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REASSESSING THE IMPACT OF RENEWABLE ENERGY USE ON CO_2 EMISSIONS IN THE EU COUNTRIES USING A PANEL QUANTILE FRAMEWORK

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Abstract: *This research investigates the factors contributing to the decrease in carbon emissions across EU countries, with a focus on renewable energy use. For this purpose, we rely on a panel data framework* covering 33 years and 27 EU *countries. We examine the influence of green energy sources on carbon pollutants, involving other variables for control, namely the income per capita growth rate, foreign investment inflows, population, and labor force (for robustness purposes). First, we use an Ordinary Least Squares (OLS) model that incorporates both fixed and random effects. Second, as novelty, we perform a panel quantile regression analysis to see if the renewables' impact on emissions is asymmetric and depends on the carbon emissions' level. The first set of results showed that increased renewable energy consumption leads to lower CO_2 emissions. At the same time, the findings generated within a panel quantile framework revealed that the effect of renewable energies is more substantial in countries with lower emissions.*
Keywords: *CO_2 emissions, carbon emissions, renewable energy, panel quantiles.*

1. INTRODUCTION

Starting with the 1992 "Earth Summit" and continuing with the 1997 "Kyoto Protocol", European countries underlined the need to reduce CO2 emissions that contribute to climate change worldwide.

In difficult times, the concession between sustaining market growth and protecting the environment is reconsidered. However, there is a pressing global need to design appropriate policies for an eco-friendly environment, underlying the negative effects of pollution.

Global economic activity threatens the natural balance of atmospheric gases, leading to increased air pollution, acid rain, and global warming. Environmental pollution has begun to take on worrying aspects and proportions. Atmospheric pollution has caused the average global temperature to increase by approximately half a degree Celsius, and the resulting changes will have a profound impact on people's lives. The fight against pollution requires great caution, both in avoiding air pollution and water and soil pollution. From this perspective, the contribution of green energy use emerges as fundamental.

The threats of pollution prompted policymakers to design economic growth strategies that consider sustainable environmental policies and the potential implications for public health. Following this approach, the Paris Agreement was established in 2015 to combat global warming. As a result, the goal of the "European Climate Law" of 2021 was to reduce carbon emissions by 55% by 2030. To do that, each EU member state, through the application of European Directive 2004/35/EC, is ensuring adherence to current pollution standards and targets.

Most economic activities generate air pollution, whereas the economic sectors with a higher contribution to emissions are industry, agriculture, transport, and energy production. Although air pollution has generally decreased in the EU economies in recent decades, the objective of 'achieving a level of air quality that does not have serious harmful consequences for human life and ecosystems' has not yet been achieved. Air quality standards are often

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violated, especially in urban areas, which are hotspots for air pollution and where most Europeans live. Currently, the most problematic pollutants are fine particles and nitrogen oxides, but carbon emissions also contribute to global warming, with worse consequences for society. As [6] suggested, European air pollution regulations contributed to a reduction in NO_2 and SO_2 emissions, but the effect was not as expected. Therefore, the effectiveness of EU environmental policies is also called into question.

Under these circumstances, the main scope of the present study is to reassess the outcome of renewables use on CO_2 pollution, considering the asymmetric impact of pollution levels, given that CO2 accounts for 80% of greenhouse gases. Our dataset includes 27 EU countries spanning from 1990 to 2023.

In addition to the role of renewables, we also assess the leverage of other factors on CO_2 emissions. First, we control the influence of GDP per capita. As Kuznets [2] demonstrated in 1955, income per capita positively influences pollution up to a turning point, after which income is exceptionally high and pollution decreases. Second, we check for the influence of foreign capital invested, to see if the "Pollution Haven Hypothesis", or rather the "Pollution Halo Hypothesis" is validated in European states. [3] reported a pollution hallo effect for a sample of 29 provinces from China from 1995 to 2010, underlining that foreign inflows reduce carbon emissions [3].

This study builds on [4,5], highlighting that renewable energy use contributes to lower CO_2 emissions.

We contribute to existing studies and literature in two distinct approaches. First, we employ static panel data models and the OLS estimator to investigate the effect of green energy on air pollutants. With a focus on the European states and the 1990 to 2023 period, we compare fixed effects and random models' specifications. Second, we posit that the level of pollution in each country can also determine the implications of renewables' use on the pollution level. More precisely, if the pollution level is reduced, authorities privilege the use of renewable energy in their environmental policy frameworks. On the contrary, in high-pollution states, the influence of renewables on CO2 pollutants might be negligible, and other policy constraints are necessary to control the pollution level. In this context, we use a panel data quantile approach.

The research is structured as follows: Section 2 outlines the theoretical framework and summarizes the literature; Section 3 details the data and methodological approach; Section 4 reports the findings and compares six models with respect to CO_2 emissions; and the final section highlights the limitations and the policy and managerial implications.

2. THEORETICAL BACKGROUND

Previous studies underlined different factors impacting carbon emissions: economic growth [6,7,8]; the level of human capital [9,10]; urbanization [11,12]; export and import [13,4].

A series of studies are arguing that the use of renewable energy in a more intensive way reduces carbon emissions [4,5,14]. Nevertheless, a trade-off might appear between environmental protection and economic growth. For example, Acheampong [15] discovered that worldwide renewable energy use negatively impacts economic results, while income growth enhances carbon emissions.

The relationship between renewable energy and pollutant emissions is complex. Apergis et al. [16] use data for 19 developed countries covering 27 years (1984-2007), and a Granger framework, and find that renewable energy consumption positively influences gas emissions. On the contrary, Chen et al. [17] uses a database of 128 countries spanning 24 years, showing a decrease in emissions. Meanwhile, [4] in a study conducted in an oil-rich country found that a 1% growth in renewables consumption implies a 0.27% drop in CO_2 air pollution.

The influence of FDI on emissions is ambiguous. In cases where multinational companies invest in countries with lax environmental standards, the "Pollution Haven Hypothesis" holds, implying a positive relationship between FDI and pollution. On the contrary, if FDI is green and contributes to a reduction of pollution level, the halo hypothesis will be confirmed. Previous work has outlined that foreign investments decrease emissions in countries with a high income, while generating

an increase of carbon emissions in middle-income countries [18]. Less developed countries are hunting foreign investments to amplify their economies with the latest green technologies but paying a high price: "the transfer of the polluting industries "[19].

At the same time, countries with more flexible environmental regulations can attract more foreign investments because of the benefits: reduced cost of energy due to eco-friendly technologies and know-how [18, 20]. According to [20], there has been identified an inverse link between foreign direct investment and CO_2 emissions [21].

Regarding population, [22] examined Southeast Asian countries and found that population size positively influences green energy usage but has no significant impact on carbon emissions. Additionally, research by [24], using data from 78 regions at both regional and global levels, indicated that population dynamics are the main cause of carbon pollutants, as reflected in per capita GDP. Therefore, our study contributes to this body of literature and builds upon this work. of [5, 22, 23].

3. RESEARCH METHODOLOGY

This research seeks to analyze how green energy consumption influences CO2 air pollution and also control for the effects of other factors on carbon emissions. The sample encompasses data from 1990 to 2023, sourced from World Bank statistics, focusing on 27 EU countries.

The main variable being measured is carbon emissions per capita (CO2_cap). The independent variable of interest is the share of green energy in total final energy consumption (RENEW). The control variables are the annual percentage growth rate of GDP per capita (GDP), net foreign direct investment inflows (FDI), and the logarithm of the number of inhabitants (POP). For robustness checks, the labor force (LBF) replaced the population size, with both variables measured in natural-log form.

In the first stage, using panel data static models, we tested the following hypotheses: H1: The increase in renewable energy consumption negatively impacts the EU-level carbon emissions.

H2: GDP per capita growth rate increases carbon emissions.

In line with [5], the general equations are:

- for the fixed effects model:

$$y_{it} = \beta_0+\beta_1 X_{i,t}+\beta_2 Z_{i,t}+\alpha_i+ \varepsilon_{i;t} \quad (1)$$

where y_{it} represents the CO_2 emissions (dependent variable); X_{it} represents the interest variable (renewables use); Z_{it} represents the control variables (GDP, FDI, POP, LBF); β_0 is the constant term; α_i - stable elements (fixed effects); β_1, β_2 -coefficients; $\varepsilon_{i,t}$ represents the error term.

- for the random effects model:

$$y_{it} = \beta_0+\beta_1 X_{i,t}+\beta_2 Z_{i,t}+\alpha_i+ \mu_{i,t+} \varepsilon_{i,t} \quad (2)$$

where $\mu_{i,t}$ are associated with the cross-entity errors; $\varepsilon_{i,t}$ captures the within-entity variation.

4. RESULTS

The statistical overview shows that the series lacks a normal distribution (please refer to Table 1). It can be observed that some countries are almost entirely dependent on fossil fuels or other non-renewable energy sources, while others use nearly 57.9% green energy.

Regarding carbon dioxide emissions, a few highly polluting countries have reached the maximum level. In 2023, for example, Luxembourg, Estonia, the Czech Republic, Poland, Belgium, Germany, the Netherlands, and Austria recorded the highest per-capita carbon emissions. At the same time, Sweden, Finland, Latvia, Denmark, Estonia, Austria, Croatia, and Lithuania are the countries with the highest levels of renewable energy use.

Table 1

Summary statistics.

	CO2_capita	RENW	GDP	POP
Mean	8.137	15.318	2.005	6.858
SD	3.951	11.868	4.447	0.591
Min	2.998	0.000	-31.177	5.549
Max	32.193	57.900	23.443	7.932

CO2_cap – carbon emissions per capita; RENW – renewable energy consumption (% of total energy consumption); GDP – is the GDP per capita growth (annual %); POP – represents the total population (expressed in natural logarithm)

Before conducting the estimations, we utilized the panel unit root test, which examines the stationarity of the variables. We note that all our series are only stationary in first differences (D) (the authors can provide these results upon request). To validate our hypothesis, the general equation we have tested is the following:

$$D(CO2\_cap)_{it} = c + \alpha^* D(RENW)_{it} + \beta^* D(GDP)_{it} + \lambda^* D(FDI)_{it} + \delta^* D(POP)_{it} + \varepsilon_{it} \quad (3)$$

According to Table 2, across all situations and both fixed- and random-effects models, the use of renewables negatively influences carbon emissions, a statistically significant effect at the 99% confidence level. More precisely, a 1% growth in green energy use is expected to lead to a 0.18% diminish in per-capita emissions. This result is very robust and holds across all specified models, confirming the work of [4,5,14]. The first hypothesis is supported. It seems that the action of promoting green sources helps reduce the effect of climate change. Additionally, if the level of production increases, this will also increase the level of emissions (the second hypothesis is validated). This result confirms the findings of [24]. Using panel data at regional level, [24] demonstrates that the growth of GDP per capita is associated with increased carbon emissions. Our results show that a 1% increase in per capita growth rate is associated with a 0.02% growth in CO_2 emissions. These findings contradict the results reported in the work of [22].

Other factors, such as the inflow of foreign investments, have been investigated, yielding results with no significant impact on emissions, as noted in the work of [5].

An increase in population leads to a decrease in emissions, which demonstrates that larger EU countries pollute less compared with their counterparts, in terms of emissions per capita. However, given the involvement of large EU countries in environmental protection, we can conclude that these countries pollute less per capita. According to [26], Germany and France are the biggest countries in the EU and big energy consumers. France has, however, among the lowest emissions per capita. Overall, the results suggest that emissions are more strongly influenced by energy use than by population size.

To verify the asymmetries in per capita CO2 emissions between high- and low-polluting countries, we will continue with a quantile panel regression. The quantile findings are presented in Table 3. A substantial negative effect of renewables on emissions is observed across all quantiles. Nevertheless, the effect of using renewables is more pronounced in less-polluting countries (lower quantiles) than in high-polluting countries (higher quantiles). For example, countries like Malta, Latvia, Lithuania, Sweden, and Portugal have experienced a significant impact from using green energy. Consistent with the findings reported in Table 2, economic expansion is a significant driver of emissions, primarily due to more intensive industrialization.

Table 2

Panel data findings

D(CO2_capita)	Model I (naïve regression)	Model II Rd. Ef.	Model III Fi. Ef.	Model IV (Rd. Ef. robustness)
C	-0.023	0.011	0.011	-0.001
D(RENW)	-0.187***	-0.163***	-0.163***	-0.163***
D(GDP)		0.024***	0.024***	0.026***
D(FDI)		0.000	0.000	0.000
D(POP)		-17.673***	-17.673***	
D(LBF)				-2.045
Note: ***, **, * means significance at 99%, 95% and 90% respectively.				

Table 3

Results of panel data analysis in quantiles

D (CO2_capita)	Entire sample	0.10Q	0.25Q	0.50Q	0.75Q	0.90Q
C	0.011	-0.419***	-0.210***	-0.000	0.175***	0.375***
D(RENW)	-0.163***	-0.177***	-0.169***	-0.132***	-0.117***	-0.108***
D(GDP)	0.024***	0.023***	0.022***	0.022***	0.019***	0.015**
D(FDI)	0.000	-0.000	0.000	-0.000	-0.000	-0.000
D(POP)	-17.73***	-32.63***	-18.34***	-7.657	-6.879**	-10.86*
Note: ***, **, * means significance at 99%, 95% and 90% respectively.						

In contrast with the work of [24] the population size negatively impacts to emissions. An explanation could be that some countries have more effective environmental policies and restrictions than others (for example, France).

At the middle quantiles (0.50), the effect of the population became insignificant. In the first quantile, the effect of using green energy is very strong (indicating that a 1% grow in renewables diminishes air pollutants by 0.17%).

The change in GDP growth is positive and significant across most quantiles, concluding that income development rise the level of air emissions.

In the higher quantiles, the effect is slightly smaller (that is, for high-emission countries). Regardless of the quantiles, FDI has no significant impact on emissions, as confirmed by [25].

4. CONCLUSION

Since 2000, EU governments have been working to reduce their CO2 emissions and promote green energy to environmental change. Therefore, studying the factors of air emissions and the significance of renewables from a European perspective is the best way to assess climate targets.

The novelty of the research is highlighted by performing this investigation in a panel quantile framework, which reveals a discrepancy between economies with small and large emission levels.

The study relies on the following variables to assess the determinants of CO_2 emission: green energy use (our interest variable), gross domestic product growth per capita, foreign direct investment, population size, and labor force (our control variables).

In all empirical specifications, we have found that renewables diminish CO_2 emissions, whereas GDP per capita growth boosts them. Several previous studies documented that growing economies attract more foreign investment and tend to generate more emissions. However, our research indicates that FDI does not directly affect air emissions in all European states between 1990 and 2023. In this way neither the “Pollution Halo Effect”, nor the “Pollution Haven Effect” are validated.

Transition to renewable energy matters more compared to other factors in explaining CO_2 dynamics in the EU countries. Likewise, in less polluting countries, such as Latvia, Sweden, and Malta, the renewables sources have a greater leverage on ecological degradation than in more polluting countries, including Luxembourg, Estonia, Belgium, the Czech Republic, and Germany.

An economic boost increases emissions, especially in countries with low carbon emissions, while higher shares of renewable energy significantly reduce them. Increasing income can only be achieved by using more green energy.

On average, our findings highlight that a 1% growth in renewables utilization will lead to a 0.18% diminishment in per capita CO_2.

From a practical perspective, this paper presents two policy implications.

First, our findings reveal the importance of green energy. Public policies should focus on establishing a financial framework that enables companies to utilize green energy sources. This can happen by organizing awareness campaigns regarding the benefits of renewable energy consumption. Additionally, the governments should streamline the bureaucratic process of accessing European funds for green energy.

Second, governments should focus on attracting more quality foreign investments for sustainable industries and foster the use of green energy. In this way, a country can foster sustainable economic growth while still benefiting from international capital inflows. In February 2025, the Clean Industrial Deal [27] was launched, where the European Union targeted high-pollution industries with the intention of financially supporting them to reduce energy costs and promote green energy sources

The study has some limitations, including the number of control variables used. Additionally, the research did not consider the environmental regulations of each country. Further studies should focus on integrating other variables, such as export, import, and urbanization.

5. TRENDS AND FUTURE RESEARCH

In 2026, the European Union is undergoing a significant "second-look" at its renewable energy strategy. While the deployment of wind and solar is at an all-time high, policymakers and researchers are moving beyond simple "total generation" metrics to more nuanced assessments of actual carbon displacement. In the following, the key trends in reassessing the effect of green energies on carbon pollutants across European states:

1. Shift from average to marginal emission factors (MEFs) - Traditionally, the EU calculated carbon savings using the "Grid Average" (total emissions divided by total power). In 2025 and 2026, there is a strong shift toward marginal emission factors. Thus, when a new wind turbine starts spinning, it does not displace average power; it displaces the most expensive, last-on plant, usually coal or gas. Using MEFs often reveals that renewables are 15 - 25% more effective at cutting carbon than previously thought, because they specifically knock "dirty" marginal fossil fuels off the grid first.
2. Full Life Cycle Assessment (LCA) transparency - There is a growing trend to scrutinize the "embodied carbon" of renewable infrastructure. This includes emissions from mining lithium in South America or manufacturing solar panels in high-coal regions of China. The key focus is on the EU Carbon Border Adjustment Mechanism (CBAM), which is now prompting a reassessment of the "net" benefit of imported renewable components. The "Greenlash" factor force policymakers addressing concerns that shifting to renewables merely "exports" carbon emissions to other countries during the manufacturing phase.
3. Addressing the "cannibalization" and curtailment effect - As solar and wind penetration increases (now exceeding 45% of electricity in some months), the EU is seeing more curtailment where green energy is wasted because the grid cannot handle the surge. Thus, reassessment trend is given by the fact that researchers are highlighting that simply adding more capacity has diminishing returns on carbon reduction if it is not paired with storage. Success is increasingly measured by system-level visibility, how well renewables integrate with batteries and cross-border interconnectors to ensure 24/7 carbon displacement.
4. Land use and "indirect" carbon impacts - A major reassessment is occurring in the LULUCF, which refers to the forestry and exploitation of land sector, particularly regarding biofuels. The ILUC Paradox arises when land used for food is diverted to biofuels, forcing deforestation elsewhere to meet food demand. Thus, EU is phasing out "high ILUC-risk" fuels (like palm oil-based biofuels) because their total carbon footprint, when including land-use changes, can sometimes be worse than fossil fuels.
5. The "two-speed" transition impact - Reassessments are showing a widening gap between Northern/Western Europe (e.g., Denmark, Sweden) and Eastern/Southern Member States (e.g., Romania, Croatia). The Finding are related to the fact that in coal-heavy grids (like Poland), a single solar panel has a massively higher carbon-displacement impact than the same panel in a nuclear-heavy grid (like France). The policy trend seems to be related to a call for "Impact-Adjusted Investment", where EU funds are directed to where the Marginal Carbon Displacement is highest, rather than where it is easiest to build.

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Evaluarea impactului utilizării energiei regenerabile asupra emisiilor de carbon în țările UE utilizând un cadru cuantilic de panel

Această cercetare investighează factorii care au contribuit la scăderea emisiilor de CO2 în țările Uniunii Europene (UE), cu accent pe utilizarea energiei regenerabile. În acest scop, ne bazăm pe un cadru de date panel care acoperă perioada 1990-2023 și 27 de țări ale UE. Examinăm impactul energiei regenerabile asupra emisiilor de CO2 utilizând un set de variabile de control, și anume rata de creștere a PIB-ului pe cap de locuitor, fluxurile de investiții străine, populația și forța de muncă (în scopuri de robustețe). Într-o primă etapă, folosim un model de minime pătrate ordinare (OLS), care încorporează atât efecte fixe, cât și efecte aleatorii. Într-o a doua etapă, ca noutate, efectuăm o analiză de regresie cuantilă panel, pentru a vedea dacă impactul energiei regenerabile asupra emisiilor este asimetric și depinde de nivelul emisiilor de carbon. Primul set de rezultate a arătat că un consum crescut de energie regenerabilă duce la emisii mai mici de CO_2. În același timp, concluziile generate în cadrul unui cadru cuantilă panel au relevat că efectul energiilor regenerabile este mai substanțial în țările cu emisii mai mici.

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