Vol. 1 No. 1

Advances in Engineering and Multidisciplinary Knowledge

Are renewables associated with greenhouse gas emissions?

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Abstract: The industry is undergoing a significant transformation since the introduction of Industry 4.0 and Industry 5.0, with a special focus on sustainability, circular economy and the digitalization of manufacturing processes. This shift from traditional industry is primarily influenced by the digital revolution, climate protection, and environmental sustainability. Key technological developments in the sector include the intensive use of data, carbon-waste recycling and the production of base chemicals using H2 from renewable energy in combination with CO2. Our research investigates potential factors affecting greenhouse gas emissions, considering energy production from hydropower, wind and solar photovoltaic sources. With the help of publicly available data provided by the Directorate-General for Energy of the European Commission for the period of 1990-2021, we conduct a comprehensive statistical analysis. The findings of our study reveal statistically significant differences in renewable energy production between countries with high versus low CO2 emissions. Furthermore, we examine the relationship between greenhouse gas emissions, renewable energy production and economic indicators, using gross domestic product as a measure of the wealth of a country. These insights offer valuable guidance for countries developing environmental policies aimed at increasing the production and usage of renewables, while maintaining low greenhouse gas emissions.

Keywords: Renewable energy; Greenhouse gas reduction; Sustainability.

1 Introduction

Reducing global greenhouse gas emissions (GHG) is one of the most crucial challenges of the 21st century. The concept of Sustainable Development Goals (SDGs) introduced by Hoegh-Guldberg et al. [1], and the 2016 Paris Agreement [2] provide the framework for achieving the long-term goals of GHG reduction. The 28th Conference of the Parties to the United Nations Framework Convention on Climate Change (COP28) in 2023 emphasized the need for urgent actions by 2030. They highlighted that the transition from fossil fuels to renewable energy sources, especially to wind and solar power, should be prioritized. While implementation strategies vary among countries based on their natural and financial resources, Levin-Nally & Gómez [3] show that SDG 13 (Climate Action) provides guidance for reducing carbon footprints. They suggest for companies sourcing renewable electricity from wind, solar or hydro power, and improving transport efficiency by optimizing the fuel usage. According to the 2023 SDG Report [4], renewable energy adoption has increased, though stronger cross-sectoral policies are needed to accelerate this growth. The European Union has already achieved a 30% reduction in GHG emissions compared to 1990 levels [5], but the new target is to reach at least 55% by 2030. Renewable energy production in the EU has grown significantly, becoming the largest share of primary energy production by 2021. Energy consumption in the EU is distributed across several sectors: over 20% for energy transformation, more than 15% for transportation, more than 15% for households, and more than 15% for the industry sector. Given this economic dependence on energy services, policies promoting the efficient use of clean energy are essential. Industry 5.0 initiatives are supporting this transition by integrating SDGs into industrial processes and facilitating both digital and environmental transformations.

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To sustain the reduction of greenhouse gas emissions is a complex challenge that has been extensively studied across the European Union. Su et al. [6] identified the primary GHG-emitting countries among 28 EU nations between 1991 and 2012. Lamb et al. [7] further categorized emission reduction patterns into three distinct trajectories: long-term increases followed by a rapid decrease, or a continuous decline since 1970, or sudden drops around 1990 followed by stabilization. Their study identified 22 European countries that successfully reduced CO2 emissions between 1970 and 2018. Yang et al. [8] analyzed 13 major renewable energy producers from 2010 until 2019, and their investigation revealed that countries with higher renewable energy production often exhibit higher CO2 emissions. The study of Marotta et al. [9] highlighted the challenges faced by countries with a higher population and higher GDP in reducing emissions. The research work of Lin et al. [10] projected that 15 EU countries might increase their emissions by 2030, and seven countries could achieve optimal balance between CO2 emissions and renewable energy production. Huang et al. [11] also studied GHG emissions by examining the relationship between emission reduction and renewable energy consumption. Anghelache et al. [12] documented an increasing trend in renewable energy usage across EU, emphasizing the need for expanded renewable production. As Haller et al. [13] noted, future research should broaden its scope beyond energy production to consider economic conditions, technological advancements, and digitalization, which can also be crucial factors in emission reduction.

The present research work investigates and discusses the relationship between renewable energy production and greenhouse gas emission in Europe. Specifically, we examine the correlations between CO2 emissions and renewable energy production from three key sources: hydropower, wind, and solar energy. Our analysis extends beyond environmental impacts to consider economic factors, using gross domestic product as a measure of national economic capacity. Through this comprehensive analysis, we aim to develop evidence-based policy recommendations for nations seeking to expand their renewable energy capacity while maintaining low greenhouse gas emissions. These recommendations will focus on practical strategies for increasing renewable energy production and utilization within the context of each country's economic capabilities.

2 Methods

The present study analyzes data provided by the European Commission's Directorate-General for Energy, which contains annual energy statistics for EU member states since 1990. We examine CO2 emissions measured in Mt in relation to three primary renewable energy sources: hydropower (electricity generated from water in hydroelectric plants), wind energy (electricity produced by wind turbines), and solar photovoltaic energy, all measured in millions of tons of oil equivalent (Mtoe). CO2 is a significant contributor to global warming, and it is analyzed as the primary non-fluorinated greenhouse gas. Our statistical analyses consist of the following key steps:

1. Analysis of time-series trends in CO2 emissions in the last 30 years.
2. Analysis of the descriptive statistics of CO2 emissions, renewable energy production from hydro, wind and solar power, and GDP.
3. Analysis of the distribution of CO2 emissions.
4. Classification of EU countries based on their CO2 emissions relative to the EU-wide average.
5. Statistical test (t-test) of average renewable energy production between high and low CO2-emitting countries.
6. Analysis of pairwise correlations between CO2 emissions and renewable energy production sources.
7. Comprehensive assessment of countries in both emission categories, considering their

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environmental, economic, and financial characteristics.

3 Results

The analysis of CO2 emission data from the past three decades reveals two distinct periods, as shown in Figure 1. From 1990 to approximately 2005, emissions remained relatively stable, fluctuating around a very high value of 3800 Mt. However, since the second half of 2000s, emissions exhibit a steep downward trend, decreasing by approximately 1000 Mt by 2020s. As the national total CO2 emissions exhibit a great decrease after 2005, the present analysis focuses on the relationship between greenhouse gas emissions and renewable energy production after 2005.

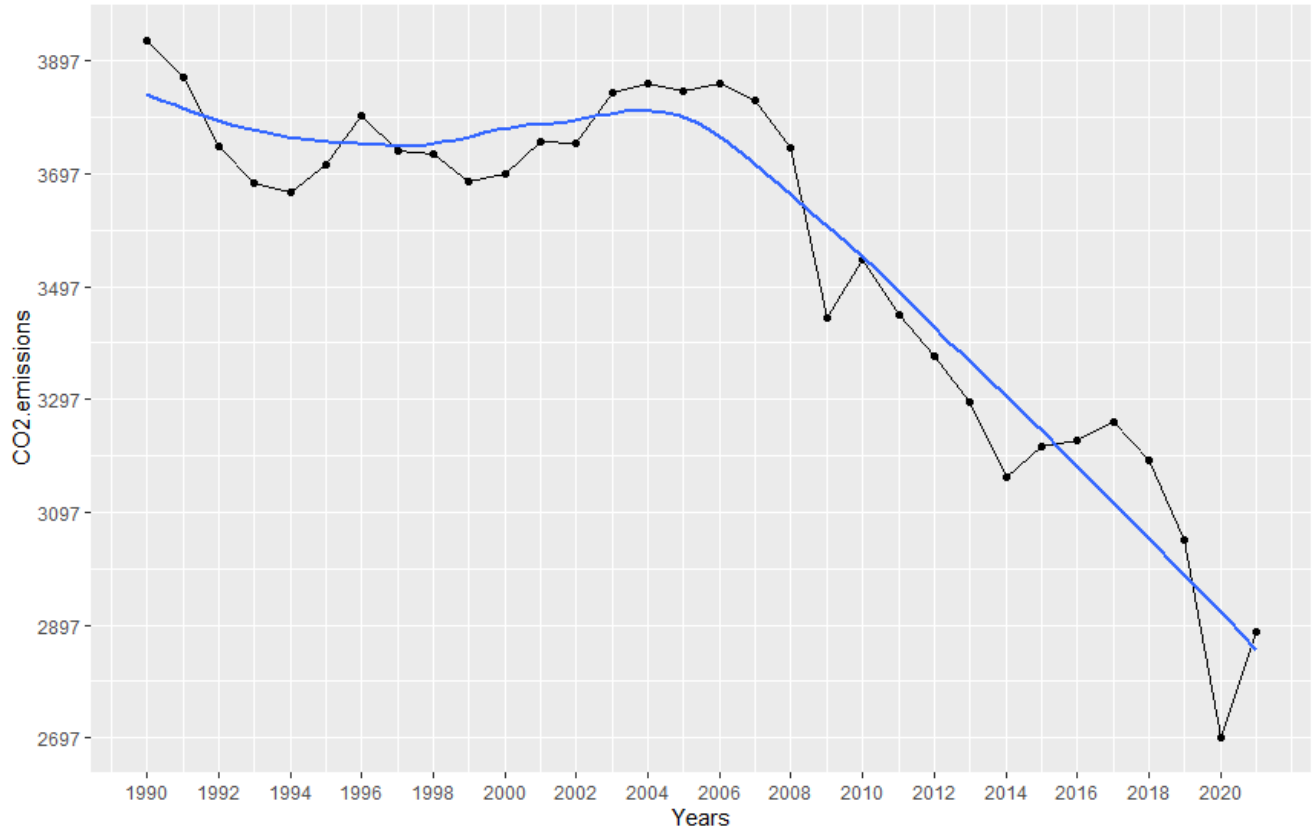

Figure 1: Time series plot for national total CO2 emissions between 1990 and 2021, exhibiting a great decrease in CO2 emissions after 2005.

The descriptive statistics of CO2 emissions, renewable energy production from hydro, wind and solar power, and GDP are summarized in Table 1. The data exhibit substantial variability, as indicated by high standard deviations, reflecting significant differences between minimum and maximum values across all variables. The mean values are ara also much higher than the medians for every variable, which indicates a right-skewed distribution. For example, we can observe a great variability in CO2 emissions, ranging between 8 and 818 Mt. The average emission in all countries is 135.51 Mt, however, the median is only 53.46 Mt, indicating that half of the data is above this value. A more detailed analysis of the distribution of CO2 emissions confirms these patterns as shown by the boxplot in Figure 2. We can observe the right-skewed distribution of CO2 emissions with several outliers, indicating that some countries have much lower emissions than others and vice versa.

Table 1: Descriptive statistics of CO2 emissions, renewable energy production from hydro, wind and solar power, and GDP

CO2 emissions		Hydro	Wind	Solar	GDP
Min.	8.0	0.0016	0.0003	0.0001	20.8
Max.	817.9	5.8	5.9	2.3	2953.5
Median	53.5	0.4	0.3	0.05	196.7
Mean	135.5	1.2	0.8	0.2	483.9
St. Dev.	187.8	1.7	1.4	0.5	739.1

Considering these patterns observed in the data, including outliers, indicating distinct patterns in different countries, we split the data into two parts. As a threshold, we calculated the ratio of the cumulative average amount of CO2 emissions for all countries provided by the Directorate-General for Energy of the European Commission, and the total number of countries (135.5).

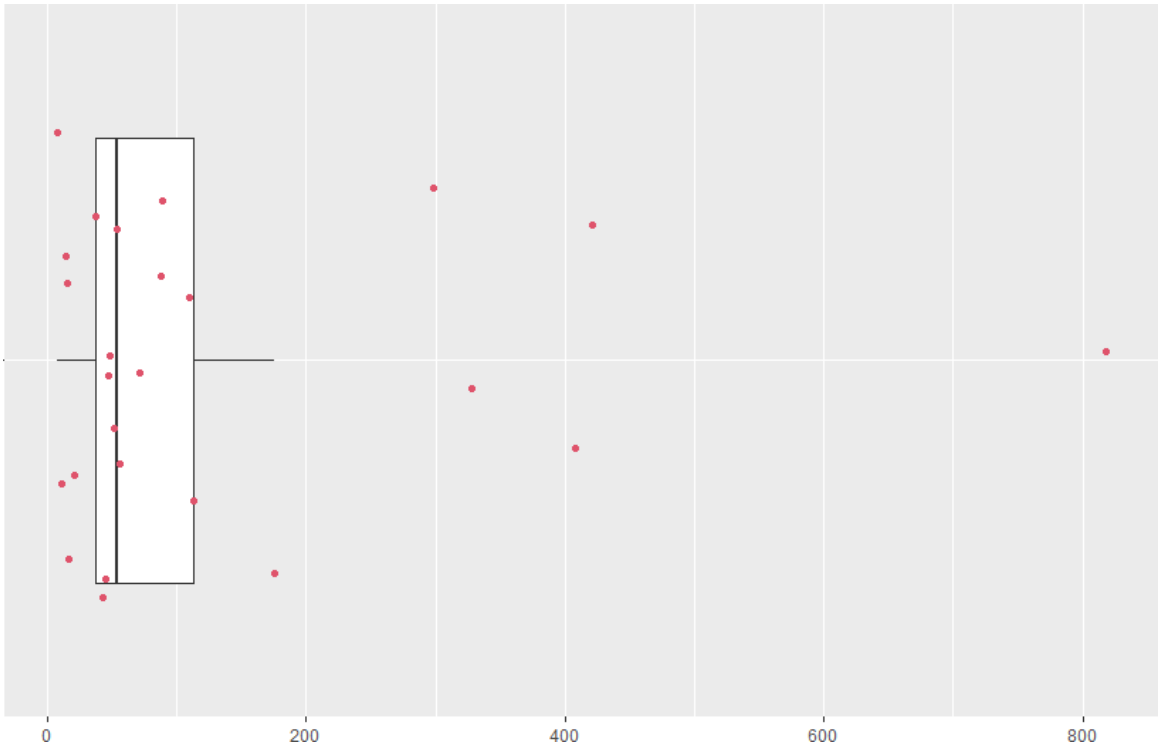

Figure 2: Figure 2 The distribution of CO2 emissions (in Mt) in the European Union since 2005

So, we conduct further detailed analyses based on two groups of countries, six with low versus nineteen with high levels of CO2 emissions. Table 2 reveals that there is a statistically significant difference in the average amount of CO2 emissions between the two groups of countries, indicated by the small p-value (0.01). The results of the statistical analyses also revealed significant differences in the average amount of energy production from wind and solar power in countries with low versus high CO2 emissions (at $\alpha = 0.1$). There is also a statistically significant difference in the average amount of GDP between the two groups of countries. For this exploratory study the significance level is rather high, so that it can reduce the risk of false negatives, and it as well considers the rather small sample size.

Table 2: Statistical analysis of the variables in countries with low vs. high level of CO2 emissions

	High (N = 6)	Low (N = 19)	High (N = 6)

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	(mean, SD)		(mean, SD)
CO2	408 (220)	49.4 (32.6)	0.01
Hydro	2.2 (1.9)	0.8 (1.5)	0.2
Wind	2.3 (2.2)	0.3 (0.3)	0.1
Solar	0.8 (0.8)	0.05 (0.06)	0.1
GDP	1502 (960)	162 (131)	0.02

Besides categorizing the countries based on their levels of CO2 emissions, we can also classify the countries of the European Union based on the ratio of the cumulative average amount of renewables for all countries provided by the Directorate-General for Energy of the European Commission, and the total number of countries. Table 3 highlights further patterns between countries with high vs. low CO2 emissions in terms of renewables. It uses the following color- coding:
High CO2 emissions are colored red, and low CO2 emissions are colored blue.
Given that CO2 emissions are low, and at the same time renewable energy production from hydro, wind and solar power are all low, the cells of the 3 renewables are white.

Given that CO2 emissions are low, and at the same time renewable energy production from hydro or wind or solar power (at least one) is high, the cells of the 3 renewables are orange.
Given that CO2 emissions are high, and at the same time renewable energy production from hydro, wind and solar power are all high, the cells of the 3 renewables are also red.
Given that CO2 emissions are high, and at the same time renewable energy production from hydro, wind and solar power are all low, the cells of the 3 renewables are green.
Renewable productions from all three sources and CO2 emissions are below the thresholds in fifteen countries, indicated with white color. Both renewable energy production and CO2 emissions are above the thresholds in four countries, indicated with red color. All renewable energy productions are below the thresholds while CO2 emissions are above the thresholds in two countries, indicated with green color. CO2 emissions are below the thresholds, while either hydro or wind energy productions, or both at the same time are above the thresholds in six countries, indicated with orange color.

Hydro (1.2)	**Wind (0.8)**	**Solar photovoltaic (0.2)**	**CO2 emissions (135.5)**
low	low	low	low
low	low	low	low
low	low	low	low
low	high	low	low
high	high	high	high
low	low	low	low
low	low	low	low
low	low	low	low
high	high	high	high
high	high	high	high
low	low	low	low

high	high	high	high
low	low	low	low
low	low	low	low
low	low	low	low
low	low	low	low
low	low	low	low
low	low	low	low
low	low	low	high
high	low	low	low
low	low	low	high
low	high	low	low
high	low	low	low
low	low	low	low
low	low	low	low
high	low	low	low
high	high	low	low

Additionally, we observed that in four countries the greenhouse gas emissions are below the thresholds, however the values are still very high compared to the other values that are below the threshold. Therefore, we might also consider these four countries with high levels of greenhouse gas emissions.
The pairwise correlation coefficients of CO2 emissions and the variables representing renewable energy (hydro, wind and solar) shown in Figure 3 indicate a strong negative linear relationship between CO2 emissions and wind, as well as between CO2 emissions and solar energy (ρ < -0.9). There is a rather weak negative linear relationship between CO2 emissions and hydro energy (ρ = -0.44).

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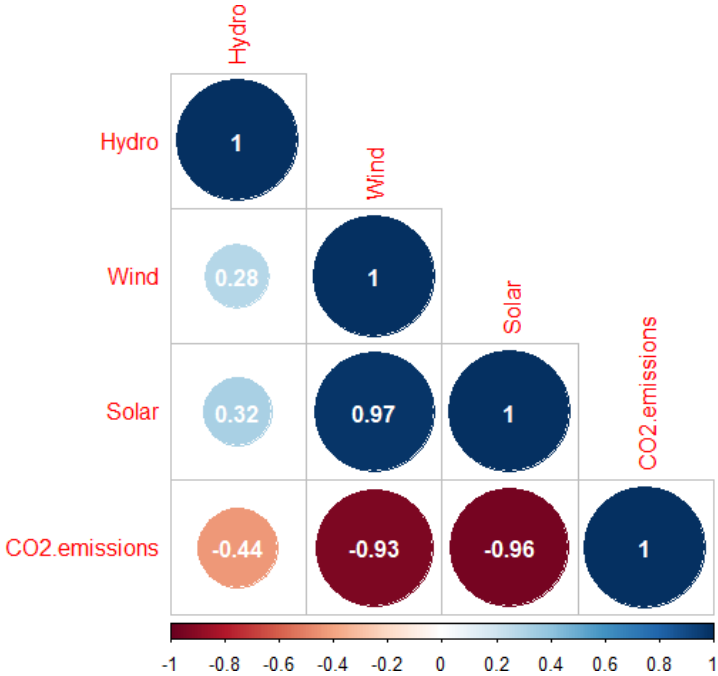

Figure 3: Correlation coefficients of CO2 emissions and renewable energy from hydro, wind and solar power.

These results indicate that when the energy production from renewable energy sources increases, the CO2 emissions tend to decrease, especially in case of solar and wind energy. We will use these preliminary results to further explore the countries in the two categories, also in terms of their environmental, economic and financial capacities.

4 Discussion

The current data suggest that the utilization of renewable energy sources tends to decrease the carbon dioxide emissions dramatically, especially after 2005. The present work assesses the possible relationships between carbon dioxide emissions and energy production from the three main renewable energy sources: hydro, wind and solar power. Based on our results, energy production from hydro power does not exhibit significant effects on CO2 emission reductions, which is in-line with previous findings [8]. The statistical analyses of this study reveal that energy production from solar power is the most promising type of renewable energy production, followed by energy production from wind. The usage of wind and solar power seems to be a potential factor to help with greenhouse gas emission reduction in European countries.

There are mainly 6 countries that are responsible for CO2 emissions in Europe. Renewable energy-based electricity production is very low in two countries, which can be the explanation for the high CO2 emissions. However, there are 4 countries that highly utilize renewable energy sources, and are still responsible for high CO2 emission in the European zones as also observed by Yang et al. [8], who show that countries that produce more renewable energy, tend to have higher levels of CO2 emissions. Further recent studies such as by B. Lin & Okoye [14] confirm that renewable energy generation in high-income countries still do not exhibit strong impact on GHG emission reduction. This requires detailed investigation of these 4 countries and to see if they have significant decrease in CO2 emissions although they hold the highest amounts. It was observed that renewable energy consumption reduces the per capita ecological footprint of high- income countries [15].

Technological advancements have facilitated the shift from fossil fuels to renewable energy sources such as wind, hydro, and solar power. However, the availability of natural resources varies across European

countries, influencing their renewable energy potential. Economic factors also play a crucial role, as some countries face financial constraints in adopting new sustainable energy technologies. Therefore, careful planning is necessary to balance resource availability and economic feasibility within the framework of circular economies.
Our current observation leads us to further examine the countries in the two categories with low versus high CO2 emissions, and how gross domestic product as an indicator of the wealth of a country is related to greenhouse gas emissions. We also plan to further investigate the patterns based on the thresholds for renewable energy production from hydro, wind and solar power.

5 Conclusion

The primary objective of this study is to investigate whether the adoption of renewable energy sources is linked to a reduction in greenhouse gas emissions in Europe. Our research findings emphasize the crucial role of renewable energy production from hydro, solar and wind power in mitigating CO2 emissions. The analysis of available data revealed distinct patterns that enabled us to categorize countries based on their emission levels, distinguishing between those with low and high CO2 emissions. Additionally, we identified clear differences in renewable energy production, allowing us to differentiate between countries with low and high levels of renewable energy productions from hydro, solar and wind power. Moreover, our study uncovered a statistically significant difference in the average GDP between countries with low vs. high CO2 emissions, suggesting that economic factors may play a key role in emission levels. These insights can serve as a valuable resource for policymakers, guiding them in the development of effective environmental policies aimed at increasing renewable energy production while maintaining greenhouse gas emissions at a manageable level. However, any recommendations for practical implementations should consider the diverse environmental, economic, and financial conditions of individual countries to ensure feasible and sustainable policy adoption. Based on the preliminary results of the present study, we aim to further investigate the factors associated with greenhouse gas emissions, by developing statistical models.

Conflicts of Interest Statement

The authors certify that they have NO affiliations with or involvement in any organization or entity with any financial interest (such as honoraria; educational grants; participation in speakers' bureaus; membership, employment, consultancies, stock ownership, or other equity interest; and expert testimony or patent-licensing arrangements), or non-financial interest (such as personal or professional relationships, affiliations, knowledge or beliefs) in the subject matter or materials discussed in this manuscript.

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