SDIJournals

Journal of Sustainable Development Issues, 2024, 2(2),

p. 89-103.

Journal homepage: https://journalsdi.com/index.php/jsdi/index; **ISSN: 3078-2546**

The Impact of Renewable and Non-Renewable Energy Consumption on CO_2 Emissions in Türkiye: Evidence from Augmented ARDL Approach

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ABSTRACT

Abstract. The increase in CO2 emissions, recognized as a global problem, is significantly influenced by energy consumption. Türkiye, which is among the developing countries, is a country dependent on foreign sources to meet its energy needs. Nevertheless, it satisfies its energy requirements through both renewable and non-renewable sources. The primary objective of this study is to elucidate the impact of consumption from renewable and non-renewable energy sources in Türkiye between 1990 and 2020 on CO2 emissions and investigate the validity of the Environmental Kuznets Curve hypothesis. We apply the traditional and structural break unit root tests to check whether the variables are stationary. We employed the newly accepted Augmented Autoregressive Distributed Lag (ARDL) method to estimate the long-run relationship between variables. According to the findings, there is a U-shaped relationship between economic growth and CO2 emissions. It means that the Environmental Kuznets Curve hypothesis is not applicable in Türkiye. Moreover, it concluded that non-renewable energy consumption plays a role in emission increase, while renewable energy consumption is effective in emission reduction.

Keywords: Renewable Energy Consumption, Non-Renewable Energy Consumption, Augmented ARDL, Environmental Kuznets Curve Hypothesis

JEL Classification: Q2, Q4, Q5

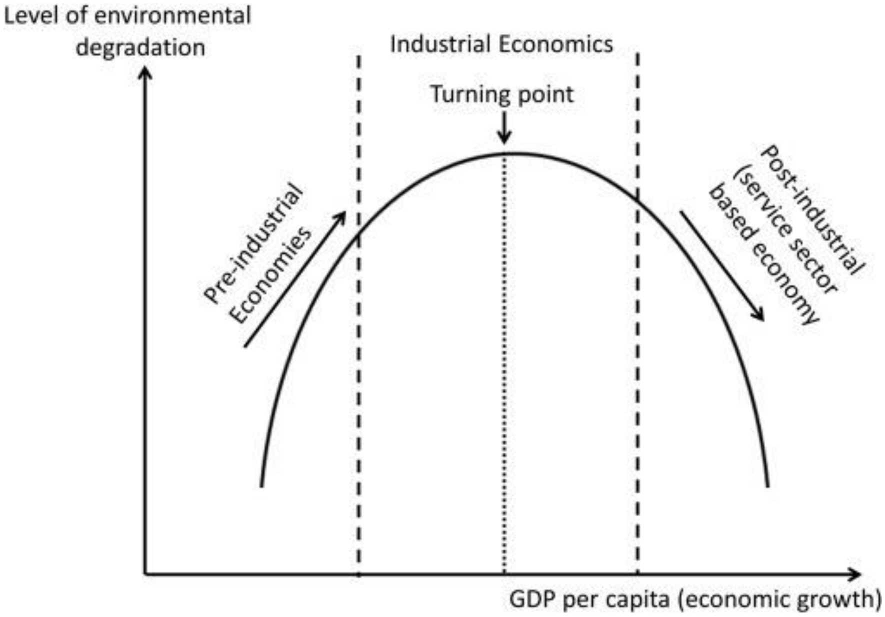
DOI: 10.62433/josdi.v2i2.28

Received: September, 2024 | 1st Revision: November, 2024 | Accepted: December, 2024

1. INTRODUCTION

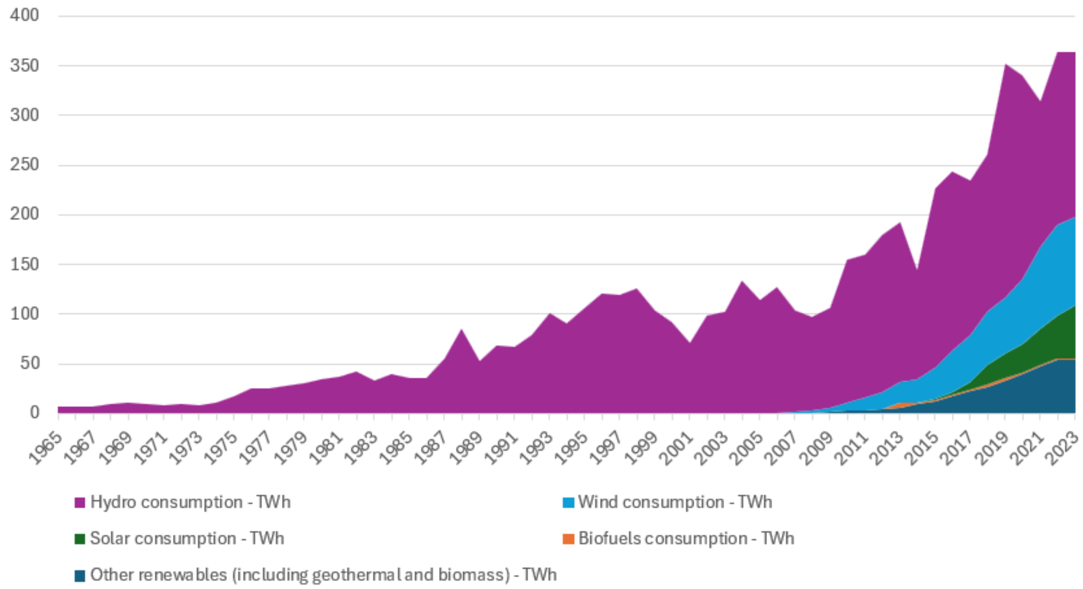
The environmental impact of carbon emissions has become increasingly severe. Research and development efforts, particularly in carbon capture, storage, and clean coal technology, aim to reduce these emissions. A significant portion of carbon emissions comes from using fossil fuels in the energy sector, and as energy consumption rises, emissions increase correspondingly. When fossil fuels are burned for energy, they produce solid and gaseous waste that cannot be repurposed, leading to further environmental degradation (DEKTMK, 2010; Çoban and Kılınç, 2015). In this study, the impact of renewable and non-renewable energy consumption on carbon emissions in Türkiye is examined within the framework of the Environmental Kuznets Curve (EKC) hypothesis. This topic has been extensively studied for Türkiye, as seen in works by Koçak (2014), Bölük and Mert (2015), Ertuğrul et al. (2016), Lebe (2016), Pata and Yurtkuran (2018), Çetin and Saygın (2019), Ceylan and Karaağaç (2020), Güzel (2021) and Özbek and Oğul (2022). However, the difference between this study and the others lies in its use of the newly introduced Augmented Autoregressive Distributed Lag (A-ARDL) method, which investigates the long-run cointegration relationship between variables under structural breaks, thereby aiming to contribute to the literature.

Figure 1: Environmental Kuznets Curve (EKC)



The EKC, depicted in Figure 1, illustrates the relationship between economic growth and environmental degradation. This important theory is grounded in the foundational work of Kuznets (1955), which identified an inverted U-shaped relationship between income distribution and economic growth. This provides valuable insights into the complexities of economic development and environmental sustainability. Subsequently, this approach was developed by various researchers, who included variables such as per capita income and environmental pollution. According to this model, environmental pollution initially rises with economic growth. However, upon reaching a certain threshold, while economic growth continues to advance, environmental pollution tends to decline. This relationship indicates an inverted U-shaped curve between economic growth and environmental degradation (Grossman and Krueger, 1991). Therefore, economic growth does not necessarily lead to continuous environmental degradation; on the contrary, once a certain income level is reached, environmental pollution gradually decreases.

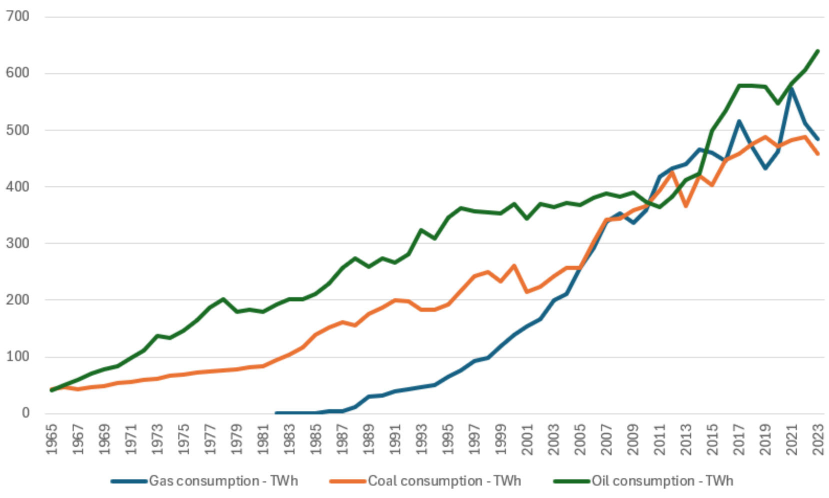
Figure 2: Renewable Energy Consumption in Türkiye



Source: Our World in Data (2024)

Figures 2 and 3 depict the consumption of renewable and non-renewable energy sources in Türkiye between the period of 1965 to 2023. Figure 2 shows that it is evident that hydro energy, one of the renewable energy sources, is the most consumed renewable energy source in Türkiye. And it is followed by wind, solar, and other renewable energy sources. In Figure 3, the time series graph shows the consumption of non-renewable energy sources such as gas, coal, and oil in Türkiye. This graph illustrates that oil was the most consumed energy source in Türkiye; however, after 2013, the consumption of all three sources (gas, coal, and oil) converged, indicating that they followed a similar consumption pattern.

Figure 3: Non-Renewable Energy Consumption in Türkiye



Source: Our World in Data (2024)

The remainder of this paper is structured as follows. The literature review section provides a comprehensive examination of previous studies that assess the validity of the EKC while analyzing the impacts of both renewable and non-renewable energy consumption on carbon dioxide (CO_2) emissions. In the third section, we detail the data, the model, and the econometric methodologies. In the next section, we interpret and discuss the findings in depth. In the conclusion, we offer policy recommendations for Türkiye based on the study's findings.

2. LITERATURE REVIEW

Since the 1990s, it is noteworthy that the number of empirical studies on EKC has gradually increased. In the literature, Grossman and Krueger (1991) first proposed the relationship between economic growth and environmental degradation. This study, which analyzed the NAFTA country sample, used SO2, smoke, and particulate matter as indicators of environmental degradation. It has shown that environmental degradation tends to increase during the early stages of economic growth. However, once growth surpasses a certain threshold, environmental degradation declines. These findings suggest an inverted U-shaped relationship between economic growth and environmental degradation. This pioneering study was followed by many important studies in literature (Shafik and Bandyopadhyay (1992); Panayotou (1993); Selden and Song (1994)).

This section focuses on recent studies from the perspective of the EKC. Studies that examine the impact of non-renewable and renewable energy consumption and economic growth on carbon emissions are analyzed. Panel A of Table 1 presents the studies conducted in Türkiye, while Panel B highlights studies from other countries.

Table 1: Summary of previous literature

Panel A: Studies Conducted for Türkiye				
Author(s)	***Years***	***Variables***	***Method(s)***	***Results***
Koçak (2014)	1960-2010	CO_2, Y, Y^2, Y^3, EC	ARDL	×
Boluk and Mert (2015)	1961-2010	CO_2, Y, Y^2, REC	ARDL	✓
Ertugrul et al. (2016)	1971-2011	CO_2, Y, Y^2, EC, TR	ARDL	✓
Lebe (2016)	1960-2010	CO_2, Y, Y^2, EC, FD, TR	ARDL	✓
Katircioglu and Taspinar (2017)	1960-2010	CO_2, Y, Y^2, EC, FD	DOLS	✓
Pata and Yurtkuran (2018)	1981-2014	CO_2, Y, Y^2, REC, FD, PD	ARDL	✓
Cetin and Yuksel (2018)	1960-2014	CO_2, Y, Y^2, EC, TR, FD	GMM, DOLS	✓
Cetin and Saygin (2019)	1960-2014	CO_2, Y, Y^2, EC, TR	ARDL	✓
Ceylan and Karaagac (2020)	1960-2014	CO_2, Y, Y^2, Y^3, EC	ECM	×
Okumus (2020)	1968-2014	CO_2, AGR, Y, Y^2, NREC, REC, TR, URB	ARDL	✓
Ozdemir and Koc (2020)	1960-2017	CO_2, Y, Y^2, Y^3, NREC, REC, TR	ARDL	×
Eylasov et al. (2023a)	1990-2020	CO_2, GDP, REN, EX, IMP	ARDL and Bayer-Hanck	×
Guzel (2021)	1960-2015	CO_2, Y, Y^2, Y^3, EC	ARDL	×
Ozbek and Ogul (2022)	1990-2018	CO_2, Y, Y^2, EC	ARDL, FMOLS, CCR	✓
Dalli and Kutukcu (2023)	1974-2019	CO_2, Y, Y^2, AGR, NREC, REC, FD, FDI	ARDL	✓
Eylasov et al. (2023b)	1971-2019	CO_2, Y, Y^2, EC	ARDL	✓
Panel B: Studies Conducted for Other Countries				
Author(s)	***Years (Countries)***	***Variables***	***Methods***	***Results***
Shahbaz et al. (2014)	1971-2010 (Tunusian)	C, Y, Y^2, EC, TR	ARDL, Johansen	✓
Ahmad et al. (2016)	1971-2014 (India)	CO_2, Y, Y^2, EC	Johansen and ARDL	✓
Kartal et al. (2023)	1970-2021 (France)	CO_2, GAS, NUCLEAR, COAL, OIL, RENEW	DYARDL and KRLS	×
Mikayilov et al. (2018)	1992-2013 (Azerbaijan)	CO_2, Y, Y^2, Y^3	ARDL, FMOLS, and DOLS	×
Rayhan et al. (2018)	1973-2013 (Bangladesh)	CO_2, Y, Y^2, TR, EC, URB, FDI	ARDL	✓
Hasanov et al. (2019)	1992-2013 (Kazakhstan)	CO_2, Y, Y^2, Y^3	ARDL, FMOLS, and DOLS	×
Dong et al. (2020)	1995-2015 (120 Countries)	CO_2, Y, Y^2, REC, NREC, ES, URB, TR	MG, CCEMG and AMG	✓

Aziz et al. (2021)	1995-2018 (MINT)	CO_2, Y, Y^2, REC, NAR, GLOB	FMOLS, DOLS, FE-OLS and MMQR	✓
Leitão et al. (2021)	1990-2015 (BRICS)	CO_2, Y, Y^2, ECI, REC	FMOLS, DOLS, FE-OLS and MMQR	✓
Ulussever et al. (2023)	January 1973 and December 2021 (USA)		ML and TS	×
Ali et al. (2021)	1975-2014 (Pakistan)	CO_2, Y, Y^2, FDI, NREC	ARDL	✓
Imamoglu and Onbasioglu (2023)	1975-2015 (Pakistan)	CO_2, Y, Y^2, EC, GLOB	ARDL	✓
Yilanci et al. (2023)	1850-2018 (United Kingdom)	CO_2, Y, Y^2, EC	Johansen and time varying causality tests	✓

Note: *The ✓symbol indicates that the EKC hypothesis is valid, and the × symbol indicates that the EKC hypothesis is not valid. The variable abbreviations mean: CO_2: Carbon emission, Y: per capita GDP, EC: Energy consumption, REC: Renewable energy consumption, NREC: Non-renewable energy consumption, TR: Trade openness, URB: Urbanization, GLOB: Globalization, FD: Financial development, ECI: Economic complexity index, FDI: Foreign direct investment, ES: Economic structure, PD: Population density, NAR: Natural resources, AGR: Value-added agriculture. The method abbreviations mean: ARDL: Autoregressive Distributed Lag, FMOLS: Fully Modified OLS, DOLS: Dynamic OLS, FE-OLS: Fixed effect OLS, MMQR: Method of Moments Quantile Regression, MG: Mean Group, CCEMG: Correlated effect mean group, AMG: Augmented mean group.*

Upon analyzing Panel A of Table 1, it becomes evident that many studies have focused on using the ARDL bounds test approach to examine the relationships between variables. The prevalence of this approach in the research is mainly due to its effectiveness in estimating both short-run and long-run relationships between variables in Turkey (Qoyash ve Eren, 2022). In the majority of the studies analyzed, the findings indicate that the Environmental Kuznets Curve (EKC) hypothesis holds true for the sample from Türkiye. Additionally, it can be observed that non-renewable energy consumption significantly contributes to an increase in CO2 emissions, whereas renewable energy consumption plays a crucial role in reducing CO2 emissions. Similar results are found in Panel B, which examines samples from other countries.

In summary, this study presents an analysis of samples that encompass both Türkiye and other countries, demonstrating general support for the validity of the EKC hypothesis. A key distinction of this research lies in its method of incorporating energy consumption variables, which are categorized separately into non-renewable and renewable energy consumption during the investigation of the EKC hypothesis's validity. This approach enhances our understanding of the relationship between economic development and environmental impact. Thus, the direct effects of each energy consumption on emissions can be estimated. Furthermore, the newly accepted A-ARDL bounds test approach is employed to ascertain both the short- and long-run relationships between the variables involved. This methodology is anticipated to enhance the existing literature, particularly as it has not yet been applied in investigating the validity of the EKC hypothesis within the context of Türkiye.

3. RESEARCH MODEL AND METHODOLOGY

3.1. Dataset and Model

This study analyzes data from the period 1990 to 2020 to assess the impact of renewable and non-renewable energy sources on changes in CO_2 emissions in Türkiye. Furthermore, it assesses the validity of the EKC hypothesis. The renewable energy sources analyzed in this research include hydro, solar, wind, geothermal, solid biomass, biogas, and waste, while the non-renewable energy sources addressed are coal, natural gas, and liquid fuels. Detailed definitions and sources of the variables utilized in the study are presented in Table 4.

Table 4: Definitions and Sources of Variables

Symbol	Variable	Unit	Source
CO_2	CO_2 emissions	Kiloton	World Bank
GDP	GDP per capita	Constant 2015 US Dollars	World Bank
NEC	Non-renewable energy consumption	Ejoule (EJ)	BP
REC	Renewable energy consumption	Percentage of total final energy consumption	World Bank

In this context, three alternative models have been developed to evaluate the validity of the EKC hypothesis and to analyze the influence of various energy sources on CO_2 emissions:

Model 1: $lnCO_{2t} = f(lnGDP_t, lnGDP_t^2, lnNREC_t, lnREC_t)$

Model 2: $lnCO_{2t} = f(lnGDP_t, lnGDP_t^2, lnNREC_t)$

Model 3: $lnCO_{2t} = f(lnGDP_t, lnGDP_t^2, lnREC_t)$

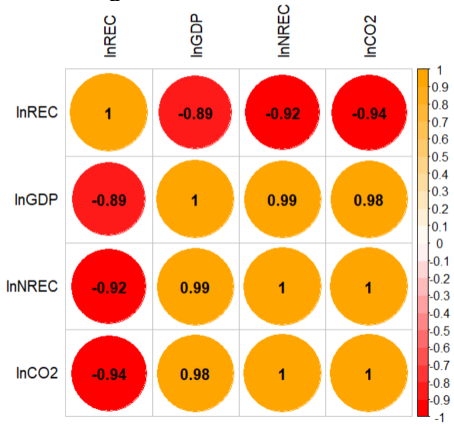
To effectively interpret the elasticity of each independent variable present in the equations, logarithmic transformations have been applied to all variables. In Models 1-3, the coefficient associated with the $lnGDP$ variable is positive, whereas the coefficient for $lnGDP^2$ is negative. This suggests an inverted U-shaped relationship between per capita income and CO_2 emissions (Koçak, 2014; Aliyev et al., 2024). These findings provide support for the validity of the EKC hypothesis. Furthermore, theoretical analysis indicates that renewable energy consumption is associated with a decrease in CO_2 emissions, whereas non-renewable energy consumption correlates with an increase in emissions (Adebayo, 2022; Raihan, 2023; Saba, 2023; Raihan and Tuspekova, 2022; Bekun, 2022). For a comprehensive overview, Table 5 summarizes the descriptive statistics of the analyzed variables, while Figure 4 presents a visual representation of the correlation matrix.

Table 5: Descriptive Statistics of Variables

	$lnCO_2$	lnGDP	lnNREC	lnREC
Mean	12.413	8.947	1.319	2.791
Median	12.367	8.942	1.277	2.730
Max	12.943	9.398	1.887	3.193
Min	11.843	8.567	0.704	2.433
Std. Deviation	0.346	0.278	0..372	0.255
Skewness	-0.026	0.269	0.008	0.296
Kurtosis	1.759	1.692	1.793	1.627
Jarque-Bera	*1.991*	*2.585*	*1.881*	*2.887*
Prob	*0.369*	*0.274*	*0.390*	*0.236*

According to Table 5, all variables are found to have a normal distribution. The p-values from the Jarque-Bera test are greater than 0.05, indicating that the null hypothesis of normality is not rejected. Notably, the skewness coefficients for all variables, except for carbon emissions, yield positive values. This suggests that the normal distribution graphs for lnGDP, lnNREC, and lnREC are skewed to the right, while the graph for $lnCO_2$ is skewed to the left. Furthermore, the kurtosis values for all variables are found to be less than 3, leading to the conclusion that the normal distribution graphs generally exhibit a platykurtic structure.

Figure 4: Correlation Matrix

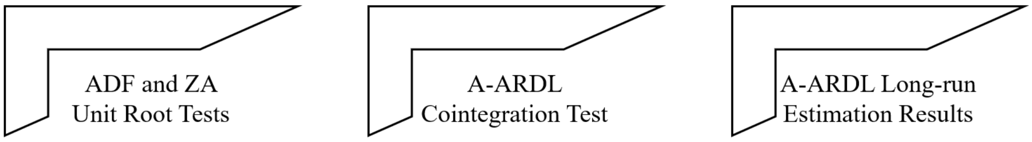


When analyzing the findings of the correlation matrix shown in Figure 4, it is noted that there exists a significant correlation among all variables. Specifically, a strong positive correlation is observed between economic growth, non-renewable energy consumption, and carbon emissions. Conversely, a notable negative correlation is found between renewable energy consumption and carbon emissions.

3.2. Methodology

This section offers a comprehensive overview of the econometric methods utilized in this study. Figure 5 illustrates the sequence of these methodologies. Initially, we assessed the stationarity of the variables through both conventional and structural break unit root tests. Following this, we examined the cointegration relationship among the variables using the A-ARDL approach. Finally, we present the long-run estimation results from the A-ARDL model in detail. A brief overview of these econometric methods is provided below.

Figure 5: Methodology Sort



3.2.1. Augmented Dickey Fuller (ADF) Unit Root Test

In the econometric literature, numerous unit root tests exist to assess the stationarity of variables. These tests vary based on the characteristics of the time series data. Given the occurrence of sudden breaks in the time series variables examined in this study, the Zivot-Andrews (ZA) unit root test, which accounts for structural breaks, was employed in addition to the traditional Augmented Dickey-Fuller (ADF) unit root test. The ADF unit root test was introduced to the literature by Dickey and Fuller (1981).

The difference between the ADF test and the Dickey-Fuller (1979) test, which previously introduced to the literature, lies in its approach to addressing the autocorrelation problem. This new test effectively addresses the issue of autocorrelation by incorporating a lag of the dependent variable into the model. The regression equations utilized in the ADF unit root test have been specifically tailored to align with the variables examined in this study and detailed in Equations 1 to 3.

Model with constant term and no trend.

$$\Delta lnCO_{2t} = \beta_1 lnCO_{2t-1} + \sum_{i=1}^{p} \beta_i lnCO_{2t-1} + u_t \quad (1)$$

Model with constant terms and no trend.

$$\Delta lnGDP_t = \beta_0 + \beta_1 lnGDP_{t-1} + \sum_{i=1}^{p} \beta_i lnGDP_{t-1} + u_t \quad (2)$$

Constant and trend model.

$$\Delta lnREC_t = \beta_0 + \beta t + \beta_1 lnREC_{t-1} + \sum_{i=1}^{p} \beta_i lnREC_{t-1} + u_t \quad (3)$$

In the equations, β_0 represents the constant term, u_t denotes the error term, and βt represents the trend. The variable p indicates the optimal lag length calculated using either the Akaike or Schwarz information criteria. The hypotheses of the ADF unit root test are shown below:

H_0: There is a unit root; the series is non-stationary.

H_1: There is no unit root; the series is stationary.

If the tau statistic value calculated for one lag of the dependent variable β_1 is found to be significantly larger in absolute terms than the critical values from MacKinnon (1996), the null hypothesis will be rejected. Thus, the series will be found to be stationary at the level (Aliyev et. al., 2022; Eylasov and Çiçek, 2024).

3.2.2. Zivot-Andrews (ZA) Single Break Unit Root Test

The ADF unit root test is not reliable when structural breaks are present. To address this issue, the study also utilized the Zivot and Andrews (1992) single-break unit root test, which provides reliable results in the presence of structural breaks. The ZA unit root test, developed by Zivot and Andrews (1992), accommodates a single structural breakpoint at the level. In this study, the variable lnCO2 is examined in the forms outlined in Eqs. 4 to 7.

$$\Delta lnCO_{2t} = \alpha + alnCO_{2t-1} + bT + cD_t \quad (4)$$

$$\Delta lnCO_{2t} = \beta + \beta lnCO_{2t-1} + ct + bDT_t + \sum_{j=1}^{k} d_j \Delta lnCO_{2t-j} + \varepsilon_t \quad (5)$$

$$\Delta lnCO_{2t} = \gamma + \gamma lnCO_{2t-1} + ct + dDT_t + \sum_{j=1}^{k} d_j \Delta lnCO_{2t-j} + \varepsilon_t \quad (6)$$

$$\Delta lnCO_{2t} = \Omega + \Omega lnCO_{2t-1} + ct + dD_t + dDT_t + \sum_{j=1}^{k} d_j \Delta lnCO_{2t-j} + \varepsilon_t \quad (7)$$

In the equations, D is a dummy variable representing the mean shift at each point in time. DT_t represents a trend change. According to Zivot and Andrews (1992), the hypotheses of the test are as follows:

H_0: There is no structural break in the series, and the series is non-stationary.

H_1: There is an unknown structural break in the series, and the series is stationary.

If the calculated test statistic is greater than the critical value, the null hypothesis is rejected. This indicates that the series is stationary at the level and that there is a significant break.

3.2.3. Augmented Autoregressive Distributed Lag (A-ARDL) Bounds Test

Various cointegration tests are available in the literature that assess the presence of a long-run equilibrium relationship among variables. Among these, the tests developed by Bayer and Hanck (2013) and Johansen (1988) are particularly recognized and applicable when the variables exhibit stationarity at the first difference. Additionally, Pesaran et al. (2001) introduced the ARDL bounds test methodology, which facilitates the analysis of cointegration relationships in instances where the dependent variable is stationary at the first difference, while independent variables may be stationary at different levels. It is essential to highlight that none of the variables should display stationarity at the second difference. The ARDL bounds test has been adapted for the variables in this study, as demonstrated in Eqs 8 to 10.

Model 1;

$$\Delta lnCO_{2t} = \upsilon_0 + \upsilon_1 DU2001_t + \sum_{i=1}^{p} \alpha_{1i} \Delta lnCO_{2t-i} + \sum_{i=0}^{k} \alpha_{2i} \Delta lnGDP_{t-i} + \sum_{i=0}^{c} \alpha_{3i} \Delta lnGDP_{t-i}^2 + \sum_{i=0}^{d} \alpha_{4i} \Delta lnNREC_{t-i} + \sum_{i=0}^{h} \alpha_{5i} \Delta lnREC_{t-i} + \gamma_1 lnCO_{2t-1} + \gamma_2 lnGDP_{t-1} + \gamma_3 LGDP_{t-i}^2 + \gamma_4 lnNREC_{t-1} + \gamma_5 lnREC_{t-1} + \varepsilon_t \quad (8)$$

Model 2;

$$\Delta lnCO_{2t} = \upsilon_0 + \upsilon_1 DU2001_t + \sum_{i=1}^{p} \alpha_{1i} \Delta lnCO_{2t-i} + \sum_{i=0}^{k} \alpha_{2i} \Delta lnGDP_{t-i} + \sum_{i=0}^{c} \alpha_{3i} \Delta lnGDP_{t-i}^2 + \sum_{i=0}^{h} \alpha_{4i} \Delta lnREC_{t-i} + \gamma_1 lnCO_{2t-1} + \gamma_2 lnGDP_{t-1} + \gamma_3 LGDP_{t-i}^2 + \gamma_4 lnREC_{t-1} + \varepsilon_t \quad (9)$$

Model 3;

$$\Delta lnCO_{2t} = \upsilon_0 + \upsilon_1 DU2001_t + \sum_{i=1}^{p} \alpha_{1i} \Delta lnCO_{2t-i} + \sum_{i=0}^{k} \alpha_{2i} \Delta lnGDP_{t-i} + \sum_{i=0}^{c} \alpha_{3i} \Delta lnGDP_{t-i}^2 + \sum_{i=0}^{d} \alpha_{4i} \Delta lnNREC_{t-i} + \gamma_1 lnCO_{2t-1} + \gamma_2 lnGDP_{t-1} + \gamma_3 LGDP_{t-i}^2 + \gamma_4 lnNREC_{t-1} + \varepsilon_t \quad (10)$$

In the equations above, Δ denotes the first difference of the variable, and ε_t represents the error term. υ_1 indicates the break point (dummy variable) found by the ZA unit root test. p, k, c, d, and h refer to the optimal lag lengths determined by the Akaike or Schwarz information criteria. According to the bounds test by Pesaran et al. (2001), the long-run equilibrium relationship among the variables is identified using the F_{all} and $t_{dependent}$ tests. The null hypotheses of the F test by Narayan (2005) and the t test by Pesaran et al. (2001) are shown in the equations below.

F and t test hypotheses for Model 1;

$$F_{all}\ test;\ H_0: \gamma_1 = \gamma_2 = \gamma_3 = \gamma_4 = \gamma_5 = 0 \quad (11)$$

$$t_{dependent}\ test;\ H_0: \gamma_1 = 0 \quad (12)$$

F and t test hypotheses for Models 2 and 3;

$$F_{all}\ test;\ H_0: \gamma_1 = \gamma_2 = \gamma_3 = \gamma_4 = 0 \quad (13)$$

$$t_{dependent}\ test;\ H_0: \gamma_1 = 0 \quad (14)$$

If the calculated values of the F and t statistics, which are in absolute, exceed the upper critical values established by Narayan (2005) and Pesaran et al. (2001), the null hypotheses, the above, will be rejected. This outcome suggests that there is a cointegration relationship among the variables. In their study, Sam et al. (2019) extended the ARDL bounds test by developing the $F_{independent}$ test, which tests the cointegration relationship among the independent variables, and provided critical values that allow for testing the long-run equilibrium relationship among the independent variables as well. The advantage of this A-ARDL bounds test is that it ignores the requirement of the dependent variable being first-order stationary, as imposed by the traditional ARDL bounds test. The null hypothesis of the $F_{independent}$ test developed by Sam et al. (2019) is shown in Equations 15 and 16.

$F_{independent}$ hypothesis for Model 1.

$$F_{independent}\ test;\ H_0: \gamma_2 = \gamma_3 = \gamma_4 = \gamma_5 = 0 \quad (15)$$

$F_{independent}$ hypothesis for Model 1 and Model 2.

$$F_{independent}\ test;\ H_0: \gamma_2 = \gamma_3 = \gamma_4 = 0 \quad (16)$$

If the calculated value for the $F_{independent}$ test is found to be greater than the upper critical value of Sam et al. (2019) in absolute terms, the null hypothesis will be rejected, indicating the existence of a long-run equilibrium relationship among the variables. If any of the F_{all}, $t_{dependent}$, or $F_{independent}$ tests are found to be smaller than the upper critical values of Narayan (2005), Pesaran et al. (2001), and Sam et al. (2019) respectively, different degenerate cases will emerge, and a cointegration relationship will not be present.

4. EMPIRICAL RESULTS

In time series analysis, examining the stationarity of the series is crucial to avoid the issue of spurious regression when establishing relationships among variables. Traditional unit root tests, like the ADF test, and structural break unit root tests, such as the ZA test, are commonly used to assess whether the variables under consideration are stationary. The results of these unit root tests are presented in Table 6.

Table 6: ADF and ZA Unit Root Test Results

Variables	ADF Unit Root Test		ZA Unit Root Test		
	Test stat.	Lag	Test stat.	Break Date	Lag
lnCO_2	-2.963	0	-4.316	**2001**	1
$\Delta ln$$CO_2$	-5.839***	0	-5.136**	2005	1
lnGDP	-2.577	0	-3.855	1999	0
ΔlnGDP	-5.436***	0	-5.903***	2003	0
lnNREC	-3.051	0	-4.255	1999	0
ΔlnNREC	-6.478***	0	-7.255***	2003	0
lnREC	-1.921	0	-5.178**	2007	0
ΔlnREC	-6.292***	0	---	---	---

Note: **** and ** denote significance at the 1% and 5% levels, respectively.*

The ADF unit root test results indicate that all variables have a unit root at levels. However, they become stationary when their first differences are taken. In other words, all variables are statistically stationary at their first differences at the 1% significance level, meaning they are I(1). The findings of the ZA structural break unit root test indicate that all variables, except for renewable energy consumption, are stationary at their first differences. The carbon emissions variable is stationary when it takes its first difference, with a structural break identified in 2001. This break date represents the structural break caused by the 2001 crisis. We consider the results of the structural break unit root test. Because the ZA structural break unit root test is considered more reliable than the traditional ADF unit root test. Moreover, we apply the A-ARDL model to estimate the long-run relationship between the variables since the variables have different integration orders. In the study, the 2001 crisis was included as an exogenous variable in the A-ARDL model, represented by a dummy variable. In time series analyses, failing to account for structural breaks may result in unreliable outcomes (Yildirim, 2011). Table 7 presents the findings on a long-run relationship within the framework of alternative models.

Table 7: A-ARDL Bound Test Results

Models	Dummy		Lag Length		Test stat.		Results
Model 1 lnCO2 | lnGDP, lnGDP², lnNREC, lnREC	2001		1,1,0,1,0		$F_a = 24.7^{***}$, $t_d =$ -9.9***, $F_{id} =$ 30.6***		Cointegration
Model 2 lnCO2 | lnGDP, lnGDP², lnNREC	2001		1,0,0,0		$F_a = 18.81^{***}$, $t_d = -7.94^{***}$, $F_{id} = 24.86^{***}$		Cointegration
Model 3 lnCO2 | lnGDP, lnGDP², lnREC	2001		1,0,3,0		$F_a = 10.63^{***}$, $t_d = -4.32^{**}$, $F_{id} = 14.14^{***}$		Cointegration
Critical Values	%1		%5		%10		For $k = 4$
Tests	I(0)	I(1)	I(0)	I(1)	I(0)	I(1)	Search
F_{all}	4.768	6.67	3.354	4.774	2.752	3.994	Narayan (2005)
$t_{dependent}$	-3.43	-4.6	-2.86	-3.99	-2.57	-3.66	Pesaran et al. (2001)
$F_{independent}$	4.60	7.72	2.96	5.14	2.30	4.11	Sam et al. (2019)
Critical Values	%1		%5		%10		For $k = 3$
Tests	I(0)	I(1)	I(0)	I(1)	I(0)	I(1)	Search
F_{all}	5.333	7.06	3.71	5.01	3.00	4.15	Narayan (2005)
$t_{dependent}$	-3.43	-4.4	-2.86	-3.78	-2.57	-3.46	Pesaran et al. (2001)
$F_{independent}$	4.15	6.83	2.80	4.70	2.22	3.84	Sam et al. (2019)

Note: **** and ** denote significance at the 1% and 5% levels, respectively.*

In the alternative models presented in Table 7, which examine the effects of renewable and non-renewable energy consumption on CO_2 emissions and test the validity of the EKC hypothesis, the 2001 structural break period was included as an exogenous variable. For Model 1, the calculated test statistics F_{all} , $t_{dependent}$, and $F_{independent}$ are greater in absolute terms than the critical values provided by Narayan (2005), Pesaran et al. (2001), and Sam et al. (2019) at the 1% significance level. Therefore, the null hypothesis, which states that there is no long-run equilibrium relationship among the variables, is rejected. Similarly, the calculated test statistics F_{all}, $t_{dependent}$, and $F_{independent}$ for both Model 2 and Model 3 are also greater in absolute terms than the critical values provided by Narayan (2005), Pesaran et al. (2001), and Sam et al. (2019). The results indicate that we can reject the null hypothesis of no long-run relationship between the variables in all models, thereby confirming the existence of a cointegration relationship. The diagnostic tests must be valid to ensure the reliability of the results derived from the A-ARDL approach. Table 8 demonstrates the outcomes of these diagnostic tests for alternative models.

Table 8: Results of Diagnostic Tests for A-ARDL

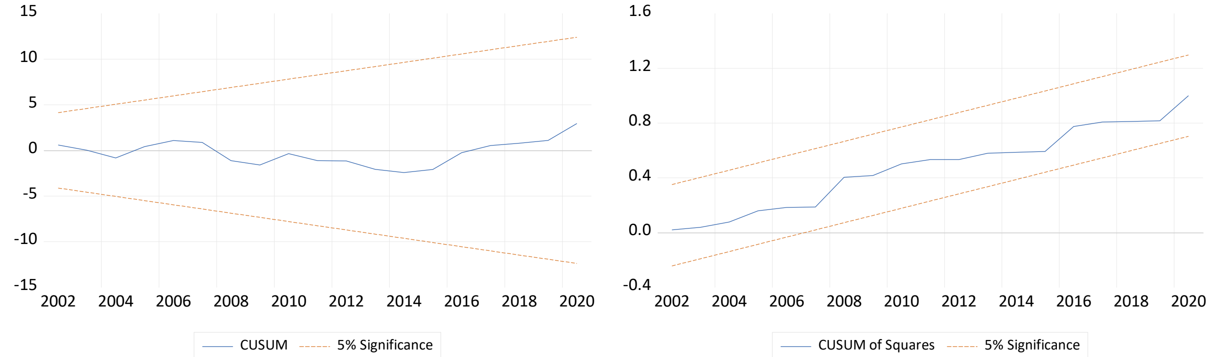
Models	***Model 1***		***Model 2***		***Model 3***	
Tests	***F stat.***	***Prob***	***F stat.***	***Prob***	***F stat.***	***Prob***
BPG	0.462	0.868	0.612	0.756	0.728	0.608
LM	1.481	0.252	0.666	0.526	1.834	0.183
JB	0.573	0.750	1.882	0.390	0.383	0.825
RR	1.169	0.292	1.822	0.193	0.167	0.686
CUSUM	Stable		Stable		Stable	
CUSUMsq	Stable		Stable		Stable	

Note: *BPG stands for Breusch-Pagan-Godfrey heteroscedasticity test, LM stands for Breusch-Godfrey LM autocorrelation test, JB stands for Jarque-Bera normality test, RR stands for Ramsey-Reset specification error test.*

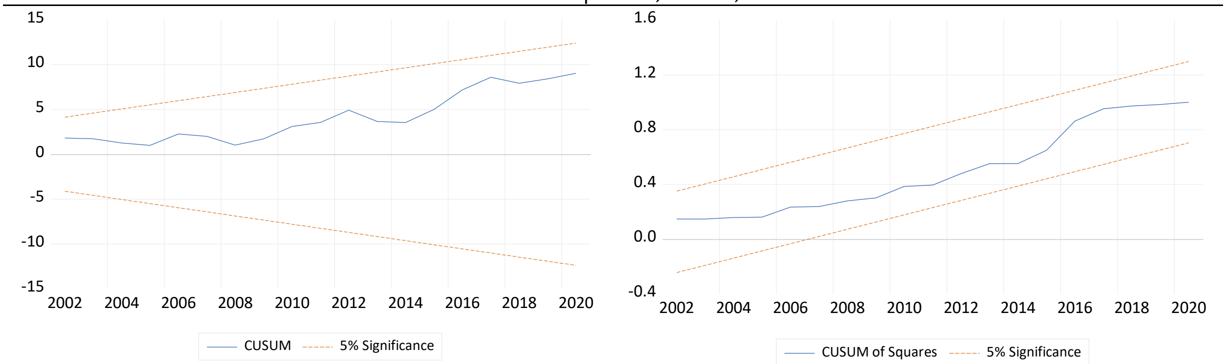
The results presented in Table 8 reveal that the A-ARDL residuals of all models do not exhibit issues related to heteroscedasticity, autocorrelation, normality, or model specification errors. Additionally, cointegration results across all three models are deemed reliable. Figure 6 illustrates the CUSUM and CUSUMSQ graphs for each model. It indicates that the parameter estimates remain within the 95% confidence interval, demonstrating stability. Table 9 presents the long-run parameter estimates among the variables.

Figure 6: CUSUM and CUSUMsq Graphs

Model 1 = $lnCO_2$ | lnGDP, $lnGDP^2$, lnREC, lnNREC



Model 2 = $lnCO_2$ | lnGDP, $lnGDP^2$, lnREC



Model 3 = $lnCO_2$ | lnGDP, $lnGDP^2$, lnNREC

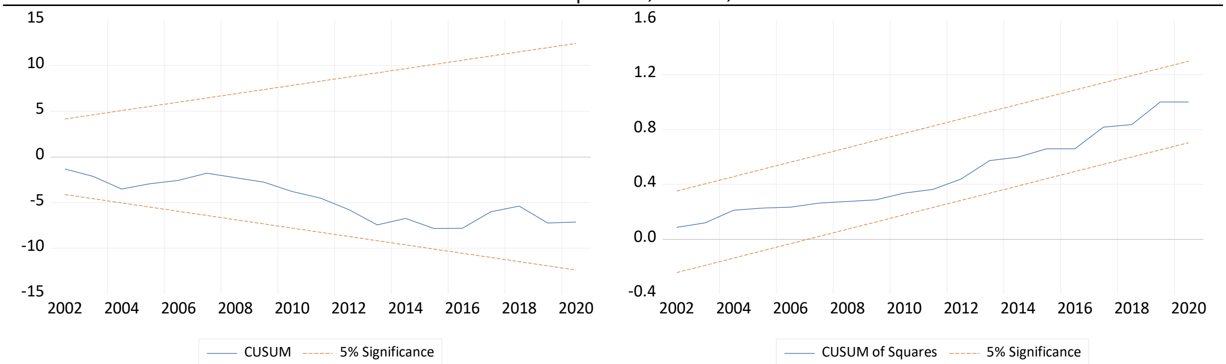


Table 9: Augmented ARDL Long-run Estimation Results

Variables	Model 1		Model 2		Model 3	
	Coefficient	Prob	Coefficient	Prob	Coefficient	Prob
$lnGDP$	-6.335	0.003	3.129	0.574	1.418	0.597
$lnGDP^2$	0.335	0.003	-0.124	0.680	-0.082	0.567
$lnREC$	-0.363	0.000	-0.524	0.013	---	---
$lnNREC$	0.978	0.000	---	---	0.958	0.000
Dummy2001	-0.029	0.016	-0.041	0.073	0.010	0.600

According to Table 9, the long-run parameter estimation findings for Model 1 indicate that $lnGDP$ negatively affects carbon emissions, while the $lnGDP^2$ positively affects carbon emissions. This finding suggests a U-shaped relationship between economic growth and carbon emissions, indicating that the EKC hypothesis is not valid in Türkiye. This result is consistent with the findings of Koçak (2014), Güzel (2021), and Ceylan and Karaağaç (2020), but it does not align with the findings of Lebe (2016), Özbek and Oğul (2022), Bölük and Mert (2015), Pata and Yurtkuran (2018), and Çetin and Saygın (2019). Additionally, a 1% change in non-renewable energy consumption leads to a 0.97% increase in carbon emissions, while a 1% change in renewable energy consumption leads to a 0.36% reduction in carbon emissions. This finding suggests that the consumption of non-renewable energy contributes to an increase in emissions, while the utilization of renewable energy plays a significant role in their reduction. These results are consistent with the findings of Ertugrul et al. (2016), Katircioglu and Taspinar (2017), Çetin and Yüksel (2018), and Dallı and Kütükçü (2023). Furthermore, the 2001 structural break period included in the model is statistically significant and negative, indicating a reduction in carbon emissions during the 2001 crisis period in Türkiye. For Model 2, the long-run estimation results show that the coefficients of $lnGDP$ and $lnGDP^2$ are statistically insignificant. Similarly, it is found that renewable energy consumption has a statistically significant and negative effect on CO_2 emissions. These findings align with the studies of Çetin and Saygın (2019), Ceylan and Karaağaç (2020), and Pata and Yurtkuran (2018). The break date was also found to be negative and significant. Lastly, similar findings to Model 2 were obtained for Model 3. In this alternative model, it was concluded that $lnGDP$ and $lnGDP^2$ have no statistically significant effect on emissions. However, non-renewable energy consumption has a statistically significant and positive effect on carbon emissions. A 1% change in non-renewable energy consumption increases CO_2 emissions by 0.96%. This result is consistent with the findings of Ozdemir and Koç (2020), but it does not align with the findings of Okumuş (2020) and Qoyash and Eren (2022). Unlike the other models, the break date added to Model 3 was found to be insignificant and positive.

The differences observed between the empirical findings of this study and prior research concerning Türkiye might be attributed to the various methodologies employed in time series or panel data analyses, as well as the specific periods chosen for study. Notably, some studies have implemented methods that account for structural breaks, whereas others have not incorporated these approaches. This divergence in methodology may clarify the conflicting results presented in the existing literature.

5. CONCLUSION

This study examines the effect of renewable and non-renewable energy consumption on carbon emissions in Türkiye, framed within the context of the (EKC) hypothesis. Initially, we employed the ADF and ZA unit root tests to assess the stationarity of the variables. The results indicated that all variables, except for renewable energy consumption, are stationary at their first difference. To explore the long-term cointegration relationship among the variables, we applied the A-ARDL approach and confirmed the presence of a long-run cointegration relationship between them. According to the A-ARDL long-run estimation results, the $lnGDP$ variable negatively affects carbon emissions, while the $lnGDP^2$ variable has a positive effect. This finding suggests a U-shaped relationship between economic growth and carbon emissions in Türkiye. It means that the EKC hypothesis is not valid. Additionally, the analysis reveals that renewable energy consumption negatively impacts carbon emissions in Türkiye, while non-renewable energy consumption contributes positively to these emissions. The findings of this study provide several policy recommendations aimed at improving environmental sustainability and reducing carbon emissions in Türkiye. The research indicates that increased renewable energy consumption significantly reduces carbon emissions. Therefore, it is essential to boost investments in renewable energy sources, focusing on sustainable energy projects such as solar, wind, and hydropower, along with appropriate government support. As non-renewable energy consumption contributes to increased carbon emissions, it is essential to implement policies should be adopted to limit the use of fossil fuels. It includes enacting environmentally friendly regulations such as imposing taxes on coal and natural gas usage and implementing carbon taxes. Additionally, the study reveals that economic growth influences carbon emissions in a U-shaped relationship. Therefore, environmental factors should be taken into consideration while formulating Turkey's economic growth policies. It is crucial to harmonize policies with sustainable development goals. In addition, it is very important to adopt "green growth" strategies and to increase the use of clean technologies and energy efficiency. Furthermore, it is necessary to promote energy efficiency, encourage the use of energy-saving technologies both in the industrial sector and in households, and implement measures to reduce energy waste. Reducing carbon emissions should be addressed as a societal issue, and governments should organize educational campaigns to improve environmental awareness. These campaigns can encourage individuals and companies to shift towards eco-friendly energy consumption. Additionally, Türkiye should consider establishing national or regional carbon markets with carbon trading. Such market mechanisms can help limit emissions in sectors with high carbon outputs. Lastly, to finance renewable energy projects and accelerate the transition to sustainable energy, Türkiye should seek funding and technical support from international organizations and develop policies aligned with international agreements such as the Paris Climate Agreement. These recommendations can contribute to reducing Türkiye's carbon emissions while advancing economic growth on a sustainable path.

Author Contributions: Adil Huseynov; writing—original draft preparation, methodology, software, validation, formal analysis. Seyhat Bayrak Gezdim; writing—review and editing, visualization, supervision, writing—original draft preparation

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflict of interest.

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