emissions, while the inclusion of a broader set of control variables is left as a natural direction for future research.

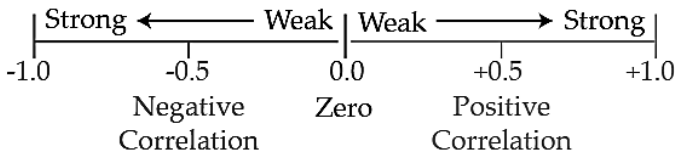
Stage II was a statistical analysis to identify links between the share of renewable energy and CO₂ emissions per capita in EU Member States. Our correlation analysis evaluated the strength and direction of links between quantitative variables calculated with the equation shown below (Śleszyński, 2020):

$$\hat{r} = \frac{\sum_{t=1}^n (x_t - \bar{x})(y_t - \bar{y})}{\sqrt{\sum_{t=1}^n (x_t - \bar{x})^2 \sum_{t=1}^n (y_t - \bar{y})^2}} \tag{1}$$

where \bar{x} and \bar{y} are the arithmetic means of the values of features x and y .

The correlations were interpreted in accordance with the diagram in figure 2.

Figure 2.
Strength and direction of the correlation coefficient



Source: Gogtay, N. J. & Thatte, U. M., 2017.

In the paper, correlation analysis measures the strength and direction of the linear relationship between the share of renewable energy and changes in CO₂ emissions, enabling the preliminary hypothesis to be verified and laying the groundwork for further analyses. The literature confirms that this method is applicable in studies of renewable energy impacts in the EU, where Qin et al. (2023) explicitly used this method to examine the relationship between CO₂ emissions and renewable energy consumption in industrialised countries. Also, Dogan & Seker (2016) and Radmehr et al. (2021) demonstrated exploratory associations without implying causality.

In stage III, we classified the EU 27 into three groups:

Group I: countries with < 15% of renewable energy (below EU average);

Group II: countries with 15–30% of renewable energy (RED II targets);

Group III: countries with > 30% of renewable energy (energy transition leaders).

The adopted grouping reflects the empirical data distribution for the years 2000–2023 and aligns with EU climate policy targets, including RED II pathways assuming either a 14.5% reduction in GHG emissions or a 29% share of renewable energy in transport by 2030 (Pająk, 2025). This classification was then used in a one-way analysis of variation (ANOVA) to verify any statistically significant differences in the mean CO₂ emissions per capita between EU Member States with different renewable energy consumption rates. The averages are calculated using the equations below (Aczel & Sounderpandian, 2018):

$$\text{Sample average: } \bar{x}_i = \frac{\sum_{j=1}^{n_i} x_{ij}}{n_i} \quad (2)$$

$$\text{Overall average: } \bar{x} = \frac{\sum_{i=1}^r \sum_{j=1}^{n_i} x_{ij}}{n} \quad (3)$$

where x_{ij} is the j th result for observations in a sample from population i .

Still, ANOVA has several constraints that need to be addressed (Ostertagová & Ostertag, 2013):

- independent observations;
- normally distributed dependent variable;
- homogeneous variance.

If these assumptions are not addressed, a non-parametric counterpart should be used, the Kruskal-Wallis test, calculated with the following equation (Koronacki & Mielniczuk, 2001):

$$T = \frac{12}{n(n+1)} \sum_{i=1}^k n_i \left[\bar{R}_i - \frac{n+1}{2} \right]^2 \tag{4}$$

where: $\bar{R}_i = \frac{1}{n_i} \sum_{j=1}^{n_i} R_{ij}$, n is the sum of the sizes of all samples.

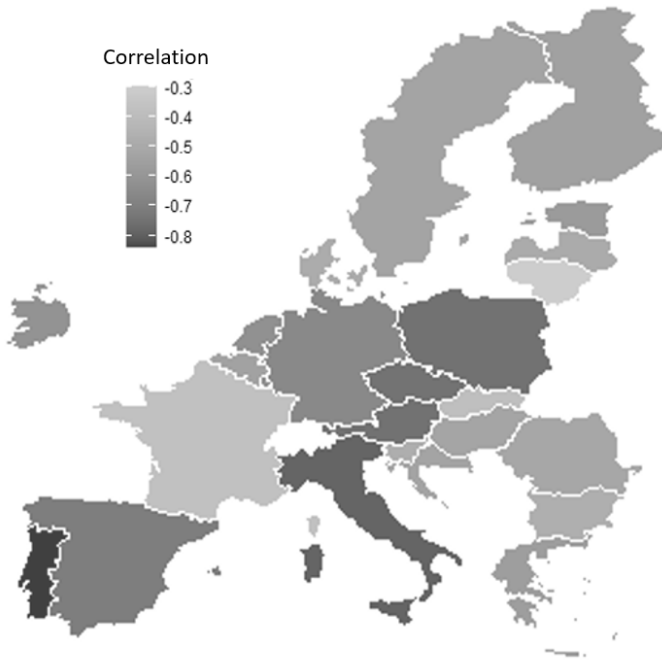
One-way ANOVA enables the comparison of means between groups, directly verifying the adopted hypothesis. When normality assumptions were not met (as verified later in the analysis), the non-parametric Kruskal-Wallis test was applied. Use of this test for heterogeneous energy data is confirmed by Ostertagová & Ostertag (2013). In the literature, studies by Szczubelek & Rzewowski (2024) applied similar grouping and variance tests, validating inter-group differences using Dunn’s post-hoc test.

The fourth and final stage involved presenting and analysing the results to evaluate the relationship between the share of renewables and CO₂ emissions per capita in EU Member States. We discussed both the correlation analysis results and the one-way analysis of variance in relation to the research objective.

4. Results and discussion

4.1 Correlation analysis

The correlations were investigated based on annual carbon emission increases per capita and renewable energy increases in primary energy. To this end, we calculated the differences in values for consecutive years in EU Member States and then determined the Pearson correlation coefficient. The correlation analysis revealed an unmistakable inverse relationship between the variables. Figure 3 shows the results visualised on a map to help with the spatial interpretation of the correlations.

Figure 3.*Map of correlations between renewables and CO₂ in EU Member States*

Note: correlations by country: Austria: -0.75; Belgium: -0.54; Bulgaria: -0.47; Croatia: -0.53; Cyprus: -0.50; Czechia: -0.75; Denmark: -0.49; Estonia: -0.57; Finland: -0.55; France: -0.37; Germany: -0.66; Greece: -0.56; Hungary: -0.53; Ireland: -0.62; Italy: -0.79; Latvia: -0.49; Lithuania: -0.29; Luxembourg: -0.63; the Netherlands: -0.63; Poland: -0.75; Portugal: -0.84; Romania: -0.52; Slovakia: -0.39; Slovenia: -0.47; Spain: -0.71; Sweden: -0.53.
 Source: original work

The strongest negative correlations were found for Portugal (-0.84), Italy (-0.79), Austria, Czechia, Poland (-0.75), and Spain (-0.71). Changes in the energy mix show a particularly strong inverse relationship with CO₂ emissions. Moderate negative correlations (ranging from -0.50 to -0.70) were observed in countries such as Germany (-0.66), Ireland (-0.62), Luxembourg (-0.63), and the Netherlands (-0.63). This suggests a distinct but slightly lower decrease in emissions accompanying the increase in the share of renewable energy. The weakest correlation between the dynamics of renewables and changes in CO₂ emissions was identified in Lithuania (-0.29), France (-0.37), and Slovakia (-0.39). These findings may be due to different energy mix structures with many low-emission sources other than renewables (such as nuclear power in France) or insignificant variability in the share of renewable sources over the investigated period. It is essential to emphasise that the variation in correlation strength reflects diverse energy mix structures and national strategies. In France (where nuclear power accounts for approximately 70% of electricity production), a weaker relationship between renewable energy share and emission levels was observed due to the low-carbon nature of nuclear energy. In contrast,

Portugal and Italy, which have intensively developed offshore wind and photovoltaics, achieve the strongest emission reduction effects due to consistent renewable energy support policies. Meanwhile, Poland and Czechia, relying on coal and energy-intensive industry, derive, in relative terms, the greatest benefits from each unit of renewable energy displacing fossil fuels. Note that no country exhibited a positive correlation coefficient. Therefore, an increase in renewable energy in the mix was linked with a lower carbon footprint on an annual basis (for the surveyed period). From an economic perspective, in countries exhibiting the strongest relationships, a 10% increase in renewable energy share in the energy mix translates (assuming a linear relationship) into a CO₂ emissions reduction of 8–12% annually. In countries with moderate correlation levels, this effect is approximately 6–7%, confirming the significant role of energy transition in the decarbonisation process. The present findings are consistent with those of Dogan & Seker (2023), who revealed a bidirectional causal relationship between renewable energy and carbon emissions. Moreover, our results confirm those of previous analyses by Radmehr et al. (2021) or Leitao and Lorente (2020). These researchers found a significant correlation between the use of renewable energy sources and carbon emissions. This suggests that the role of renewable energy in the mix should be promoted. Busu and Nedelcu (2021) and Petruška et al. (2022) noted that the consumption of renewable energy leads directly to CO₂ emission reduction. Similar results confirm a negative correlation between an increase in renewable energy in the mix and carbon emissions. The observed relationships are consistent with the theory of reciprocal feedback between climate policy and energy transition, though this study does not provide direct empirical evidence for such a mechanism.

4.1 One-way ANOVA

We categorised the EU Member States into three groups, depending on the share of renewable energy sources for a more in-depth comparison. This classification was based on data for three years: 2000 and 2023, as the first and last years of the period, and 2010, when critical regulations and targets of the climate and energy package were implemented.

Table 1.
Groups of countries by renewable energy share

Group	Country		
	2000	2010	2023
Group I	Belgium, Bulgaria, Cyprus, Czechia, Denmark, Estonia, France, Germany, Greece, Hungary, Ireland, Italy, Lithuania, Luxembourg, the Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain	Belgium, Bulgaria, Cyprus, Czechia, Denmark, Estonia, France, Germany, Greece, Hungary, Ireland, Italy, Lithuania, Luxembourg, the Netherlands, Poland, Romania, Slovakia	Belgium, Bulgaria, Cyprus, Czechia, Estonia, Hungary, Luxembourg, Poland, Slovakia

Group	Country		
	2000	2010	2023
Group II	Croatia, Finland, Latvia	Croatia, Finland, Latvia, Portugal, Slovenia, Spain	Croatia, France, Germany, Greece, Ireland, Italy, Lithuania, the Netherlands, Romania, Slovenia, Spain
Group III	Austria, Sweden	Austria, Sweden	Austria, Denmark, Finland, Latvia, Portugal, Sweden

Note: Group I: countries with < 15% of renewable energy; group II: countries with 15–30% of renewable energy; group III: countries with > 30% of renewable energy.

Source: original work

The grouping results in table 1 demonstrate a shift in the share of renewable energy in EU Member States that were dominated by low values in 2000 towards higher levels in 2023. In 2000, a majority of EU Member States were classified in group I, which reflects the low level of renewable energy at the time. Changes in 2010 were minimal, but 2023 saw a distinct decline in the group's size, reflecting progress. Only two countries belonged to group II in 2000. Subsequently, the group grew larger, which may suggest a progressive commitment to increasing the role of renewable energy in energy mixes. Group III initially only included Austria and Sweden because of earlier climate regulations. Sweden enacted a carbon tax in 1991 (Bohlin, 1998), while Austria has an extensive network of Alpine rivers and has traditionally invested in large hydropower stations, which increased the share of renewable energy in its energy mix (Writer, 2009). Poland remained in group I, among countries with the lowest share of renewable energy over the entire study period. The growth of renewable energy in Poland was relatively slow compared to most other Member States. This suggests that Poland's energy mix remains largely based on fossil fuels, primarily coal (Marciniuk-Kluska & Kluska, 2025).

The normality of CO₂ emission per capita distribution within groups was tested using the Shapiro-Wilk test ($\alpha = 0.01$) on time series data from 2000–2023 for each country individually. The Shapiro-Wilk test is more capable of detecting deviations from normality compared to other tests (Kubala, 2025). The results are presented in table 2.

Table 2.

Shapiro-Wilk test results

Country	Result	Country	Result	Country	Result
Austria	W=0.97, p-value=0.71	France	W=0.92, p-value=0.07	the Netherlands	W=0.88, p-value=0.01
Belgium	W=0.90, p-value=0.02	Germany	W=0.90, p-value=0.02	Poland	W=0.93, p-value=0.11
Bulgaria	W=0.98, p-value=0.84	Greece	W=0.90, p-value=0.02	Portugal	W=0.95, p-value=0.25
Croatia	W=0.90, p-value=0.02	Hungary	W=0.93, p-value=0.08	Romania	W=0.93, p-value=0.12

Country	Result	Country	Result	Country	Result
Cyprus	W=0.86, p-value<0.01	Ireland	W=0.89, p-value=0.02	Slovakia	W=0.92, p-value=0.05
Czechia	W=0.92, p-value=0.06	Italy	W=0.87, p-value<0.01	Slovenia	W=0.96, p-value=0.38
Denmark	W=0.92, p-value=0.06	Latvia	W=0.97, p-value=0.78	Spain	W=0.90, p-value=0.03
Estonia	W=0.90, p-value=0.03	Lithuania	W=0.91, p-value=0.04	Sweden	W=0.92, p-value=0.06
Finland	W=0.96, p-value=0.50	Luxembourg	W=0.95, p-value=0.30	X	

Source: original work

The lack of data normality was identified in 25 out of the 27 countries (p-value > 0.01), with 15 countries showing significantly higher p-values and the remaining series exhibiting distributions close to the adopted significance level (p-values ranging from 0.01 to 0.05). This justified the use of the non-parametric Kruskal-Wallis test, the results of which are presented in table 3.

Table 3.
Kruskal-Wallis test results

Value	p-value
106.95	< 0.001

Source: original work

The results in table 3 indicate statistically significant differences in medians of annual carbon emissions per capita between at least one pair of EU Member States identified according to the share of renewable energy. This means that countries with different shares of renewable energy have different CO₂ emissions levels per capita. The raw statistical data show that countries with more than 30% of renewable energy in their energy mixes have lower average CO₂ emissions per capita than countries with less than 15% of renewable energy. We identified pairs of groups with statistically significant differences through a post-hoc analysis using Dunn’s test, reported in table 4.

Table 4.
Results of Dunn’s post-hoc test with the Bonferroni correction

Group comparison	Value	p-value uncorrected	p-value corrected
group I – group II	9.10	< 0.001	< 0.001
group I – group III	6.45	< 0.001	< 0.001
group II – group III	-0.71	0.48	1

Source: original work

There is a very strong (statistically significant) difference in the CO₂ emissions per capita median between countries in group I and those in group II, which means that countries with a RES share >15% have significantly lower emissions. We obtained similar results for countries in group I and those with a very high share of renewable energy (group III). Countries with low shares of renewable energy exhibit substantially higher CO₂ emissions per capita than those with more energy from renewable sources. Countries in Group III emit on average 3.2 tonnes of CO₂ per capita less than Group I, representing 25% of the EU average emissions in 2023. When the 15% renewable energy threshold is exceeded (transition from Group I to II) there is a reduction of 1.8 tonnes of CO₂ per capita. Additionally, no significant difference was observed between Groups II and III, indicating a threshold effect where further increases in renewable energy share (above 30%) yield continued positive but smaller benefits compared to countries with lower renewable energy penetration. This effect aligns with findings by Akkus & Güler (2025). Optimal renewable energy support policy should focus on Group I countries, where the unit cost of CO₂ reduction is the lowest. The results are consistent with findings shared by Piłatowska & Geis (2021), who indicated that consumption of clean energy contributes to carbon emission reduction, especially during economic expansion. When combined with the results, these findings demonstrate that an increase in renewable energy alone is no guarantee of a complete severance of links between economic growth and emissions, but suggest a clear direction towards such a decoupling. Moreover, Kartal et al. (2023) demonstrated that energy generation from renewable sources (hydropower, solar, or wind) has a substantial effect on carbon emissions in the largest European economies. The strength and direction of the impact depend on the time, frequency, and quantile of the distribution. The authors showed that specific renewable energy technologies had different emission-reduction capabilities in individual countries. Note that the empirical results confirm the observations in a cross-sectional framework: countries with a greater share of renewable energy (over 15%) exhibit significantly lower CO₂ emissions per capita than countries with low shares of energy from renewables. Similar patterns were observed for countries with very high shares of renewable energy, confirming that the intensification of the energy transition leads to tangible emission reductions. Szczubelek & Rzczowski (2024) also noted higher carbon footprint reduction in groups with greater shares of renewable energy, which was confirmed by Wang et al. (2023). What is more, Akkus and Güler (2025) concluded that the relationship between the share of renewable energy and CO₂ emissions is non-linear, because the use of renewable energy reduces carbon emissions more significantly up to a certain threshold of renewable energy share, after which the effect is often much weaker.

The obtained results indicate a strong link between the share of renewable energy sources (RES) and CO₂ emission reductions, although other factors also contribute, including improvements in energy efficiency (LED technology, heat pumps), implementation of the EU ETS, and structural changes in industry (mine closures, ICT development). Such analysis requires a multifactor approach, so the authors encourage further research in this area and will continue to pursue this in subsequent works. The study shows that EU Member States with higher shares

of renewable energy in their energy mixes reach faster rates of carbon emission reduction than those with low renewable energy contributions. This finding confirms the hypothesis.

5. Conclusions

The article examines the impact of renewable energy on carbon emission reduction in EU Member States between 2000 and 2023. The original contribution made by this study to the literature is a comparative analysis of EU Member States with respect to the rate of CO₂ emission reduction resulting from differentiated levels of renewable energy shares in the energy mix. The empirical analysis was conducted using correlation analysis and the non-parametric Kruskal-Wallis test. The adopted research framework enabled the identification of statistically significant differences between groups of countries with varying shares of renewable energy in their energy mix. The analysis supports the following conclusions:

1. The results show that an increase in renewable energy promotes carbon emission reduction on an annual time scale. This effect results from the phasing out of fossil fuels, which have a large carbon footprint and emit other pollutants detrimental to the environment and public health. Despite this, the magnitude of the effect varies across the community. The reason could be different levels of effectiveness and scopes of energy transitions in individual states, the initial shares of renewable energy, and distinctive constraints of national economies. Many countries that historically addressed their energy needs with fossil fuels (such as the Visegrád Group countries) tend to transition more slowly towards renewable energy. Their carbon reduction is also below that of countries that have had renewable energy as part of their mixes for years (such as Scandinavian countries) because of favourable natural conditions. Good examples include the hydropower industry in Sweden and Finland, as well as wind turbines in Denmark. Moreover, as decarbonisation through renewable energy sources requires high capital investments to upgrade power infrastructure, it is within the reach of more developed countries rather than developing ones.
2. The classification of EU Member States into three groups depending on the shares of renewable energy in their mixes (< 15%; 15–30%; and > 30%) in 2000, 2010, and 2023 identified a substantial increase in the number of countries in groups with a greater commitment to renewable energy. The regulations and strategies pursued in the EU in the twenty-first century set the course towards renewable energy and carbon footprint reduction.
3. The research hypothesis that EU Member States with a substantial share of renewable energy in their mixes exhibit a greater decline in carbon emissions than countries with a lower renewable energy percentage has been confirmed. The results show a particularly beneficial impact of renewable energy on carbon emission reduction in countries with more than 15% of renewable energy in the mix. In contrast, countries with low shares

of renewable energy exhibit higher levels of CO₂ emissions. The results demonstrate that improved carbon footprint reduction rates require a specific threshold of renewable energy in the mix to be exceeded. Moreover, countries seeking to expand their renewable energy capabilities can expect a synergistic effect on carbon reduction, as such governments often address other climate-related issues, such as improving energy efficiency, investing in transmission networks, or installing energy storage facilities.

4. The empirical analysis revealed a threshold of renewable energy share in the energy mix with potential policy implications. The results show that the effects on CO₂ emission reduction remain limited until this threshold is exceeded. This observation prompts reflection on the type and design of implemented climate and energy policy instruments. These may include various forms of subsidies and preferential loans facilitating investments in renewable energy, the introduction of feed-in tariffs, or streamlined administrative procedures. The key characteristics of such instruments should be their effectiveness and rapid impact in achieving this threshold, as well as in ensuring that a high share of renewable energy is maintained in the energy structure in the long term.
5. The economic policy towards reducing carbon emissions through renewable energy in EU Member States should take into account its initial share in the country's energy mix. Improved access to support schemes for renewable energy (such as grants or preferential loans) should translate into a substantial reduction of carbon emissions, especially in countries with low shares of renewable energy. Clearly, the renewable energy policy should accommodate national environmental conditions that favour specific energy generation technologies, such as strong winds or high solar irradiance. Auxiliary issues critical for the expansion of renewable energy use include upgrading and expanding power infrastructure, improving energy efficiency, and implementing fiscal mechanisms that support clean and accessible energy while discouraging the use of conventional fuels (such as subsidies for renewable energy over fossil fuels). Despite this, a successful energy transition has to win public approval. For this to happen, there needs to be a raising of awareness of the role of renewable energy in reducing carbon emissions and improving environmental well-being and public health.
6. The study has certain limitations, which can inspire future analyses of the topic. It investigates a single variable, accounting for carbon emission reduction only in EU Member States over an arbitrarily selected period. This issue could be analysed for the EU or other international organisations (such as the OECD) over the long term, taking into account other factors that help reduce CO₂ emissions, such as energy efficiency, quality of climate policy, or public attitudes towards saving energy.

The present study is exploratory in nature and focuses on two key variables. The authors plan to extend the analysis by incorporating a broader set of explanatory variables, which will provide a more comprehensive understanding of the mechanisms underlying the energy transition in the European Union.

Data availability

The data and materials used in this study are publicly available at <https://ourworldindata.org>

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