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How Did the Transition from Fossil Fuels to Renewable Energy in European Union Countries Affect Carbon Emissions? A Study Using Panel Data Analysis Method

Avrupa Birliği Ülkelerinde Fosil Yakıtlardan Yenilenebilir Enerjiye Geçişin Karbon Emisyonları Üzerindeki Etkisi: Panel Veri Analizi

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Abstract

This study examines the impact of fossil fuel and renewable energy consumption on carbon emissions (CO_2) in European Union (EU) countries by employing panel cointegration and coefficient estimation methods over the period 1990–2021. The empirical findings reveal that a 1% increase in renewable energy consumption reduces carbon emissions by 0.30%, whereas a 1% increase in fossil fuel consumption increases emissions by 1.61%. Furthermore, a 1% increase in the fossil-to-renewable energy consumption ratio leads to a 0.25% rise in carbon emissions, indicating that the structure of energy consumption is a critical determinant of environmental outcomes. The results are consistent with theoretical expectations and provide strong evidence supporting the effectiveness of the European Union's energy transition policies. Country-level findings indicate that the impact of renewable energy consumption on carbon emissions is significant in all countries except Slovenia, while fossil fuel consumption is insignificant in Austria, Slovenia, and Croatia. In contrast, the fossil-to-renewable energy ratio has a positive and statistically significant effect on carbon emissions across all countries. These findings highlight that not only the level but also the composition of energy consumption plays a decisive role in shaping carbon emissions. The study contributes to the literature by incorporating the fossil-renewable energy ratio into the analysis, offering a more comprehensive perspective on energy transition dynamics. From a policy perspective, the results suggest that increasing renewable energy investments, reducing fossil fuel dependency, and implementing effective policy instruments such as carbon pricing and subsidy reforms are essential for achieving sustainable environmental outcomes.

Keywords: Fossil Fuel Consumption, Renewable Energy Consumption, Carbon Emissions, Panel Data Analysis

Öz

Bu çalışma, 1990-2021 dönemi kapsamında panel eş bütünleşme ve katsayı tahmin yöntemleri kullanarak Avrupa Birliği (AB) ülkelerinde fosil yakıt ve yenilenebilir enerji tüketiminin karbon emisyonu (CO_2) üzerindeki etkisini incelemektedir. Ampirik bulgular, yenilenebilir enerji tüketimindeki %1'lik bir artışın karbon emisyonunu %0,30 oranında azalttığını, fosil yakıt tüketimindeki %1'lik bir artışın ise emisyonu %1,61 oranında artırdığını ortaya koymaktadır. Ayrıca, fosil yakıt-yenilenebilir enerji tüketim oranındaki %1'lik bir artış, karbon emisyonunda %0,25'lik bir artışa yol açarak, enerji tüketim yapısının çevresel sonuçların kritik bir belirleyicisi olduğunu göstermektedir. Sonuçlar teorik beklentilerle uyumludur ve Avrupa Birliği'nin enerji geçiş politikalarının etkinliğini destekleyen güçlü kanıtlar sunmaktadır. Ülke bazındaki bulgular, yenilenebilir enerji tüketiminin karbon emisyonları üzerindeki etkisinin Slovenya hariç tüm ülkelerde anlamlı olduğunu, fosil yakıt tüketiminin ise Avusturya, Slovenya ve Hırvatistan'da anlamsız olduğunu göstermektedir. Buna karşılık, fosil yakıt-yenilenebilir enerji oranı, tüm ülkelerde karbon emisyonları üzerinde pozitif ve istatistiksel olarak anlamlı bir etkiye sahiptir. Bu bulgular, enerji tüketiminin sadece seviyesinin değil, bileşiminin de karbon emisyonlarını şekillendirmede belirleyici bir rol oynadığını vurgulamaktadır. Çalışma, fosil yakıt-yenilenebilir enerji oranını analize dâhil ederek, enerji geçiş dinamiklerine daha kapsamlı bir bakış açısı sunarak literatüre katkıda bulunmaktadır. Politika açısından bakıldığında sonuçlar, sürdürülebilir çevresel sonuçlara ulaşmak için yenilenebilir enerji yatırımlarını artırmanın, fosil yakıt bağımlılığını azaltmanın ve karbon fiyatlandırması ve sübvansiyon reformları gibi etkili politika araçlarını uygulamanın şart olduğunu göstermektedir.

Anahtar Kelimeler: Fosil Yakıt Tüketimi, Yenilenebilir Enerji Tüketimi, Karbon Emisyonu, Panel Veri Analizi

Introduction

With the acceleration of industrialisation, global energy demand has increased significantly. This increased energy demand is largely met by fossil fuels. Carbon emissions resulting from the intensive use of fossil fuels cause serious environmental problems such as global warming and climate change. For this reason, policies aimed at reducing carbon emissions are coming to the fore worldwide, and the use of renewable energy sources is becoming increasingly important (IEA, 2022). In a broad sense, renewable energy sources are an energy system that constantly renews itself and causes less pollution. These sources do not contain CO_2 like fossil fuels. The main advantage of renewable energy sources is that they can be found anywhere in the world, depending on geographical and geopolitical conditions. Countries do not need to import them, and these sources alleviate the problem of energy dependence (Kralova and Sjöblom, 2010).

The burning of fossil fuels causes CO_2 emissions, leading to climate change and other environmental problems. Therefore, the extraction, transportation, and consumption of fossil fuels have caused countless problems for the environment and human health. The consumption of fossil fuels such as coal, oil, and natural gas causes large amounts of CO_2 emissions into the atmosphere, leading to global warming and climate change. The extraction and transportation of fossil fuels also cause numerous destructive ecological damages, including habitat destruction and water pollution. The environmental impacts of fossil fuels highlight the need to transition to renewable energy sources that are more sustainable and less harmful to the environment. As the world becomes more aware of the environmental damage caused by fossil fuels, it has begun to shift towards alternative energy sources (Haggar, 2011).

Renewable energy sources, which are considered the main component of energy conversion, have the potential to reduce greenhouse gas emissions by limiting the use of fossil fuels. In this context, the relationship between the transition to renewable energy and fossil fuel consumption and carbon emissions constitutes an important area of research. The European Union (EU) is at the forefront of regions that have adopted environmentally conscious energy policies and are leading the fight against global climate change. As a party to international agreements such as the Kyoto Protocol (1997) and the Paris Climate Agreement (2015), the EU has made commitments to increase the use of renewable energy and reduce carbon emissions. In this context, it has become extremely important to measure the impact of EU member states' efforts to implement renewable energy policies and reduce fossil fuel use on carbon emissions (World Bank, 2023).

Fossil fuel consumption is the main source of emissions of various greenhouse gases, primarily carbon dioxide (CO_2). Greenhouse gases released into the atmosphere as a result of the combustion of energy sources such as oil, coal and natural gas are triggering global warming by intensifying the greenhouse effect. The environmental sustainability of fossil fuel-based energy systems is quite low (Climate Watch, 2023). On the other hand, renewable energy sources (such as wind, solar, hydroelectric, geothermal, and biomass) have significant advantages over fossil fuels in terms of carbon emissions. Increasing the use of renewable energy sources reduces the carbon intensity of energy production, limits greenhouse gas emissions, and thus contributes significantly to the goal of preventing climate change (IEA, 2022). However, the transition from fossil fuels to renewable energy is directly related not only to increasing the use of renewable sources but also to reducing the use of fossil sources. Therefore, the decline in fossil fuel consumption rates, the increase in renewable energy rates, and the combined effect of these two factors on carbon emissions must be considered together. The fundamental objectives of EU energy policies are to ensure energy supply security, increase the competitiveness of energy markets, and establish environmental sustainability. Since the 1990s, the EU has been shaping its energy policies around strategies that support the transition to a carbon-neutral economy. In this context, the process that began with the Kyoto Protocol has been further strengthened by the Paris Climate Agreement, which has set ambitious targets for the period 2030-2050. These targets include increasing the share of renewable energy, improving energy efficiency, and significantly reducing carbon emissions (European Commission, 2022). As a result of the policies implemented by the EU, the share of renewable energy in total energy consumption has steadily increased, while the share of fossil fuel consumption has decreased. These trends are expected to have positive environmental outcomes. In this context, demonstrating the concrete impact of the transition to renewable energy on carbon emissions is of great importance in shaping future policies.

Today, the damage caused by carbon emissions to the environment has reached significant proportions. Research and development activities aimed at reducing environmental damage (carbon capture and storage and clean coal technologies) seek to reduce gas emissions. A significant portion of carbon emissions stems from the use of fossil fuels in the energy sector, and as energy consumption increases, carbon emissions also continue to rise. Fossil fuels used as energy sources leave behind solid and gaseous residues after combustion. These residues not only cannot be utilised but also contribute to environmental pollution (DEKTMK, 2010).

This study distinguishes itself from previous works in the literature by analyzing the impact of the transition from fossil fuels to renewable energy on carbon emissions in European Union countries not only through energy consumption levels, but also through a panel data approach that considers the fossil-renewable energy mix and the ratio between these two sources.However, the study evaluates not only the direction of the energy transition but also its effectiveness and depth. Including the ratio between renewable energy and fossil fuels in the model reveals the extent to which the transformation occurring in energy systems reflects a structural change. In this respect, the study more accurately measures the success of carbon reduction policies.Finally, this study contributes to the literature by addressing the relationship between energy transition and environmental consequences from a policy perspective. Revealing the effects of the energy mix on carbon emissions offers important insights into which policy tools might be more effective in achieving sustainable and low-carbon growth targets.

The study has examined in detail the effects of the EU's transition from fossil fuels to renewable energy sources on carbon emissions. In this context, relevant data from EU countries between 1990 and 2021 have been used. The energy crisis in Europe following the Russia-Ukraine War and the selection of EU countries for this study highlight the importance of this research. In this context, the effects of changes in the EU's energy policies will be analysed, and the effectiveness of energy transition policies in achieving environmental goals will be evaluated. The aim of this research is to analyse the impact of the transition from fossil fuel use to renewable energy sources on carbon emissions in the EU between 1990 and 2021, and to scientifically demonstrate the effectiveness of the policies implemented during this process. In this context, it is crucial to determine the impact of fossil fuel consumption rates on carbon emissions, measure and evaluate the impact of renewable energy consumption on carbon emissions, and reveal how the ratio of fossil fuel consumption to renewable energy consumption affects carbon emissions. The findings of this study will serve as an important guide for policymakers shaping the EU's energy policies. The results of the analysis can be used to validate the effectiveness of renewable energy policies, assist in the development of existing policies, and determine future strategies for energy transition.

1. Literature

Carbon dioxide emissions, which cause the greenhouse effect, are largely caused by fossil fuels used in energy production and consumption. In this context, numerous studies have been conducted recently to reduce carbon emissions from energy production or consumption.

Sato et al. (1998) analysed Japan's future energy options in their studies highlighting the importance of energy. They used MARKAL, an optimal allocation model in the energy market, to analyse the period from 1990 to 2050. According to the results of their study, it is not possible to reduce carbon emissions below 1990 levels without utilising nuclear energy. Therefore, carbon emissions can be significantly reduced by increasing nuclear energy expenditures. Liaskas et al. (2000) aimed to identify the factors causing changes in the level of industrial carbon emissions in their study. In their study, they analysed changes in output level, energy intensity, fuel mix, and structural change factors using algebraic decomposition methods. As a result of their study, they concluded that it is possible to reduce carbon emissions without negatively affecting economic growth. Apergis et al. (2010) used a panel error correction model for the period 1984-2007 in 19 developed and developing countries to test the causal relationship between carbon emissions, nuclear energy consumption, renewable energy consumption, and economic growth. According to long-term forecasts, there is a negative relationship between nuclear energy consumption and emissions, while there is a statistically significant positive relationship between renewable energy consumption and emissions. It was concluded that nuclear energy consumption plays an important role in reducing carbon emissions in the short term, whereas renewable energy consumption does not contribute to reducing emissions.

Pao and Tsai (2011) tested the dynamic relationship between pollutant emissions, energy consumption, and output in Brazil between 1980 and 2007. According to the causality results, a strong two-way causal relationship was found between income, energy consumption, and emissions. As a result of their studies, a dual strategy was adopted, recommending that Brazil increase its energy infrastructure investments to reduce CO_2 emissions and prevent negative effects on economic growth, and accelerate its energy conservation policies to reduce energy waste and increase energy efficiency. Abolhosseini et al. (2014) examined the effects of developments in renewable energy, innovations in energy technologies, and environmental taxes implemented to increase renewable energy on CO_2 emissions in their study, which considered data from 15 EU countries for the period 1995-2010. As a result of their study, they concluded that increases in environmental taxes and innovations in energy technologies reduced CO_2 emissions.

Bölük and Mert (2014) examined the relationship between fossil and renewable energy consumption, greenhouse gases, and

economic growth for 16 EU countries during the period 1990-2008. Using panel data analysis, the study determined that fossil fuel consumption, renewable energy, and economic growth negatively impact carbon emissions.

Zaidi et al. (2018) analysed the effects of renewable and non-renewable energy types on CO_2 emissions in their study, which considered data from Pakistan for the period 1970-2016. In this context, they concluded that renewable energy reduces CO_2 emissions. They also found that natural gas and coal, which are non-renewable energy sources, are the products that increase carbon emissions the most. Lorente et al. (2019) investigated the relationship between ecological footprint, economic growth, and renewable energy consumption in MINT countries during the period 1990-2013. According to the panel data analysis results, an inverse U-shaped relationship was found between foreign direct investment and ecological footprint. To strengthen our analysis, we confirmed the environmental Kuznets curve hypothesis for MINT countries by checking the link between economic growth and ecological footprint. The empirical findings also indicate a negative link between renewable energy use, urbanization, and changes in ecological footprint. These results offer a number of useful recommendations for policymakers, highlighting the necessity of promoting clean industries and energy efficiency actions to reduce environmental damage in MINT countries.

Ansari et al. (2020) examined data from 1991 to 2016 using Pooled Multiple Group Estimator (PMGE), FMOLS, and DOLS methods in their study on selected countries with the highest consumption of renewable energy. Economic growth and non-renewable energy consumption have a positive effect on CO_2 emissions, while renewable energy consumption, globalisation, and urbanisation have a negative effect. Hadj (2021) examined the effect of biofuel consumption on CO_2 emissions in Saudi Arabia using the NARDL method, considering the period 1984-2017. The results of the study revealed that increases in biofuel consumption and urbanisation levels reduced CO_2 emissions in both the short and long term. In the short term, the financing of green energy projects reduces CO_2 emissions by decreasing the use of fossil fuels and natural resources. However, in the long term, increases in the use of fossil fuels and natural resources increase CO_2 emissions.

Fareed et al. (2021) investigated the relationship between renewable and non-renewable energy, biocapacity, and economic growth in Indonesia during the period 1965Q1-2014Q4 using Fourier quantile causality and Fourier Toda Yamamoto causality analysis. Their findings showed that renewable energy and export diversification increase the load capacity factor and support environmental quality. On the other hand, an increase in the consumption of non-renewable energy reduces the load capacity factor.

Shah et al. (2021) investigated the relationship between economic complexity, fossil fuel consumption, and CO_2 emissions in the United States for the period 1965-2017 using the Quantile ARDL method. As a result of their study, they found that economic complexity and fossil fuel consumption increase CO_2 emissions. Zhang (2022) tested the effects of renewable energy sources and R&D expenditures on CO_2 emissions in a study that took the E5 countries as examples. According to the results of the study, which used the Dynamic GMM and FMOLS methods, increases in geothermal and hydro energy production increase environmental degradation, while nuclear and wind power sources and R&D expenditures reduce environmental degradation. Pata and Samour (2022) tested the relationship between renewable and nuclear energy and environmental quality in France for the period 1977-2017 using Fourier ARDL and Fourier Toda Yamamoto causality analysis. Their findings showed that nuclear energy reduces carbon emissions and increases the load capacity factor.

Arnaut and Dada (2023), in their study using the United Arab Emirates as an example, examined the effects of economic complexity, non-renewable and renewable energy on CO_2 emissions, taking into account data from the 1995-2017 period. Using the ARDL method, their study concluded that non-renewable energy, income level, financial development, and globalisation variables positively influence CO_2 emissions.

Öztürk et al. (2023) examined the relationship between ecological footprint and financial development in Southern African countries for the period 1971-2018 using panel data analysis techniques. The empirical findings show that financial development increases environmental protection, while energy use significantly degrades the environment in the selected South Asian countries.

Pata et al. (2023) examined the relationship between renewable energy consumption and carbon emissions in ASEAN countries by adding different control variables. Using data from 1995-2018, the study yielded the following results: Tourism and foreign direct investment increased CO2 emissions, while economic growth and trade openness reduced environmental degradation. Furthermore, it was found that renewable energy only reduced carbon emissions in the short term and had no long-term effect on environmental quality. The findings also revealed a causal relationship between renewable energy and carbon emissions.

Perone (2024), in their study, examined the relationship between renewable energy and carbon emissions for 27 OECD countries using panel cointegration and causality analysis. The findings showed that hydroelectric, nuclear, solar, and wind energy were negatively and significantly correlated with CO2 emissions. The Granger causality approach showed unidirectional causality from hydroelectric, solar, and wind energy to CO2 emissions, bidirectional causality between CO2 and biofuels and energy sources, and unidirectional causality from CO2 emissions to nuclear energy.

In the study by Sadiq et al. (2024), the impact of green finance, eco-innovation, renewable energy production, renewable energy consumption (REC), and carbon taxes on carbon dioxide emissions in BRICS countries between 2001 and 2020 is examined. According to the CS-ARDL approach, green finance, eco-innovation, renewable energy production and consumption, carbon taxes, and industrialization are found to be effective because the relationship between these variables and carbon emissions is negative. Based on these findings, the study recommends formulating environmentally friendly practices to reduce carbon emissions and making progress in the field of green finance.

Şimşek et al. (2025) examined the effects of globalization, economic complexity, urbanization, and real income on CO2 emissions, ecological footprint, and load capacity factor for E-7 countries during the period 1995-2020. Using panel data techniques, they found that renewable energy and globalization are significant factors in reducing environmental degradation and enriching environmental quality. Furthermore, the findings revealed that urbanization and economic growth negatively impact the environment of E-7 countries, while economic complexity is a statistically significant factor for all environmental variables.

Özbek et al. (2025) investigated the relationships between natural resource income, energy transition, economic growth, and environmental degradation during the period 1970-2021. Using ARDL bounds test, DOLS, and Toda-Yamamoto causality analysis, the study found an inverse U-shaped relationship between economic growth and environmental degradation. The findings indicate that natural resource income has a positive effect on environmental degradation, while renewable energy consumption contributes to its mitigation. Conversely, fossil fuel consumption is associated with increasing environmental degradation. Similar findings have been obtained in the long term as well, confirming the validity of the Reverse Load Capacity Curve hypothesis.

Güler et al., (2025), examined the relationship between economic growth, foreign direct investment, and ecological footprint in China for the period 1979-2022 using various control variables. Fourier Bootstrap ARDL analysis was used. The findings showed that economic growth and foreign direct investment increased environmental degradation, but urbanization and value-added agriculture, forestry, and fishing improved sustainability in some areas.

Özbek et al. (2025) examined the effects of economic growth, trade openness, green energy, and military spending on carbon emissions in E-7 countries for the period 1993-2023 using panel data analysis. The study confirms that economic growth and trade openness increase carbon emissions and reduce environmental quality, while green energy and military spending reduce carbon emissions and improve environmental quality.

Büyükkör (2025), in his study, tested the relationship between renewable energy and fossil fuel consumption and carbon emissions in a sample of 10 countries consuming renewable energy for the period 1990-2021 using panel data analysis techniques. The empirical findings show that fossil fuels increase carbon emissions, and renewable energy consumption also increases carbon emissions. Pata et al. (2025), in their study for the USA, used time series techniques based on the Fourier method from 1973 to 2022. They examined the effect of renewable energy and income on carbon emissions. The findings present results supporting the validity of RKC and EKC.

Idroes et al. (2025) investigated the factors affecting environmental quality in Indonesia for the period 1965-2022 using the ARDL technique. The findings show that natural disasters, fossil fuel consumption, and economic growth increase CO2 emissions in the long term, while renewable energy consumption helps to reduce them.

2. Empirical Analysis

2.1. Data Set and Model

This study aims to test the impact of the transition from fossil fuels to renewable energy on carbon emissions in EU countries using panel cointegration and coefficient estimation methods. The study uses data from 1990 to 2021, and explanatory information about the data set is presented in Table 1. All variables used in the model were obtained from the World Bank database.

Table 1. Explanations of Variables

Variables	Explanations	Source
lnCO	Logarithmic per capita carbon emissions (metric tonnes)	World Bank/1990-2021
lnREN	Logarithmic Renewable Energy Consumption (% of Total Energy Consumption)	World Bank/1990-2021
lnFFC	Logarithmic Fossil Fuel Consumption (%)	World Bank/1990-2021
lnFREN	Logarithmic Fossil/Renewable Energy Consumption Ratio	World Bank/1990-2021

The model of the study, created using the variables described in Table 1 and their logarithmic transformations, is shown in Equation 1:

$$\ln CO_{it} = \alpha_0 + \beta_{it} \ln REN_{it} + \beta_{2it} \ln FFC_{it} + \beta_{3it} \ln FREN_{it} + \varepsilon_{it} \quad (1)$$

i=(1....26) ve t=(1990....2021) represents.

Table 2 presents the descriptive statistics for the variables.

Table 2. Descriptive Statistics

	lnCO	InFFC	InFREN	InREN
Mean	2.034957	4.309905	1.899850	2.410055
Median	2.033307	4.359206	1.724262	2.533665
Maximum	3.471766	4.605170	5.805938	4.058717
Minimum	1.116356	3.223664	-0.835053	-1.203973
Std. Dev.	0.413618	0.243274	1.099134	0.940052
Skewness	0.440280	-1.729370	0.363598	-0.721621
Kurtosis	3.364233	6.750059	3.016111	3.170909
Jarque-Bera	31.47916	902.2287	18.34119	73.22153
Probability	0.0060619	0.022517	0.000104	0.000000
Sum	1693.084	3585.841	1580.675	2005.165
Sum Sq. Dev.	142.1672	49.18046	1003.927	734.3528
Observations	832	832	832	832

According to Table 2, there are 832 observations for each variable, which confirms the balanced panel data in empirical studies. Looking at the descriptive analysis results, lnFFC has the highest mean, followed by lnREN, lnCO, and lnFREN, respectively.

Table 3. Correlation Coefficients

	lnCO	lnREN	lnFFC	InFREN
lnCO	1.0000			
lnREN	-0.5981	1.0000		
lnFFC	0.4917	-0.6999	1.0000	
InFREN	0.5144	-0.9836	0.7173	1.0000

The correlation matrix was created to evaluate the relationships between independent variables and the dependent variable. Correlation coefficients between the variables were calculated to determine the direction and strength of the relationship between the variables in the series, and are shown in Table 3. The correlation coefficient can vary between -1 and 1 and expresses the relationship between the variables (Beaumont, 2012; Bal, 2025). Looking at the table, it can be seen that there is a negative relationship between lnCO and InREN, as expected, and a positive relationship between lnCO and lnFFC and InFREN.

2.2. Methodology and Evaluation of Empirical Results

2.2.1. CrossSection Dependency Test and Results

In this study, a stepwise method using different econometric tests was employed to examine the impact of the transition from fossil fuels to renewable energy on carbon emissions in EU countries. In panel data analyses, it is necessary to determine whether there is cross section dependence at the model and variable level in the first stage. This is because, in empirical studies, the unit root and cointegration methods to be used are determined according to cross section dependence and heterogeneity (Ünal and Atasel, 2021).

In testing for cross-sectional dependence, this study also utilised the LM test developed by Breusch–Pagan (1980), which is frequently used in the literature and yields effective results. The null hypothesis of the Breusch Pagan LM test is 'there is no cross-sectional dependence,' while the alternative hypothesis is 'there is cross-sectional dependence.' The functional representation of the test is as follows (Breusch-Pagan 1980):

$$LM = T\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\hat{\rho}i^{2}j \qquad (2)$$

Another cross section dependence test is the Pesaran (2004) CDlm test. It is used in cases where both T and N dimensions are large. The equation of the test is as follows (Pesaran, 2004).

$$CD_{LM} = \sqrt{\frac{1}{N(N-1)}}\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}(T\hat{\rho}i^{2}j-1) \sim N(0,1) \qquad (3)$$

Cross section dependence is important in panel data analysis. Otherwise, analyses and selected methods may produce erroneous results (Chudik and Pesaran, 2013).

The results of the cross-sectional dependence test conducted for the variables used in the study are presented in Table 4.

Table 4. Cross Section Dependency Test Results

	lnCO	**lnREN**	**lnFFC**	**lnFREN**
	Statistical Probability Values	*Statistical Probability Values*	*Statistical Probability Values*	*Statistical Probability Values*
Breusch- Pagan(1980)	4035.66 (0.000)***	6852.03 (0.000)***	7093.9 (0.000)***	6852.0 (0.000)***
Pesaran CD_{LM} (2004)	145.54 (0.000)***	256.01 (0.000)***	265.49 (0.000)***	256.01 (0.000)***
	Cross Section Dependency Test for the Model			
Breusch-Pagan LM	1220.0 (0.000)*			
Pesaran CD_{LM}	14.2 (0.000)*			

Note: Values in parentheses are probability values. *** indicates a significance level of 1%.

When examining the Breusch Pagan LM test and Pesaran CDLM test results given in the table, it can be seen that there is cross-sectional dependence in all variables and models in EU countries during the relevant period. This is because the probability values are less than the 1% significance level. The null hypothesis that there is no cross-sectional dependence is rejected, and the alternative hypothesis is accepted. The test results obtained allow for the use of second-generation panel unit root and cointegration tests (Bayrakdar and Soyyiğit, 2020).

2.2.2. Cross Section Extended Im, Pesaran and Shin (CIPS) Panel Unit Root Test

In panel data analysis, stationarity tests are important when the T dimension is large. In the literature, panel unit root tests are categorised into two groups based on the presence of cross-sectional dependence. When cross-sectional dependence is absent, first-generation panel unit root tests are used, while second-generation panel unit root tests are employed when cross-sectional dependence is present (Ünal and Atasel, 2021). Since cross-sectional dependence is present in this study, the analysis was continued using second-generation unit root tests.

In this study, the CADF test developed by Pesaran (2007) was used to determine the stationarity levels of the variables. It re-extended the cross-sectional means of the lagged levels and first differences of individual variables by adding factors to the DF or ADF regression. It is referred to as the cross-sectional augmented Dickey-Fuller (CADF) test. It is noted that this test is used in both T>N and T<N cases (Güloğlu and İvrendi, 2010; Yerdelen Tatoğlu, 2020). While the CADF unit root test examines the stationarity status at the unit level, the CIPS test analyses the stationarity status of the panel (Gençoğlu et al., 2024).

The unit root test results for the variables are presented in Table 5.

Table 5. CIPS Unit Root Test Results

	CIPS Statistics	
Variables	*Level Values*	*1. Difference Values*
lnCO	-2.04	-5.074
lnREN	-2.00	-5.056
lnFFC	-1.06	-5.263
lnFREN	-1.19	-5.094
	Critical Values	
%1	-2.08	
%5	-2.16	
%10	-2.30	

According to Table 4, it can be seen that the variables considered in the fixed model are not stationary at the level. This is because the critical values of all variables used in the model are greater than the absolute values of the CIPS statistics. However, when the first difference of the variables is taken, the CIPS statistics are greater than the values given at the 1%, 5% and 10% confidence levels in terms of absolute value, so the variables become stationary. All variables are stationary in their first differences. The presence of a unit root at the level in the series within the scope of the panel CIPS findings enables the use of the cointegration test by Westerlund and Edgerton (2007) (Kar et al., 2019).

2.2.3. Homogeneity Test and Results

Another important step in panel data analysis is the homogeneity test. To determine heterogeneity, the Delta test proposed by Pesaran and Yamagata (2008) is used, which is an improved version of the S test developed by Swamy (1970). The null hypothesis is formulated as 'The slope coefficients are homogeneous,' while the alternative hypothesis is formulated as 'The slope coefficients are heterogeneous.' The Delta test equations are shown below (Pesaran and Yamagata, 2008).

$$\widetilde{\Delta} = \sqrt{N}\left(\frac{n^{-1}\widetilde{S} - k}{\sqrt{2K}}\right) \quad (4)$$

$$\hat{\Delta}_{adj} = \sqrt{N}\,\frac{N^{-1}\widetilde{S} - k}{\sqrt{vae}(t,k)} \quad (5)$$

Table 6. Homogeneity Test Results

	lnCO=f(lnREN, lnFFC, lnFREN)	
	t-statistic value	probability value
Delta Tilde	24.656	0.000***
Delta	26.842	0.000***

Not: ***, 1% significance level

Table 6 shows the homogeneity test results. Since the probability values of the delta test are less than 1% significance level, the null hypothesis is rejected and the alternative hypothesis is accepted. This situation shows that the effect of a change in renewable energy, fossil fuel consumption and fossil fuel consumption on carbon emissions differs between economies.

2.2.4.Westerlund and Edgerton (2007)LM Bootstrap CointegrationTest and Results

The cointegration relationship between variables was examined using the LM Bootstrap cointegration method developed by Westerlund and Edgerton (2007), which also takes cross-sectional dependence into account. The test is based on McCoskey and Kao's (1998) Lagrange multiplier (LM) test. The functional representation of the test statistic is presented in Equation 6.

$$y_{it} = \alpha_i X_{it} \beta_i + z_{it} \quad (6)$$

The vector $w_{it} = (u_{it} \Delta x_{it})$ predictor represents a linear stage.

This situation is given in equation 7:

$$w_{it} = \sum_{j=0}^{\infty} \alpha_{ij} e_{it-j} \quad (7)$$

The assumption of the test is that 'cointegration exists.' The LM Bootstrap cointegration test uses bootstrap properties to allow for correlation between and within cross-sections (Özcan and Arı, 2014). The findings are presented in Table 7.

Tablo 7. LM BootstrapCointegrationTest Results

	LM Statistics	Asymptotic p-value	Bootstrap p-değeri
LM_N^+	8.361	0.000	0.310
Bootstrap probability values were obtained from a distribution with 1000 repetitions. The lag was assumed to be 1. A fixed model was used.			

According to the findings presented in Table 7, the null hypothesis (H0) that "there is cointegration" in EU countries cannot be rejected at the 1% significance level. Since cross-sectional dependence has been determined, bootstrap values are of interest. A long-term relationship between the variables included in the model has been obtained.

2.2.5.AMG Coefficient Estimator and Results

There are many methods for estimating long-term coefficients in panel data analysis. In this study, the AMG estimator, which takes heterogeneity and cross-sectional dependence into account, was used. This method can estimate both panel-wide and country-specific coefficients. It is noted that the 'Extended Average Group (AMG)' estimator, one of the second-generation estimation methods, proposes a two-stage method. This estimator can produce effective results in unbalanced panel analyses (Eberhardt and Bond, 2009).

$$y_{it} = \beta' X_{it} + u_{it} \quad u_{it} = a_i + \lambda_i' f_t T + \varepsilon_{it} \quad (8)$$

$$x_{it} = \Pi_{mi} + \delta_{mi}' g_{mt} + \rho_{1mi} f_{1mt} + ... + \rho_{nmi} f_{nmt} + v_{mit} \quad (9)$$

M=1,...k ve $f_{mt} \subset f_t$ (10)

$$f_t = \varphi'^{ft-1} + \varepsilon_t veg_t = K'_{gt-1} + \varepsilon_t \quad (11)$$

In the equations, where i=1...N and t=1...T, xit represents the vector of observable time series, ai represents the fixed effects component of group i, ft and gt represent common factors, and ʎi represents the element belonging to cross section units.

The first-stage equation used in the AMG estimator is shown in Equation 11.

$$\Delta_{yit} = b' \Delta_{x_{it}} + c_i t + d_i \hat{\upsilon}_t + e_{it} \quad (12)$$

In the model, the reason for taking the first differences of the series is the possibility that the results obtained with the level

values of the series will be biased. In this way, the time dummy coefficients expressed by $\hat{\upsilon}_t$ are obtained. The equation estimated in the second stage is as follows:

$$y_{it} = a_i + b_i' x_{it} + c_i t + d_i \upsilon_t + e_{it} \quad (13)$$

$$\hat{b}_{AMG} = N^{-1} \sum_i \hat{b}_i \quad (14)$$

In the equation, the time dummy variable adds the regression belonging to the cross section. The AMG coefficient estimator is determined as the average value of country estimates on an individual basis. The basic hypothesis of this test is that the coefficients are meaningless, while the alternative hypothesis is that the coefficients are meaningful (Eberhardt and Bond, 2009).

Table 8. AMG Coefficient Coefficient Estimator Results

	lnCO=f(lnREN)			lnCO=f(lnFFC)			lnCO=f(lnFREN)		
	Coefficient	Standard error	p-value	Coefficient	Standard error	p-value	Coefficient	Standard error	p-value
AMG	**-0.301**	**0.052**	**0.000*** **	**1.610**	**0.195**	**0.000*** **	**0.254**	**0.032**	**0.028** **
Austria	-0.117	0.051	0.024**	0.153	0.134	0.253	0.177	0.024	0.000***
Belgium	-0.138	0.005	0.000***	3.059	0.316	0.000***	0.147	0.004	0.000***
Germany	-0.112	0.008	0.000***	2.572	0.162	0.000***	0.126	0.008	0.000***
France	-0.651	0.092	0.051**	1.944	0.169	0.000***	0.556	0.035	0.001***
Italy	-0.172	0.016	0.000***	1.642	0.162	0.000***	0.208	0.013	0.000***
Irland	-0.160	0.019	0.022**	2.706	0.445	0.000***	0.181	0.014	0.000***
Luxembourg	-0.276	0.030	0.056**	3.811	0.445	0.000***	0.265	0.022	0.005***
Sweden	-1.128	0.054	0.000***	1.601	0.115	0.000***	0.702	0.027	0.035**
Czech Republic	-0.255	0.013	0.012**	1.311	0.075	0.000***	0.240	0.010	0.058**
Poland	-0.089	0.018	0.000***	0.785	0.332	0.018**	0.078	0.015	0.000***

Note: ***, **, * indicate significance levels of 1%, 5% and 10% respectively.

Table 9. AMG Coefficient Coefficient Estimator Results

	lnCO=f(lnREN)			lnCO=f(lnFFC)			lnCO=f(lnFREN)		
	Standard error	p-value	Coefficient	Standard error	p-value	Coefficient	Standard error	p-value	
Portugal	-0.726	0.072	0.067***	1.678	0.289	0.000***	0.548	0.044	0.000***
Finland	-0.507	0.066	0.014**	0.952	0.080	0.000***	0.414	0.028	0.000***
Slovakia	-0.208	0.015	0.000***	1.312	0.098	0.000***	0.190	0.012	0.000***
Spain	-0.261	0.044	0.000***	2.349	0.298	0.000***	0.297	0.025	0.007***

Hungary	-0.181	0.013	0.089***	1.059	0.082	0.000***	0.167	0.010	0.000***
Latvia	-0.718	0.094	0.000***	1.067	0.285	0.000***	0.417	0.071	0.000***
Lithuania	-0.203	0.057	0.022**	1.666	0.270	0.000***	0.211	0.050	0.000***
Greece	-0.288	0.031	0.000***	2.544	0.314	0.000***	0.333	0.019	0.015**
Cyprus	-0.030	0.014	0.034**	2.203	0.456	0.000***	0.058	0.015	0.000***
Bulgaria	-0.062	0.016	0.000***	0.823	0.176	0.000***	0.075	0.014	0.000***
Denmark	-0.422	0.020	0.000***	1.686	0.049	0.028**	0.376	0.012	0.000***
Estonia	-0.197	0.047	0.000***	1.251	0.303	0.000***	0.215	0.036	0.000***
Netherlands	-0.094	0.006	0.000***	2.847	0.218	0.000***	0.112	0.005	0.000***
Slovenia	0.022	0.036	0.543	0.148	0.181	0.414	0.089	0.027	0.001***
Romania	-0.249	0.019	0.000***	1.391	0.159	0.000***	0.278	0.016	0.000***
Croatia	-0.555	0.221	0.012**	0.705	0.461	0.126	0.144	0.111	0.196

Note: ***, **, * indicate significance levels of 1%, 5% and 10% respectively.

Table 8 and 9 shows the AMG coefficient estimation results. The findings indicate that a 1% increase in renewable energy consumption across the panel reduces carbon emissions by 0.30%, while a 1% increase in fossil fuel consumption increases carbon emissions by 1.61%. Additionally, a 1% increase in the fossil/renewable energy consumption ratio across the panel increases carbon emissions by 0.25% across the panel. As this ratio increases, carbon emissions also increase significantly. In conclusion, the results achieved across the panel in all three variables are consistent with theoretical expectations and highlight the importance of the European Union's energy transition policy in reducing carbon emissions.

When viewed on a country-by-country basis, the impact of renewable energy consumption on carbon emissions has been found to be significant in all countries except Slovenia. Increases in renewable energy consumption have a negative impact on carbon emissions in these countries. Similarly, the impact of fossil fuel consumption on carbon emissions has been found to be significant in all countries except Austria, Slovenia, and Croatia. Increases in fossil fuel consumption have a positive effect on carbon emissions. The effect of increases in the fossil/renewable energy consumption ratio on carbon emissions has been found to be positive and significant across all Countries.

The findings clearly demonstrate a direct and strong correlation between the trajectory of carbon emissions in the European Union and the composition of energy consumption. The increase in renewable energy consumption has a positive impact on reducing emissions, confirming that clean energy sources are an effective tool for environmental sustainability; conversely, the increase in fossil fuel consumption significantly raises carbon emissions, highlighting the environmental cost of the current fossil-based energy structure. In this context, the findings reveal that accelerating the EU's energy transition policies and implementing structural reforms to reduce dependence on fossil fuels are critical for achieving a lasting reduction in carbon emissions.

Conclusion and Recommendations

This study provides robust empirical evidence on the impact of energy consumption composition on carbon emissions in European Union (EU) countries over the period 1990–2021. The findings clearly indicate that renewable energy consumption plays a significant role in reducing carbon emissions, whereas fossil fuel consumption exerts a strong positive pressure on environmental degradation. Moreover, the fossil-to-renewable energy consumption ratio emerges as a critical determinant, with increases in this ratio leading to a substantial rise in carbon emissions. These results confirm that not only the level but also the structure of energy consumption is decisive in shaping environmental outcomes.

From a methodological perspective, the analysis accounts for cross-sectional dependence and heterogeneity across countries, ensuring the robustness of the findings. The presence of a long-run cointegration relationship among the variables suggests that the interaction between energy consumption patterns and carbon emissions is persistent over time. The AMG

estimator results further reveal that, at the panel level, renewable energy contributes to emission reductions, while fossil fuel consumption and the fossil-renewable energy ratio significantly increase emissions. Although country-specific results vary in magnitude and statistical significance, the overall panel findings are fully consistent with theoretical expectations and highlight the effectiveness of the EU's energy transition policies.

The results carry important policy implications. First, reducing the share of fossil fuels in the overall energy mix should remain a primary objective for policymakers. In this context, increasing the share of renewable energy sources in total energy consumption through diversification of the energy portfolio is essential. Expanding renewable energy investments, improving energy efficiency, and accelerating the deployment of clean technologies will not only reduce carbon emissions but also enhance energy security and sustainability.

Second, policy design should consider structural differences across countries. Since the fossil-to-renewable energy ratio has a strong and consistent impact on emissions, energy transition strategies should be tailored according to countries' energy dependency, technological capacity, and economic structure. Strengthening energy infrastructure, including grid modernization and energy storage systems, is crucial to support higher shares of renewable energy. In addition, promoting private sector participation through market-oriented reforms and ensuring the effective separation of energy production, transmission, and distribution processes can improve efficiency in the energy sector.

Third, fiscal and regulatory instruments should play a more active role in accelerating the transition process. Gradual elimination of fossil fuel subsidies, implementation of carbon pricing mechanisms (such as carbon taxes and emission trading systems), and increased financial incentives for renewable energy investments are key policy tools. These measures would help internalize environmental costs, encourage cleaner production processes, and foster technological innovation, particularly in carbon-intensive industrial sectors.

Finally, future research could expand the scope of analysis by incorporating additional factors such as energy efficiency, technological innovation, institutional quality, and sectoral energy use. The inclusion of alternative environmental indicators, such as ecological footprint or load capacity factor, together with advanced econometric techniques, may provide deeper insights into the complex relationship between energy transition and environmental sustainability. Comparative studies across different country groups could also enhance the generalizability of findings and contribute to more effective and targeted policy design.

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