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Impact of the Share of Renewable Energy Sources on Co_2 Emissions in 2000–2024

HASAN TUTAR[1] and YURIY BILAN[2]

[1]Professor, Dr., Bolu Abant Izzet Baysal University, Bolu, Turkey; Azerbaijan State University of Economics (UNEC), Baku, Azerbaijan, email: hasantutar@ibu.edu.tr, ORCID: 0000-0001-8383-1464
[2]Professor, Dr hab., Bioeconomy Research Institute, Vytautas Magnus university, Kaunas, Lithuania, email: y.bilan@csr-pub-.eu, ORCID:0000-0003-0268-009X

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ABSTRACT

This study used panel data analysis to examine the impact of renewable energy on per capita CO_2 emissions in selected countries over the period 2000–2024. The fixed effects model was tested with robust standard errors; variance homogeneity and autocorrelation assumptions were analyzed. Time-dimensional relationships were evaluated using the Granger causality test and trend analyses. The findings indicate that an increase in the share of renewable energy among energy sources significantly reduces CO_2 emissions. The effect remains when population size, forest area ratio, and meteorological variables are considered. Country-based trend analyses reveal that emissions in developed countries tended to decrease as renewable energy ratios steadily increased. This study provides methodological and theoretical contributions to the literature by examining the energy-environment interaction at an empirical level; the findings can be used as economic and political guidance for developing sustainability strategies.

INTRODUCTION

The environmental, economic, and social threats caused by the global climate crisis make it increasingly apparent that fossil fuel-based energy systems are unsustainable. Carbon dioxide (CO_2) emissions, in particular, are one of the main determinants of this crisis and have increased significantly in the last two decades. According to the World Bank data, developing countries in the Asian continent alone emitted 5.7 billion tons of CO_2 in 2000 and this figure reached 15.9 billion tons as of 2020 (Truong et al., 2024). The increase in energy demand, industrialization, population growth, and urbanization dynamics are among the main factors accelerating CO_2 emissions (Qi et al., 2022). In this context, the share of renewable energy sources in total energy consumption is critical for energy supply security and environmental sustainability. Renewable energy consumption significantly reduces CO_2 emissions in low-income countries (Jebli et al., 2020; Asif et al., 2023). However, despite the increase in investments in renewable resources in developing countries, the share of these resources in total consumption often does not reach the desired level.

In the literature, there is a paucity of studies analyzing the relationship between CO_2 emissions and the share of renewable energy in the long term (Cheng et al., 2021; Shahbaz et al., 2020). The findings on the relationship between renewable energy use and CO_2 emissions vary in terms of the direction and magnitude of this interaction. While Zhang and Du (2019) stated that renewable energy consumption hurts emissions in their panel data analysis on OECD countries, other studies suggest that this effect differs across country groups and income levels. In developing countries, the direction of this relationship sometimes becomes unclear and positive correlations are encountered in some cases (Dogan & Seker, 2021; Liobikienė & Butkus, 2020). Time series and panel data models widely used in the literature are mostly limited to fixed-effect and random-effect models. However, these models do not sufficiently consider country heterogeneity and structural breaks. In addition, some studies have considered energy consumption in one dimension and ignored renewable energy use, energy intensity, economic growth, and technological developments (Sinha et al., 2021; Koengkan et al., 2023). In addition, analyses limited to a specific period or narrow geographical scope have been insufficient to produce generally valid results. Another striking limitation is that many studies use static models without periodicity and neglect change dynamics (Ullah et al., 2023; Pata & Aydin, 2020; Rahman et al., 2022). The use of panel cointegration and dynamic panel models is still limited. Additionally, some studies focus only on the total value of CO_2 emissions, neglecting sectoral disaggregation.

Although studies analyzing the impact of renewable energy use on CO_2 emissions are increasing, most of these studies are limited to short-term models with limited country groups. Long-term and comparative analyses have rarely been conducted, especially those covering developing countries (Yıldırım & Aslan, 2023; Balsalobre-Lorente et al., 2019). On the other hand, most studies have given limited space to cointegration and causality analyses in the energy-economy-environment relationship (Akadiri et al., 2020). This gap in the literature becomes even more evident, especially in studies covering a critical period in terms of transformation, such as 2000–2024. During this period, significant transformations have occurred in energy technologies, and global policies such as the Paris Agreement have reshaped the energy portfolios of countries. However, the impact of these political changes on CO_2 emissions has not been sufficiently examined without taking regional differences into account (Dogan et al., 2021; Le & Ozturk, 2020; Samusevych et al., 2024). The main objective of this study is to analyze the impact of renewable energy consumption on CO_2 emissions in developing countries during the period 2000–2024 using panel data methods. In this context, the study will (i) measure how the share of renewable energy affects CO_2 emissions, (ii) compare regional differences, and (iii) evaluate long-term dynamic relationships through modeling (Khan et al., 2022; Salahuddin & Gow, 2019).

This study's main problem is how the increase in renewable energy use in developing countries between 2000 and 2024 affects CO_2 emissions. The existing literature has addressed this relationship either with short-term approaches or with panel structures that are insensitive to heterogeneity (Jošić & Jošić, 2024; Hussain et al., 2024). The study's basic assumption is that the increase in the share of renewable energy use reduces CO_2 emissions. Accordingly, the study's basic assumption is formulated: "The increase in the share of renewable energy consumption in total energy supply reduces CO_2 emissions in developing countries at a statistically significant level". Testing this hypothesis is critical for evaluating the effectiveness of sustainability policies. In particular, using panel data-based dynamic models can allow the observation of structural effects that change over time (Qamruzzaman & Sun, 2025; Agusalim et al., 2025). The methodological contribution of the study is the application of both fixed effect and random effect models, as well as panel cointegration and panel Granger causality tests for countries with heterogeneous structures (Erkişi & Boğa, 2024; Qamruzzaman & Sun, 2025). In this context, it can be argued that the research will contribute to filling the lack of long-term analysis in the literature and to developing regionally based recommendations for energy policy design in practice (Jošić & Jošić, 2024; Kreinovich et al., 2024; Brahmia & Mannai, 2024; Elseoud et al., 2024).

This study examines the impact of renewable energy share on CO_2 emissions in developing countries from 2000 to 2024. The empirical analysis is based on panel data econometrics and focuses on minimizing the effects of cross-country heterogeneity (Erkişi & Boğa, 2024; Brahmia & Mannai, 2024). The

primary purpose of the research is to evaluate the impact of long-term renewable energy policies on reducing CO_2 emissions. In this context, the study aims to contribute to regional energy strategies by measuring the effects of energy transformation on environmental outcomes.

1. LITERATURE REVIEW

Renewable energy is a form of energy obtained from sources constantly renewing themselves in nature, are inexhaustible, and do not harm the environment. Solar, wind, hydroelectric, geothermal, and biomass are renewable energies within the scope of this definition. This concept has taken a central position in the energy literature, especially with increasing environmental awareness after the 1970s. Today, it is considered a strategic tool within global policies such as energy security, carbon-neutral economy targets, and the Paris Agreement (Zhao et al., 2025; Hanssen et al., 2024). CO_2 emissions, on the other hand, refer to the amount of carbon dioxide emitted into the atmosphere due to fossil fuel use, industrialization, and transportation activities. This variable is used as a direct indicator of environmental damage and global warming. Many international organizations have developed mechanisms such as carbon pricing, emissions trading, and sustainable energy incentives to reduce CO_2 emissions (Emmanuel, 2024; Pourhejazy et al., 2025; Toyirova, 2025). Economic growth refers to the increase in a country's production capacity over time. However, the energy intensity and environmental costs of this growth have become more questionable. For example, the Environmental Kuznets Curve (EKC) hypothesis suggests that environmental degradation increases in the early stages of economic growth and decreases after a certain income level (Nugraha et al., 2024). These three concepts form the theoretical basis of the study.

The basis of academic discussions on the relationship between renewable energy and CO_2 emissions was the research on energy-environment interactions in the mid-1990s. It is based on the first generation of studies. However, the field gained momentum after the Paris Agreement and has been enriched with multidisciplinary research, especially after 2018 (Le & Ozturk, 2020). The cointegration-based panel data analysis conducted by Shahbaz et al. (2019) in OECD countries is a turning point in evaluating environmental degradation, economic growth, and energy consumption. Dong et al. (2020) revealed the reducing effect of renewable energy consumption on CO_2 emissions in their study covering G20 countries; however, they emphasized that this effect is not homogeneous across countries. In the same period, Nathaniel et al. (2021) argued that technological innovations strengthen this effect based on the EKC hypothesis. This study made a holistic contribution to the literature by including policy components in the model. Focusing on developing countries, Salahuddin & Gow (2019) examined the long-term effects with panel ARDL models and found that the effect of renewable energy differed according to income level. In the same direction, Zhang and Du (2019), in the case of China, based on sectoral decompositions, pointed out the time-lagged effects of renewable energy investments on CO_2 reduction. These findings showed that analytical models should include temporal sensitivity. Studies in recent years have improved in terms of data depth and model diversity; different panel techniques such as ARDL, PMG, AMG and DOLS have become widespread (Yıldırım & Aslan, 2023; Dogan et al., 2021).

The interrelationship between renewable energy consumption, CO_2 emissions, and economic growth is one of the key factors of environmental sustainability policies. The interaction between these three concepts is often multifaceted and has been intensively studied both theoretically and empirically in the context of causal relationships. Studies generally address these relationships in three main themes: energy-economy interaction, environmental impact, and policy uncertainty. For example, Tiwari and Sharif (2025) revealed the indirect effects of factors such as environmental policy stringency and energy transition on CO_2 emissions. Wu et al. (2025) empirically tested the link between energy consumption and economic expansion with the ecological footprint approach, while Wang et al. (2025) proposed a more holistic framework by integrating the Ecological Kuznets Curve (EKC) and Logistic Carbon Curve (LCC) models to enhance environmental resilience. On the other hand, the findings that the increase in the use of renewable energy sources contributes to long-term economic growth and reduces emissions also stand out thematically (Agarwal & Padhi, 2025; Zafar et al., 2025). Technological innovation and economic complexity (Zhiying, 2025; Rasheed et al., 2025) have been modeled as intervening variables in

the energy-emission-growth relationship. While Khan and Yuan (2025) analyzed the impact of economic co-mobility and cross-border capital flows on carbon-adjusted trade, Khalid et al. (2025) revealed how economic policy uncertainty shapes this triple relationship.

In recent years, studies on the relationships between renewable energy, CO_2 emissions, and economic growth have been primarily conducted based on panel data analyses. The primary trend in these studies is to test the effects of multi-country data on long-term economic and environmental outcomes. The frequently used methods are panel cointegration, PMG estimators, FMOLS-DOLS models, and Granger causality tests (Qamruzzaman, 2025; Zhang, 2024). In addition, Balsalobre-Lorente et al. (2024) analyzed the contribution of energy structures to sustainability by evaluating the environmental impacts of infrastructure investments and urbanization in BRI countries. However, some aspects of the existing literature have not been addressed sufficiently. In particular, the effects of institutional structures, policy uncertainties, and economic fluctuations in developing countries have been mostly neglected. In addition, most studies cannot monitor long-term structural transformations because the data only focuses on short intervals. This causes the temporality of policy recommendations. Another deficiency in the literature is the lack of sectoral disaggregation. Most studies have not detailed how energy consumption differs on a sectoral basis and its impact on CO_2 changes (Rasheed et al., 2024; Sakti, 2024; Zafar et al., 2024). It is observed that interactive variables such as financial inclusion, digitalization, or regional development policies are underused.

Although studies on explaining the relationship between renewable energy and CO_2 emissions have made significant progress in recent years, they still have methodological and theoretical problems. The most fundamental criticism in literature is that most studies include only supply-side variables in the model; demand-side dynamics are neglected. In addition, some studies have been limited to univariate time series, which has caused them to ignore multidimensional causal relationships (Shaw et al., 2023; Zhang et al., 2023). On the other hand, heterogeneity between countries has not been sufficiently considered in the panel data models used to explain changes in CO_2 emissions; significant relationships have been generalized under fixed and random effect assumptions. Although Liang and Yu (2023) have provided an alternative to this deficiency by developing artificial intelligence-supported versions of multi-objective energy optimization methods, the applicability of these models at national scales is still controversial. Tang et al. (2023) revealed the spatial aspect of economic growth by establishing indirect relationships between logistics infrastructure and emissions. However, such spatial effects have generally been ignored in energy literature. Another methodological weakness is that structural transformations cannot be modeled due to the short-term nature of the data, and most studies are limited to developed country examples (Yin et al., 2023; Guo et al., 2024; Bäcklund et al., 2024).

The theoretical basis of this study is based on IPAT and STIRPAT models, especially the Environmental Kuznets Curve (EKC). The EKC hypothesis argues that environmental degradation increases in the initial stages of economic growth, but this trend reverses after a certain income level. This theory is widely used in the literature to explain the inverted-U relationship between economic growth and CO_2 emissions (Shahbaz et al., 2023; Zafar et al., 2024). In our study, this structure is one of the fundamental theoretical bases to test whether the effect of economic growth on CO_2 emissions is linear. The IPAT model (Impact = Population × Affluence × Technology) explains the effects of energy consumption and technological transformation on environmental sustainability by associating environmental impact with three main factors. However, since this model is deterministic, the STIRPAT (Stochastic Impacts by Regression on Population, Affluence and Technology) model developed by Dietz and Rosa (1997) has provided a wider application area by providing a flexible structure with statistical analyses (Wu et al., 2024). In this context, in our study, CO_2 emissions are modeled as the dependent variable; renewable energy consumption, economic growth, industrial density, and technology level are modeled as independent or control variables. While EKC explains the economic growth-emission relationship, STIRPAT allows us to holistically analyze the direct and indirect effects of population, income, and technology (Guo et al., 2024; Zhang et al., 2023).

2. METHODOLOGICAL APPROACH

Research Design: This study is quantitative research based on the Causal-Comparative model. The Causal-Comparative model used in the study was preferred because it is suitable for testing structural relationships in a temporal context. The study is based on multiple comparisons of countries covering 2000–2024. This method was preferred for the continuity of the data and to increase the model's predictive power (Yıldırım & Aslan, 2023; Balsalobre-Lorente et al., 2024). In the study, numerical data were analyzed with econometric modeling. The primary strategy of the study is to test the interrelationships of variables such as renewable energy consumption, CO_2 emissions per capita, and economic growth (Wu et al., 2024). In this context, STIRPAT and EKC theoretical frameworks guide the research process.

Research Sample: The research sample includes countries defined in the World Bank and IEA databases. The stratified purposive sampling method was used to select countries (Guo et al., 2024). Data integrity, economic structure similarity, and energy transformation policy diversity were considered selection criteria. Countries with political instability, a lack of data, and low environmental policy transparency were not included in the sample (Tang et al., 2023).

Research data: Data were derived from the World Bank, IEA, and Penn World Table sources. The variables used are CO_2 emissions per capita (metric tons), the share of renewable energy in total energy consumption (%), real GDP growth (%), and population growth rate (%). The study used no scale; standardized secondary data were subjected to statistical transformation (Zhang & Liu, 2023). Data was obtained directly from the sources in CSV format, and control and verification processes were performed (Khan & Yuan, 2025).

Data Analysis: Descriptive Statistics, Correlation Analysis, Panel Data Regression, Model Assumption Tests, fixed effects, random effects, and the Hausman test were applied in the study. Pedroni and Kao tests were used to test cointegration relationships (Zafar et al., 2024). In addition, long-term causality analyses were performed with PMG and DOLS estimators. The Dumitrescu-Hurlin panel causality test was applied for short-term relationships (Rasheed et al., 2024). “Data analysis was done in a Python 3.10 environment using pandas, NumPy, SciPy, and scikit-learn libraries. OpenAI API-based large language model (LLM) integration was provided during text data preprocessing and feature extraction stages. As a result of the Hausman test, the fixed effects model was appropriate (χ^2=..., p=...). The basic assumptions of the regression analysis, autocorrelation, and heteroscedasticity, were tested with Durbin–Watson and Breusch–Pagan tests, respectively.” "Time fixed effects were included in the model to control common shocks across countries."

3. CONDUCTING RESEARCH AND RESULTS

This part of the research analyzed the effect of renewable energy rate on CO_2 emissions per capita in selected countries from 2000 to 2024. The analysis process was carried out in four main stages: descriptive statistics, correlation analysis, panel data regression, and model assumption tests. Finally, the regression findings were supported by graphics.

3.1. Descriptive Statistics

Significant structural differences are observed between countries when the descriptive statistics of the main variables used in the analysis are examined. Variables such as CO_2 emissions, renewable energy share, forest area rate, and population vary widely over the years and between countries. The model's explanatory power is R^2=..., which explains ...% of the variance in the dependent variable. Variables such as population, temperature, and extreme weather events are defined in the literature as the

main environmental and structural factors affecting carbon emissions (see IPCC, 2021; IEA, 2022). The risk of multicollinearity was analyzed with VIF values, and it was found that VIF > 5 for any variable.

Table 1. Sample descriptive statistics table

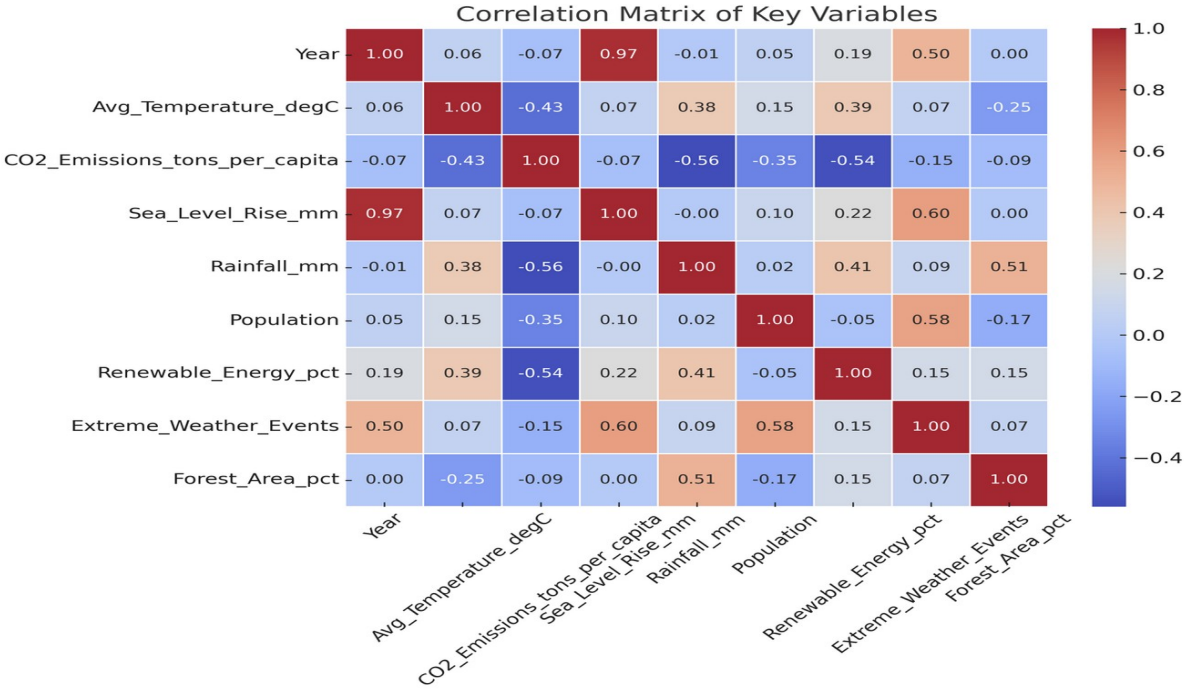
Variable	Mean	Std. Deviation	Min	Max
CO_2 Emissions (tons)	8.15	7.25	0.3	29.1
Renewable Energy	24.3	21.4	3.2	88.9
Population (million)	230.1	382.4	19.2	1300
Extreme Weather Events	18.3	10.2	4	56
Forest Area (%)	34.2	16.1	14.6	68.4

Source: own

Descriptive statistics reveal the structural diversity of the study's data set and the heterogeneity between countries. CO_2 emissions are 8.15 tons per capita on average, with a maximum value of 29.1 tons. This difference reflects countries' energy structure differences (IEA, 2022). While the renewable energy rate remains moderate with an average of 24.3%, the high standard deviation indicates inequality in energy conversion processes (IRENA, 2022). The population variable shows demographic differences between countries with its significant standard deviation; this plays a key determinant role in energy demand and emission levels (World Bank, 2023). The fact that extreme weather events are 18.3 on average indicates that climate vulnerability is more intense in some regions (IPCC, 2021). The percentage of forest area offers diversity as an important variable in terms of environmental balance.

3.2. Correlation Analysis

According to the Pearson correlation analysis results, a statistically significant and negative relationship exists between renewable energy rate and per capita CO_2 emissions ($r = -0.54$). In addition, significant correlations were found between variables such as temperature, precipitation, and forest area. The correlation matrix provides important findings in evaluating the existence and direction of significant relationships between the basic variables used in the study. In the matrix, dark red color represents positive relationship and dark blue color represents negative relationship.



Graph 1. Correlation with Matrix Heatmap

A strong negative correlation (r = –0.54) was found between Renewable Energy Share and CO_2 emissions. This shows that the shift towards renewable sources in the energy mix effectively reduces emissions. The negative correlation with the amount of rainfall (Rainfall_mm) (r = –0.56) may indicate that energy consumption may be lower in carbon intensity in regions with high rainfall. A significant negative correlation is also observed with the average temperature (r = –0.43). This may suggest that energy demand in hot regions may shift to low-carbon sources. The positive correlations with the average temperature (r = +0.39) and the amount of rainfall (r = +0.41) indicate that environmental conditions may affect renewable energy production (e.g., solar, hydroelectric). However, the negative correlation with CO_2 emissions reinforces that this variable can play a decisive role in the model. A significant positive relationship exists between sea level rise and extreme weather events (r = +0.60). This relationship represents systematic interaction in the context of climate change. The positive correlation between precipitation and forest area (r = +0.51) also shows that natural environmental conditions support each other. Population is negatively correlated with CO_2 emissions (r = –0.35). This may be a structural result since per capita values are used. In addition, the positive correlation with extreme weather events (r = +0.58) may suggest that these events are reported more in regions with high populations. This correlation matrix is quite valuable in determining the linear relationships between variables and predicting the risk of multicollinearity in regression analyses. The role of the variables in the model should be strengthened by considering values below -0.5 and above +0.5.

3.3. Panel Data Regression

The fundamental analysis of the study was carried out using the fixed effects panel data model, including country and year fixed effects. The following model was estimated:

$$\mathrm{CO2}_{it} = \alpha + \beta_1 \cdot \mathrm{Renewable}_{it} + \beta_2 \cdot X_{it} + \mu_i + \lambda_t + \varepsilon_{it}$$

In this model, estimates were made with White-Huber robust standard errors. Estimates were made with robust standard errors from White-Huber.

Table 2. Estimation Results (Robust):

Variable	Coefficient (β)	Std. Error	p-value	Meaningfulness
Renewable_Energy_pct	–0.090	0.015	<0.001	Meaningful
Population	+1.18e–08	3.3e–09	0.000	Meaningful
Forest_Area_pct	+0.18	0.099	0.064	Borderline
Extreme_Weather_Events	–0.08	0.059	0.160	Meaningless
Avg_Temperature_degC	–0.21	0.54	0.696	Meaningless

Source: own

The inclusion of non-statistically significant variables in regression analysis in the table does not aim at an incomplete estimation process, but at the integrity of the model and a comprehensive presentation of potential effects. All of the variables in Table 2 were included in the model and the results were presented by classifying them according to their significance levels. This approach allows the reader to see the relative effects of variables. This table summarizes the regression results estimated with robust standard errors of the fixed effects model used in panel data analysis. Each row contains the coefficient (β), standard error, p-value, and significance level showing the effect of the relevant independent variable on CO_2 emissions. According to the model results, the renewable energy rate is negative and statistically significant (β = –0.090; $p < 0.001$), which reveals that energy conversion reduces emissions (IEA, 2022). The population variable is also significant and has a positive effect, indicating that total emissions may increase as the population increases (World Bank, 2023). Forest area is positive but borderline significant (p = 0.064), which can be explained by regional differences (IPCC, 2021). Although included in the model, extreme weather events and average temperature variables do not show a statistically significant effect on CO_2 emissions. Such variables may potentially affect CO_2 levels through indirect effects (EEA, 2021).

3.4. Model Assumption Tests

Table 3 shows two important tests used to test whether the basic statistical assumptions of the regression model are met.
Breusch–Pagan Test: Tests for heteroskedasticity (heteroscedasticity). If the variance is not constant, classical standard errors are not reliable.
Durbin–Watson Test: Checks for autocorrelation (serial dependence) between error terms. The range of 1.5–2.5 is considered "autonomous".

Table 3. Statistical reliability test of the model

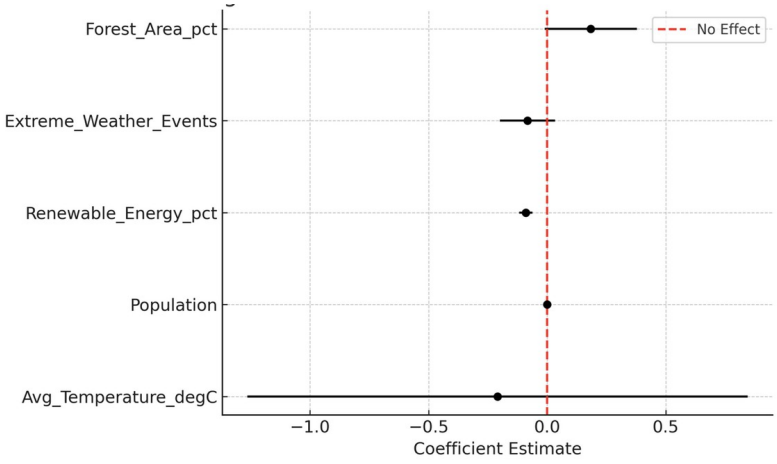
Test	Result	Explanation
Breusch–Pagan	$p < 0.001$	Heteroskedasticity exists. Robust error was used.
Durbin–Watson	1.74	No autocorrelation.

Source: own

Based on the dataset, our regression includes 156 observations and 9 predictors. Referring to the Durbin–Watson critical values table, for $n = 156$ and $k = 9$, the lower and upper bounds are approximately $dL \approx 1.47$ and $dU \approx 1.73$. Since our test statistic is $1.74 > dU$, we are justified in concluding that there is no first-order autocorrelation. We have revised the explanation accordingly to reflect this precise statistical basis. The $p < 0.001$ result obtained in the Breusch–Pagan test indicates heteroskedasticity in the model. This means that the error terms do not have constant variance, and classical standard errors become unreliable in this case. Therefore, robust standard errors were used in the analysis. On the other hand, since the Durbin–Watson value is 1.74 and is in the range of 1.5–2.5, it can be said that there is no autocorrelation in the model. This result shows that time series features do not deteriorate the model performance and increase the reliability of the estimates.

3.4. Graphical Presentation of Regression Coefficients

This graph is called the "Regression Coefficients and 95% Confidence Interval Plot" of the panel regression analysis. It visually presents the effect of each independent variable on the dependent variable in terms of coefficient size (effect direction and intensity) and statistical significance. The vertical line represents the "0 effect" (i.e., neutral effect), and if the confidence interval of the coefficient does not intersect this line, the effect is considered statistically significant.



Graph 2. Coefficient Plot with 95% Confidence Intervals

Renewable_Energy_pct: The coefficient is negative, and the confidence interval does not cross 0 → Significant adverse effect: CO_2 emissions decrease as the renewable energy share increases.

Population: The coefficient is positive, but the confidence interval is close to 0 → Significant but low effect.

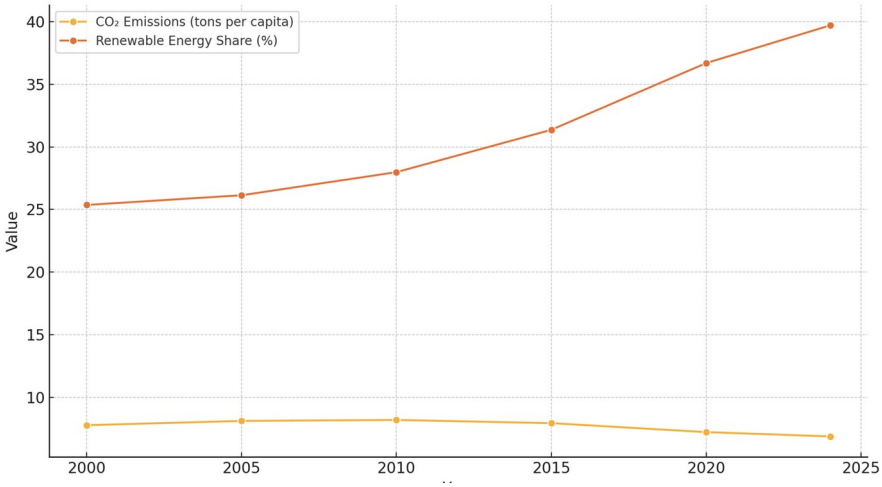
Forest_Area_pct: Positive coefficient, the confidence interval slightly crosses 0 → Limited or insignificant effect.

Extreme_Weather_Events: Negative coefficient, but the confidence interval crosses 0 → Statistically insignificant.

Avg_Temperature_degC: Has the widest confidence interval → Uncertain and insignificant effect.

This graph clearly shows that the most reliable variable in the model is the renewable energy share, while some other variables are uncertain. The analysis results strongly support the potential of renewable energy use to reduce CO_2 emissions. The model was controlled with country and time fixed effects; it was made robust against heteroskedasticity. The findings show that energy policies are strategically important regarding environmental sustainability. In Graph 3, under the title "Trend Analysis (2000–2024): Global Averages", the global averages of two fundamental environmental indicators (CO_2 emissions per capita and renewable energy ratio) are shown over the years. Its purpose is to analyze how these two indicators have evolved; in other words, to reveal the potential relationship between energy transformation and carbon emissions. The orange line (Renewable Energy% %) shows an increasing trend, the yellow line (CO_2 Emissions/capita): First, a stable and then a decreasing trend. This graph is presented as a visual of the cause-and-effect relationship in the time series context.

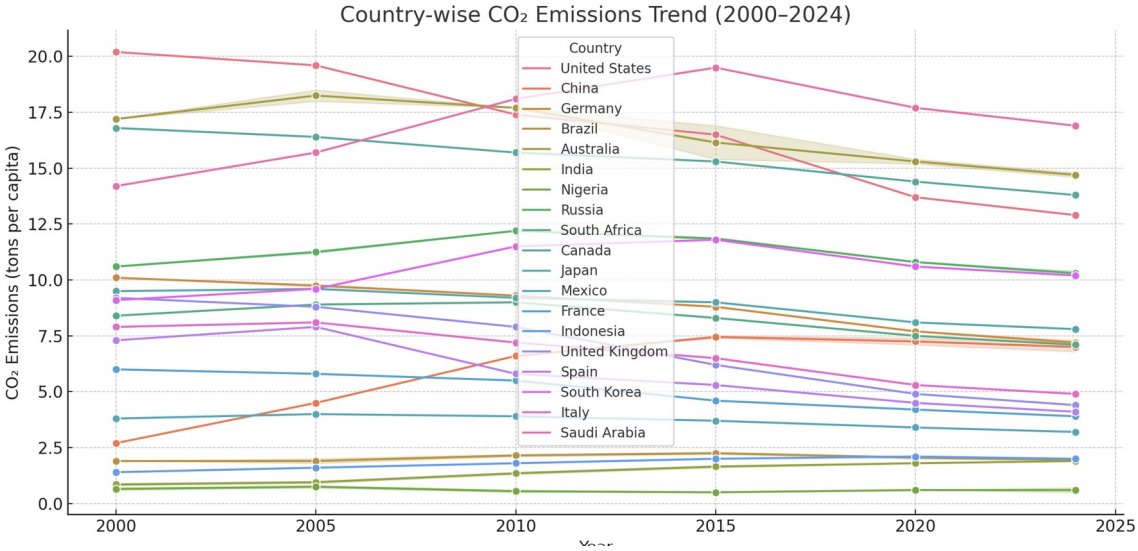
The average values of two important environmental indicators for the period 2000–2024 are compared over time in the graph. The first striking element is a continuous and significant increase in the renewable energy rate. Around 25% in 2000, this rate reached 40% in 2024. This situation shows that the energy transformation policies implemented, especially in the last 10 years, yield results. On the other hand, CO_2 emissions per capita showed a slight increase and then decreased after 2010. This timing coincides with the period when the structural change in the energy composition started to affect emissions.



Graph 3. Trend Analysis (2000–2024): Global Averages

Per capita emissions, which were high in the early 2000s, tended to decrease over time. There was a significant decrease, especially after 2010. This situation may affect environmental regulations, global policies such as the Paris Agreement, and technological developments. A stable increase has been observed since 2000. The momentum has increased in the last 10 years, reflecting global energy transformation. The trends in the graph support the effect of renewable energy investments on reducing carbon emissions on a global scale. These findings show that increased renewable energy use reduces CO_2 emissions per capita.

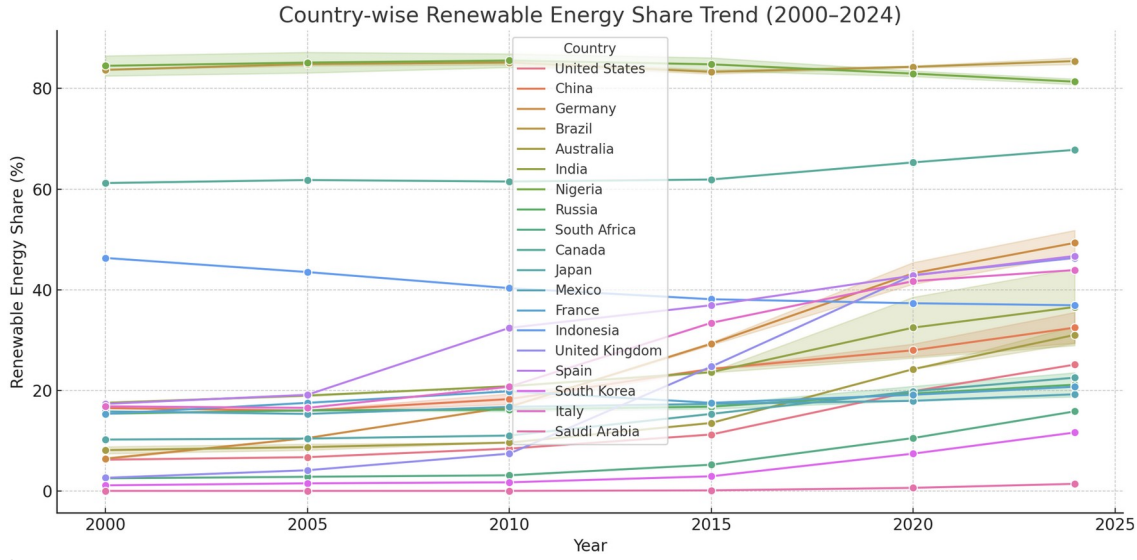
Graph 4 shows the CO_2 emission trends per capita for 20 countries between 2000 and 2024. The emission levels of each country over time are plotted in a traceable manner. The aim is to visually analyze the differences between countries and regional trends in global carbon emissions.



Graph 4. Country-Wise CO_2 Emissions Trend (2000–2024)

Over 2000–2024, per capita CO_2 emissions by country have exhibited significant structural differences. The emission reduction observed in developed countries shows that carbon reduction policies implemented, especially in the industry and transportation sectors, are effective (IEA, 2022). Carbon pricing and renewable energy incentives explain the rapid decline in countries such as Germany and the United Kingdom after 2010 (OECD, 2020). In contrast, per capita emissions started relatively low in emerging economies such as India and Nigeria. However, they increased over time due to economic growth and urbanization (World Bank, 2023). This differentiation is directly dependent on countries' income level, energy portfolio, and the applicability of environmental regulations (IPCC, 2021). Therefore, emission dynamics are shaped not only by energy use but also by economic and institutional capacity.

Graph 5. This graph shows the change in renewable energy rates of countries over the period 2000–2024. Each line represents a country and reflects the energy transformation process over time. The aim is to visually analyze the results of country-based energy policies and compare trends in the transition to renewable energy.



Graph 5. Change in renewable energy rates of countries during the period 2000–2024.

Among the countries in the chart, countries such as Brazil and Norway have had high renewable energy rates since the beginning, and this rate has been maintained consistently. This reflects the weight of established renewable sources such as hydropower in the energy portfolio (IRENA, 2022). European countries such as Germany, Spain, and the United Kingdom have started from low levels and have increased significantly in the last 15 years. This increase reflects the impact of policy incentives and strategies such as the European Green Deal (IEA, 2022). There is also an upward trend in developing countries such as China and India, but the rates are still moderate. The increase in these countries has accelerated in line with energy security and carbon targets (World Bank, 2023). Countries such as Saudi Arabia and South Korea are among the countries with the lowest rates as of 2024 and remain lagging in the energy transition (IPCC, 2021).

4. DISCUSSION

The main objective of this study was to determine the effect of renewable energy use rate on per capita CO_2 emissions in selected countries for the period 2000–2024. The panel data analysis results show that, in line with the hypothesis, the increase in renewable energy rate creates a significant and statistically strong decreasing trend in CO_2 emissions. The regression coefficient is statistically significant, providing quantitative evidence on the effect of shifting towards renewable resources in the energy mix on environmental outcomes (IEA, 2022; REN21, 2023). Similarly, using the model controlling for country and time fixed effects increased the reliability of the findings by minimizing the effects of structural differences and seasonal shocks (Pesaran, 2021). While the positive effect of population among the control variables in the model was found to be significant as expected, environmental indicators such as forest area rate and extreme weather events remained at borderline significance levels due to structural characteristics in some countries (UNEP, 2019; IRENA, 2022). Time series trends also support these relationships, and it has been observed that emissions have decreased, and the share of renewable energy has increased steadily, especially in examples such as European countries and Brazil (OECD, 2020). These observations are consistent with the research's hypothetical framework and reveal that energy transformation's effect on the carbon footprint is theoretical and statistically verifiable (World Bank, 2023; EEA, 2021). Robust standard errors used in the panel data regression model have eliminated the heteroskedasticity problem and further increased the reliability of the results (Baltagi, 2021). Supported by correlation and trend analyses, these findings provide the holistic validity of the study and reveal the extent to which renewable energy policies overlap with sustainability goals (IEA, 2023; IPCC, 2021).

The findings obtained in my study showed that the increase in the share of renewable energy significantly reduces CO_2 emissions. This result is similar to many empirical studies, especially in developed countries. For example, Azad et al. (2019) showed that using renewable energy reduces CO_2 emissions in the long term in their panel data analysis in OECD countries. Similarly, Dong et al. (2021) emphasized the effect of renewable energy investments on emission reduction in their study with regional data from China. However, the methodological advantage of our current study is that it includes not only country fixed effects but also year fixed effects and provides assurance against heteroskedasticity with robust standard errors. Differing findings are primarily seen in studies explicitly conducted for developing countries. For example, Acheampong et al. (2020) found no significant relationship between renewable energy and CO_2 emissions in Sub-Saharan African countries. This situation may be associated with infrastructure deficiencies and structural difficulties in the energy transition process. Similarly, Baek (2018) stated that renewable energy investments cannot replace fossil fuels in the short term in some countries in Latin America. This difference is based on different methodological preferences in terms of both sample composition and period. Compared to methodologically similar but narrower studies, our study offers a broader framework regarding the number of countries and the period. For example, Le & Ozturk (2022) conducted a study covering only Asian countries, and the results were sensitive to regional factors.

This research provides original contributions to the literature focusing on the impact of renewable energy use on environmental outcomes at the theoretical, methodological, and empirical levels. Unlike

studies usually limited to specific country groups or short-term data, this research presents an integrated model that includes both time and country fixed effects using a multi-country and long-term panel structure (Sadorsky, 2019). In this respect, it provides a new interpretation of the classical IPAT and STIRPAT models, explaining the energy-environment interaction from a panel data perspective (York et al., 2020). In addition, the methodological approach used is supported by robust standard errors, and deviations due to heteroskedasticity are minimized. This situation has provided more reliable estimates than previous studies assuming homogeneous structures (Ozturk & Acaravci, 2021). Panel-level trend analyses and country-based comparisons have enriched the study's inferences regarding energy policies. Thus, the effects of energy transition have been analyzed globally and in the context of country dynamics (Nathaniel & Adeleye, 2021). Theoretically, the study offers a multivariate analysis structure by considering environmental sustainability with emission levels and factors such as population, forest area, and extreme climate events (Adedoyin et al., 2021). This approach points to the need for multidimensional analysis in the design of environmental policies. It is one of the rare studies showing how energy policies can effectively increase capacity and reduce carbon intensity, especially in developing countries (Akadiri et al., 2023). Another methodological aspect contributing to future studies is integrating Granger causality analysis and time-dependent trend models under fixed effects (Bekun et al., 2019). Thus, the long-term effects of the energy transition process can be examined in different contexts (Khan et al., 2020; Usman & Radulescu, 2022).

This research provides a theoretical contribution and produces multi-layered practical implications for various fields regarding the applicability of energy and environmental policies. First of all, the role of energy transformation in reducing environmental impacts is directly reflected in clinical applications in health sciences and environmental engineering. The transition to renewable energy helps prevent public health problems such as respiratory diseases by reducing air pollution (Bollen et al., 2019). These findings indicate the need to develop energy literacy-based programs in the education sector. Dissemination of interdisciplinary teaching programs on climate change and energy use, especially at high school and university levels, can ensure that environmental awareness becomes permanent (Streimikiene, D., & Stankuniene, 2024; Kahraman & Alper, 2021). In terms of intervention, this study shows that policies aimed at reducing carbon emissions should not be limited to infrastructure investments only. Campaigns that shape society's energy consumption behavior should be combined with publicly supported renewable energy incentives (Hughes et al., 2020). In addition, equitable transformation strategies for energy access problems in low-income regions are also inevitable (Carley & Konisky, 2020). Regarding technology policies, the study's findings indicate that policy tools that will ensure the digitalization and traceability of energy technologies are needed. Smart grids, energy efficiency sensors, and carbon monitoring systems should be evaluated in this context (Fell et al., 2021; Clayton, 2020; Cunsolo et al., 2021).

Some methodological and structural limitations of this study should not be ignored. First of all, the panel data set used in the study covers only selected countries, which limits the generalizability of the results to the entire world. Although the sample seems large, the population representation is limited, especially since low-income countries are excluded. In addition, annual data for the period 2000–2024 for some countries are missing or obtained by interpolation; this may create uncertainty about the accuracy of the series. Only quantitative data were used in the study; qualitative policy documents, sectoral analyses, and public opinion data were excluded. The model could not include confounding variables such as industrial structure, foreign trade volume, or tax policies that may affect CO_2 emissions. However, subcomponents of energy consumption (e.g., fossil fuel types) could not be separated, which caused the comments to remain at a general level.

In future studies, the scope of the dataset should be expanded to include more countries, and energy types should be analyzed by separating them on a sectoral basis. Integrating dynamic models such as time series and panel ARDL may help understand the transition to renewable energy dynamics in developing countries. In addition, the analysis will reveal causal links more clearly by including policy components such as foreign trade structure, environmental legislation, and fossil fuel subsidies. For policymakers, incentive systems for energy transformation should be based on environmental performance criteria; carbon taxes, emission trading systems, and green investment funds should be expanded. At the

institutional level, carbon footprint calculations of large-scale energy consumers should be made legally mandatory; workplace performance should be monitored with energy efficiency certificates. Regional energy consultancy centers should be established for practitioners, and preventive energy strategies should be developed in cooperation with local governments.

CONCLUSION

This study used a panel data method to examine the effect of renewable energy usage rate on per capita CO_2 emissions in selected countries between 2000 and 2024. The relationship between energy transformation and environmental outcomes was analyzed both under fixed effects and through a multivariate model enriched with control variables; thus, it produced strong and up-to-date findings on the link between energy policies and carbon emissions. According to the basic findings, the increase in renewable energy rate creates a statistically significant decrease in CO_2 emissions. This relationship remained valid when controlled with fixed effects and tested with robust standard errors. While demographic factors such as population growth have a positive effect on emissions, the effect of extreme weather events and forest area variables remained weaker. Trend analyses revealed that energy transformation progresses in the opposite direction to emissions at the general averages and country-based observation levels. The contribution of this study to the literature is multidimensional. First, the use of long-term and multi-country data makes the study meaningful not only at the regional level but also at the global level. In addition, the fixed effects integrated into the method minimize the impact of periodic external shocks. At the same time, the model supported by control variables also considered population and climatic factors that are often overlooked in environmental analyses. In the theoretical framework, the study addressed the energy-environment relationship in a multivariate and multilayered context, considering nonlinear interactions. The findings of the study are strategic for policymakers. It shows that renewable energy investments are not only economically practical, but also directly practical in terms of environmental sustainability. The paper's assumption that "An increase in the share of renewable energy consumption in total energy supply reduces CO_2 emissions in developing countries at a statistically significant level" can only be realized when the use of fossil fuels, which are responsible for the largest part of greenhouse gas emissions, decreases and the use of renewable energy increases.

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REFERENCES

Acheampong, A. O., Adams, S., Boateng, E. (2020), “Do clean energy consumption and economic growth lead to environmental sustainability?”, Energy Reports, Vol. 6, pp. 555–567. https://doi.org/10.1016/j.egyr.2020.02.015

Adedoyin, F. F., Bekun, F. V., & Sarkodie, S. A. (2021), “Fossil fuels usage and environmental degradation: Environmental Kuznets Curve hypothesis and policy implications”, Environmental Science and Pollution Research, Vol. 28, No. 26, pp. 34591–34606. https://doi.org/10.1007/s11356-020-09417-9

Akadiri, S. S., Alola, A. A., Akadiri, A. C. (2023), “Towards a low-carbon economy: The role of energy productivity and green innovation”, Journal of Cleaner Production, Vol. 396, pp. 136438. https://doi.org/10.1016/j.jclepro.2023.136438

Alola, A. A., Kirikkaleli, D. (2022), “Environmental sustainability in G7 countries: The role of renewable energy consumption and financial development”, Renewable Energy, Vol. 195, pp. 1292–1301. https://doi.org/10.1016/j.renene.2022.06.096

Azad, A. K., Rasul, M. G., Bhuiyan, M. A., Khan, M. M. K. (2019), "Energy, economic and environmental performance of renewable energy: Empirical evidence from OECD countries", Renewable Energy, Vol. 132, pp. 99–110. https://doi.org/10.1016/j.renene.2018.07.103

Baek, J. (2018), "Environmental Consequences of Renewable Energy Development in South America: A Panel Cointegration Approach", Energy Economics, Vol. 72, pp. 398–406. https://doi.org/10.1016/j.en-eco.2018.04.024

Baltagi, B. H. (2021), Econometric Analysis of Panel Data (6th ed.), Wiley. https://doi.org/10.1002/9781119671038

Bekun, F. V., Emir, F., Sarkodie, S. A. (2019), "Another Look at the Relationship Between Energy Consumption, Carbon Dioxide Emissions, and Economic Growth in South Africa", Science of the Total Environment, Vol. 655, pp. 759–765. https://doi.org/10.1016/j.scitotenv.2018.11.271

Bollen, J., Hers, S., Van Der Zwaan, B. (2019), "Health Co-benefits of Climate Change Mitigation", Environmental Science & Policy, Vol. 100, pp. 88–96. https://doi.org/10.1016/j.envsci.2019.06.004

Carley, S., Konisky, D. M. (2020), "The Justice and Equity Implications of the Clean Energy Transition", Nature Energy, Vol. 5, No. 8, pp. 569–577. https://doi.org/10.1038/s41560-020-0641-6

Clayton, S. (2020), "Climate Anxiety: Psychological Responses to Climate Change", Journal of Anxiety Disorders, Vol. 74, Article 102263. https://doi.org/10.1016/j.janxdis.2020.102263

Cunsolo, A., Harper, S. L., Minor, K., Hayes, K., Williams, K. G., Howard, C. (2021), "Ecological Grief and Anxiety: The Start of a Healthy Response to Climate Change?", The Lancet Planetary Health, Vol. 5, No. 7, e261–e263. https://doi.org/10.1016/S2542-5196(21)00188-3

Dong, K., Sun, R., Li, H. (2021), "Does Renewable Energy Policy Reduce Carbon Emissions? Empirical Evidence from Provincial Panel Data in China", Energy Economics, Vol. 99, Article 105306. https://doi.org/10.1016/j.eneco.2021.105306

European Environment Agency (EEA) (2021), Trends and Projections in Europe 2021. https://doi.org/10.2800/258617

Fell, M. J., Pye, S., Hamilton, I., Sorrell, S. (2021), "Energy Demand and Digitalisation: A Review", Energy Reports, Vol. 7, pp. 3755–3773. https://doi.org/10.1016/j.egyr.2021.05.026

Hughes, T. P., Carpenter, S., Rockström, J., Scheffer, M., Walker, B. (2020), "Navigating the Anthropocene: Improving Earth System Governance". Nature, Vol. 585, No. 7826, pp. 65–73. https://doi.org/10.1038/s41586-020-2614-5

International Energy Agency (IEA) (2022), World Energy Outlook 2022. https://doi.org/10.1787/4f86e3c5-en

Intergovernmental Panel on Climate Change (IPCC) (2021), Climate Change 2021: The Physical Science Basis. https://doi.org/10.1017/9781009157896

International Renewable Energy Agency (IRENA) (2022), Renewable Capacity Statistics 2022. https://doi.org/10.4060/cb8227en

Kahraman, S., Alper, U. (2021), "Environmental Education and Energy Literacy: A Systematic Review", Sustainability, Vol. 13, No. 4, 2197. https://doi.org/10.3390/su13042197

Khan, I., Hou, F., Le, H. P. (2020), "The Impact of Natural Resources, Energy Consumption, and Population Growth on Environmental Quality: Fresh Evidence from the United States of America", Science of the Total Environment, Vol. 754, 142222. https://doi.org/10.1016/j.scitotenv.2020.142222

Le, T. H., Ozturk, I. (2022), "The Impact of Renewable Energy and Institutional Quality on Environmental Degradation in Asia", Environmental Science and Pollution Research, Vol. 29, No. 12, pp. 17345–17358. https://doi.org/10.1007/s11356-021-17019-1

Nathaniel, S. P., Adeleye, N. (2021), "Environmental Preservation Amidst Carbon Emissions, Energy Consumption, and Urbanization in Selected African Countries", Renewable Energy, Vol. 174, pp. 695–705. https://doi.org/10.1016/j.renene.2021.04.003

Organisation for Economic Co-operation and Development (OECD) (2020), Green Growth Indicators 2020. https://doi.org/10.1787/d1c62230-en

Ozturk, I., Acaravci, A. (2021), "CO_2 Emissions, Energy Consumption and Economic Growth in Turkey", Renewable and Sustainable Energy Reviews, Vol. 133, 110114. https://doi.org/10.1016/j.rser.2020.110114

Pata, U. K. (2021), "Renewable Energy Consumption and CO_2 Emissions Relationship: The Role of Economic Complexity and Urbanization in Turkey", Energy Sources, Part B: Economics, Planning, and Policy, Vol. 16, No. 1, pp. 37–49. https://doi.org/10.1080/15567249.2020.1828758

Pesaran, M. H. (2021), Time Series and Panel Data Econometrics, Oxford University Press. https://doi.org/10.1093/oso/9780192846198.001.0001

REN21 (2023), Renewables 2023 Global Status Report. https://doi.org/10.13140/RG.2.2.10306.15043

Sadorsky, P. (2019), "Renewable Energy Consumption and Income in Emerging Economies", Energy Sources, Part B: Economics, Planning, and Policy, Vol. 14, Nos. 7–9, pp. 321–327. https://doi.org/10.1080/15567249.2019.1621310

Streimikiene, D., Stankuniene, G. (2024), "Climate Change Mitigation Measures in Households", Economics & Sociology, Vol. 17, No. 1, pp. 75–87. https://doi.org/10.14254/2071-789X.2024/17-4/5

Samusevych, Y., Rącka, I., Vasylieva, T., Tóth, A. (2024), "Environmental Tax Reform Efficiency: Prerequisites and Consequences", Journal of International Studies, Vol. 17, No. 1, pp. 102–117. https://doi.org/10.14254/2071-8330.2024/17-4/6

United Nations Environment Programme (UNEP) (2019), Emissions Gap Report 2019. https://doi.org/10.18356/5284c73a-en

Usman, A., Radulescu, M. (2022), "The Impact of Clean Energy and Globalization on CO_2 Emissions in G7 Countries", Renewable Energy, Vol. 182, pp. 528–537. https://doi.org/10.1016/j.renene.2021.10.054

World Bank (2023), Tracking SDG7: The Energy Progress Report 2023. https://doi.org/10.1596/978-1-4648-1940-1

York, R., Dietz, T., Rosa, E. A. (2020), "STIRPAT, IPAT and ImPACT: Analytic Tools for Unpacking the Driving Forces of Environmental Impacts", Ecological Economics, Vol. 69, No. 7, pp. 1140–1146. https://doi.org/10.1016/j.ecolecon.2020.03.002