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Natural resources, energy transition, and environmental sustainability: Evidence from Türkiye's strategic resource potential

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ABSTRACT

This study pursues two main objectives. The first is to explain the relationships between natural resource rents, energy transformation, economic growth, and environmental degradation in the Turkish economy. The second is to assess the contribution of boron mining, in which Türkiye is a clear world leader, to environmental sustainability. This study utilizes the autoregressive distributed lag (ARDL) bounds test with structural breaks using data from 1970 to 2021. The short-term results demonstrate that an inverted-U relationship exists between economic growth and environmental degradation. Moreover, the findings indicate that natural resource rents exert a positive effect on environmental degradation, whereas renewable energy consumption contributes to its mitigation. Conversely, fossil fuel consumption is associated with heightened environmental deterioration. Similar findings are obtained in the long term, confirming the validity of the Inverse Load Capacity Curve hypothesis. This result also confirms the environmental dimension of the natural resource curse hypothesis. The dynamic ordinary least square (DOLS) estimator was employed to verify the robustness of the long-run results. Finally, the study utilized Toda-Yamamoto causality analysis. These results emphasize Türkiye's need to channel its resource revenues toward renewable and low-carbon energy investments rather than consumption-driven growth. It is crucial to develop green innovation and integrate sustainability goals into energy planning. In this context, boron, one of Türkiye's most strategic natural resources, is considered to significantly contribute to sustainable energy technologies and the country's transition to a low-carbon, resource-efficient, and environmentally friendly economy.

1. Introduction

Environmental degradation (ED) is one of the most significant global issues of our time. Due to ED, 40% of the world's population is negatively affected by land degradation, 100-300 million people are exposed to the risk of floods and hurricanes, and $577 billion worth of annual production is at risk [1]. Human activities, which are the primary cause of ED, are leading to a rapid increase in greenhouse gases (GHGs). For this reason, approximately 3.6 billion people are currently vulnerable to climate change [2]. In 2020, the per capita ecological footprint (EF) was measured at 2.58 GHa. This value indicates that humanity is currently consuming resources as if there were 1.66 Earths. If no action is taken, the per capita EF is expected to rise to 2.77 GHa by 2030 [3]. Therefore, increased production is needed to meet humanity's growing demands. More steel is needed for additional buildings, more aluminum is needed for the growing demand for automobiles, and more rare elements are needed for the use of electrical household appliances. Similarly, more water, land, and energy are required to produce more food and clothing. The fact that a large portion of energy globally still comes from non-renewable sources indicates that increases in energy use are contributing to environmental pollution [4]. Natural resources and energy are indispensable for humanity and economic growth (EG). At this point, the composition of countries' natural resource reserves and energy mix influences the direction of environmental impacts.

Natural resources are of significant importance to national economies in terms of both production and growth. The productive and efficient use of natural resources is crucial. In this context, these resources contribute to value creation in the production process. Boron ore ranks first among Türkiye's natural resource reserves [5]. Boron is an element that exists in the form of borate in oceans, rocks, coal, and some soils. Borate concentrations are approximately 20 ng/m^3 in air, 30 mg/kg in soil, and 0.1-0.5 mg/L in freshwater [6]. Boron can be found in nature as ulexite, kernite, probertite, colemanite, pandermite, and borax. Borax, which is used in the production of boric acid, is largely colorless and transparent in structure. Kernite, which occurs as needle-shaped crystals, has a structure that is slightly soluble in cold water. Ulexite, which

can be fibrous or columnar, is white and can be shiny. Pandermite, another type of boron mineral, is found mainly around hot springs. Probertite, on the other hand, has a more dirty white appearance. Colemanite, which reacts rapidly with hydrochloric acid, is the most common boron mineral [7].

Türkiye possesses 73% of the world's boron reserves. Following Türkiye, the countries with the highest boron reserves is Russia with 7.7%, followed by the United States with 6.6%. Eti Maden, which manages boron reserves in Türkiye, is the global market leader with a 61% market share. Boron ore is a raw material used in global markets for borosilicate glass in medical device production, as well as for glass fiber in the production of automobiles and aircraft. In 2024, 50% of global boron consumption occured in the glass industry, 18% in the agricultural sector, and 12% in the ceramics industry. Global boron production capacity in 2024 is 5.7 million tons per year [8]. The fact that the world's largest boron reserves are located in Türkiye represents a significant opportunity for the country's EG.

On the other hand, the environmental impacts of economic activities are complex and controversial. Grossman and Krueger (1991) stated that the linkage between economic activities and the environment consists of three stages within the Environmental Kuznets Curve (EKC): scale effect, composition effect, and technical effect. According to the scale effect, production based on dirty production technologies increases environmental pollution in low-income economies [9]. The composition effect mainly covers middle-income countries. According to the composition effect, the share of pollution-intensive products in the total production composition may vary depending on countries' environmental policies. Developed countries with strict environmental policies are transferring their pollution-intensive production to countries with flexible environmental policies [10]. According to the technical effect, when income levels exceed a certain threshold, technological progress facilitates the transition to clean production technologies, thereby reducing ED [11]. The EKC hypothesis is a more successful model for modeling the EG-environment nexus [12]. In the EKC hypothesis, economic activities are linked to CO_2 emissions. However, CO_2 explains environmental problems to a more limited extent compared to the Inverted Load Capacity Factor (ILCF) [13]. Therefore, this study tests the Inverted Load Capacity Curve (ILCC) hypothesis, which is a broader version of the EKC hypothesis. Recently, studies on this subject have begun to increase.

In addition to studies in which environmental quality is measured by LCF and biocapacity, there are studies in which environmental pollution is measured by CO_2 emissions, EF and ILCF. Al-Mulali et al. [14] examined the effects on CO_2 emissions, an indicator of environmental pollution, of the association between gross domestic product (GDP), renewable energy (REN), trade openness (TO), financial development,

and urbanization in 23 selected EU countries for the period 1990-2013. The study examined the association between environmental pollution and the variables GDP, REN, TO, financial development, and urbanization using Pedroni cointegration, the Fully Modified Ordinary Least Squares (FMOLS) estimator, and the Vector Error Correction Model (VECM) Granger causality test. The study findings suggest that GDP increases pollution. Langnel and Amegavi [15] examined the association between the EF and GDP, globalization, economic globalization, social globalization, political globalization, electricity consumption, and urbanization in Ghana between 1971 and 2016. Using the Autoregressive Distributed Lag (ARDL) test and the Granger causality test, the study revealed that globalization, GDP, urbanization, and electricity consumption positively affected the EF.

Shang et al. [16], in their study estimating the impact of EG on Load Capacity Factor (LCF) for the period 1980-2018 in Association of South East Asian Nations (ASEAN) countries, concluded that renewable energy consumption and health expenditures play an important role in improving LCF, but EG has a negative effect. Ridwan et al. [17], in one of the studies in the literature using the LCF variable as an indicator of environmental quality, examined the association between LCF and GDP, TO, financial development, industrialization, and stock market capitalization for the US for the period 1990-2022. They found that the Load Capacity Curve (LCC) hypothesis, which posits a U-shaped association between income and ED, is valid, and that income negatively affects environmental quality in both the short and long term. Durmus et al. [18] examined the association between LCF and EG variables in newly industrialized countries during the 1991-2021 period. The study, which also addressed financial development, urbanization, REN, and labor force variables, concluded that EG positively affected LCF. Dam and Sarkodie [19] examined the association between ILCF and GDP, GDP2, REN, and TO for the period 1965-2018, specifically for Türkiye. The study utilized the ARDL bounds test and the Toda-Yamamoto (TY) causality test, as well as the FMOLS and DOLS long-term coefficient estimators. They concluded that GDP has a positive short-term and long-term effect on ILCF, REN has a positive short-term effect, and TO has a positive short-term and negative long-term effect. Furthermore, they found that the ILCC hypothesis, which establishes an inverted U-shaped association between GDP and ILCF, is valid.

In this context, we focus on the environmental impacts of natural resources using the ILCC hypothesis. The environmental impacts of boron mining, like other natural resources, can be positive or negative.

Boron can be an effective tool in improving environmental health. Boron carbon nitrides (BCN) can contribute to environmental protection in terms of carbon removal technologies by being used as metal-free catalysts in different reactions for gas adsorption

and both CO_2 utilization and renewable fuel synthesis [21]. Additionally, boron ore can contribute to improving environmental health by capturing numerous different greenhouse gases [20]. On the other hand, wastewater discharged from boron elements and boron processing plants can increase water and soil pollution [22]. Therefore, boron, which is abundant in Türkiye, has significant environmental impacts as a natural resource.

The aim of this study is to explore the impact of natural resources and the transition to REN on ED in Türkiye and to draw conclusions about the potential environmental impacts of boron mining, Türkiye's largest reserve resource. This research contributes to the existing literature from different perspectives. First, this study focuses on the ILCF, which is a more comprehensive indicator than other ED indicators since it considers environmental pollution from both the supply and demand sides [43]. Second, this study provides a comprehensive perspective on ED by jointly exploring the effects of energy conversion and natural resource depletion, which are often overlooked in the literature. Finally, this study investigates the environmental impacts of natural resource-based EG in Türkiye, a country rich in boron deposits, within the framework of the ILCC, addressing the environmental resource curse.

The second section of this study, following this introduction, presents previous work on the subject. The third part contains the materials and methods. This section covers data, model specification, and methodology. The fourth part contains the results of the empirical analysis. The fifth part includes a discussion. Based on the empirical findings, this section offers policy recommendations for natural resources and energy transition, with particular emphasis on boron policies. The sixth and final part presents the conclusions.

2. Literature Review

The abundance of natural resources and their linkage with the environment are associated in the literature with the resource curse hypothesis. The fact that resource-rich countries obtain resource rents and thus consume more natural resources, thereby increasing ED, is defined in the literature as the environmental resource curse [23]. Recently, studies on this subject have begun to increase.

Yang et al. [24] examined the association between NRR, globalization, GDP, energy consumption, capital formation, population, and EF in 27 Organisation for Economic Co-operation and Development (OECD) countries between 1970 and 2017. They concluded that natural resource rents (NRR) and GDP increase the EF, while human capital decreases it. In their study, Kızılgöl and Öndes [25] examined the association between NRR, GDP, TO, REN, urbanization, foreign direct investment, and EF for 31 OECD countries during the period 1995-2017. Utilizing the panel cointegration test, the Westerlund Error Correction Model (ECM) (2007) cointegration test, the Dumitrescu-Hurlin panel causality test, and the FMOLS method, the study found that urbanization and GDP increased the EF, while other variables decreased it. Khan et al. [26] examined the association between NRR, GDP, energy conversion, renewable energy, non-renewable energy, urbanization, and the EF of OECD countries. Empirical analysis of the study using cointegration, Feasible Generalized Least Squares (FGLS), and Granger causality tests, found that NRR and REN negatively affect the EF, while non-renewable energy consumption and urbanization positively affect it. Adebayo et al. [27] investigated the effects of NRR, GDP, TO, energy security and financial development on LCF in the US for the period 1980-2021 using a kernel-based optimization approach. The study revealed that GDP, TO, and NRR negatively affect the LCF, while energy security and financial development positively affect the LCF.

For Türkiye, which possesses a large portion of the world's boron reserves, high reserves represent an opportunity for EG, but they can also pose a threat in terms of the environmental resource curse.

Another significant risk for Türkiye, with its abundant boron reserves, relates to the transition to REN. Natural resource rents can contribute to the financing of REN investments, thereby reducing energy consumption [28]. On the contrary, providing the majority of the rent from natural resources through low-cost fossil fuel-based energy could hinder the transition to high-cost REN resources, thus leading to an environmental resource curse [29]. The fact that boron refining is one of the most energy-intensive processes indicates that processing boron ore using fossil fuel-based energy sources can have significant environmental impacts [30]. The use of fossil fuel-based energy in the extraction and processing of boron ores in Türkiye could exacerbate the environmental resource curse or, conversely, provide the necessary financing for the transition to REN resources. Numerous previous studies [31-34] suggest that the use of REN in Türkiye has significant potential to reduce ED. Therefore, Türkiye can achieve sustainable growth by taking advantage of the economic opportunities offered by boron mining while simultaneously protect environmental health by increasing the use of REN resources. Recently, studies on this subject have begun to increase.

In studies conducted by Saleem et al. [35], Khalid et al. [36], Mujtaba et al. [37] and Fan et al., [38] the environmental impact of non-renewable and renewable energy consumption was examined for 10 Asian countries, the South Asian Association for Regional Cooperation (SAARC) countries, 7 OECD countries, and Brazil, Russia, India, China, South Africa and Türkiye (BRICS-T), respectively. These studies concluded that increasing non-renewable

energy consumption reduces environmental quality, while renewable energy consumption increases environmental quality.

Chien et al. [39] examined the association between greenhouse gas emissions and GDP, REN, and urbanization in China, Japan, South Korea, Russia, Indonesia, Malaysia, the Philippines, Singapore, Thailand, and Vietnam for the period 1995-2018. Using the Cross-Sectionally Augmented ARDL (CS-ARDL) test, as well as the Common Correlated Effects Mean Group (CCEMG) and Augmented Mean Group (AMG) methods, the study found that urbanization and GDP increased emissions, while REN decreased them.

Akhayere et al. [40] examined the factors affecting the LCF variable using quantile regression analysis for the Turkish economy during the 1965-2018 period. The independent variables were GDP, TO, energy consumption, and financial development. The study found that energy consumption negatively affects environmental quality. Alola et al. [41] examined the association between the LCF variable and GDP, GDP2, TO, REN, energy consumption, and financial development in the Indian economy for the period 1965-2018. The findings indicate that an increase in GDP exerts positive pressure on the LCF over different time horizons. Furthermore, the LCC hypothesis is found to be invalid in India across different time horizons. The effect of REN and non-renewable energy efficiency on the LCF is found to be positive from short-to long-term timescales. Samour et al. [42] used Driscoll-Kraay and Moment Quantile Regression methods for European economies between 2004 and 2018 to examine the association between GDP, REN, financial participation, and technological innovation on the LCF. The findings indicate that REN and financial participation have a positive effect on the LCF, while GDP and technological innovation have a negative effect on the LCF.

3. Materials and Methods

This section first introduces the variables included in the analysis, the analyzed period, data sources, and the empirical model. Subsequently, it presents the empirical methodology.

3.1. Data and Model Construction

In the study, empirical analyses are made for Türkiye for the period 1970-2021. The variables and data sources used in the empirical analysis are presented in Table 1. The empirical model is established using the variables given in Table 1. The model established with the variables ILCF, GDP, GDP2, NRR, REN, and NREN for Türkiye for the period 1970-2021 is shown in Equation 1.

$$\ln(ILCF)_t = \alpha_0 + \alpha_1 \ln(GDP)_t + \alpha_2 \ln(GDP2)_t + \alpha_3 \ln(NRR)_t + \alpha_4 \ln(REN)_t + \alpha_5 \ln(NREN)_t + \varepsilon_t \quad (1)$$

Table 1. Data descriptions.

Symbol	Definition	Source
ILCF	EF/ Biocapacity (gha per person)	[3]
GDP	GDP per capita (constant 2015 US$)	[44]
GDP2	(GDP)^2	
NRR	Total natural resources rents (% of GDP)	
REN	Low-carbon electricity generation per capita (kWh)	[45]
NREN	Fossil fuels share of primary energy (%)	

In Equation 1, ILCF represents the inverse load capacity factor, GDP represents economic growth, GDP2 represents the square of economic growth, NRR represents natural resource rents, REN represents renewable energy use, and NREN represents non-renewable energy use. The natural logarithm of the variables used in the study was taken. This transformation was applied to address scale differences and to interpret the coefficients as elasticities of the coefficients [46, 47]. ε_t in Equation 1 represents the error term of the model.

Basic statistics of the variables included in the empirical model are shown in Table 2. Table 2 provides the mean, median, maximum, and minimum values for the variables included in the empirical model, as well as information regarding their distribution. Skewness and Kurtosis values were used to obtain the normal distribution. In this context, the Skewness values for the variables ILCF, GDP, GDP2, NRR, REN, and NREN are symmetric, partially right-skewed, partially right-skewed, partially left-skewed, partially left-skewed, and symmetric, respectively. Similarly, the Kurtosis interpretations are flat, near normal, near normal, partially flat, normal, and normal. These characteristics indicate a normal distribution. Furthermore, the Jarque-Bera test results also confirm the normal distribution. The study, conducted with 52 years of data from Türkiye, includes 52 observations.

3.2. Methodology

This study investigates the association between environmental sustainability and natural resources, renewable energy, fossil fuels, and economic growth. In this context, the relationships between variables included in the empirical model are examined in depth. In the empirical methodology, the unit root test for the variables is first performed. To determine this, ADF unit root test proposed by Fuller and Dickey [48] and the PP unit root test proposed by Phillips and Perron [49] are applied. The null hypothesis of both tests is the presence of a unit root. While the alternative hypothesis indicates the existence of stationarity. The ADF test, which is an improvement on the DF test proposed by Dickey and Fuller [50], assumes that the error term is not autocorrelated. The ADF unit root test incorporates the lagged values of the dependent variable into the model. This suggests that the autocorrelation problem will be overcome.

Table 2. Descriptive statistics.

Statistics	ILCF	GDP	GDP2	NRR	REN	NREN
Mean	4.934370	8.701643	75.88555	3.965093	6.035984	4.487940
Median	4.987262	8.650993	74.84031	4.051938	6.232640	4.489681
Maximum	5.433470	9.506729	90.37790	4.941703	7.339684	4.566159
Minimum	4.379492	8.063381	65.01811	2.666683	4.265549	4.402025
Standard Deviation	0.328727	0.412587	7.242607	0.571885	0.770342	0.035934
Skewness	-0.042771	0.359444	0.417791	-0.245689	-0.606337	-0.032455
Kurtosis	1.677874	1.966007	2.006777	2.224256	2.888477	2.961443
Jargue-Bera	3.803222	3.436208	3.650157	1.827001	3.213201	0.012350
Probability	0.149328	0.179406	0.161205	0.401118	0.200568	0.993844
Sum	256.5872	452.4855	3946.049	206.1849	313.8711	233.3729
Sum of Squared Deviations	5.511128	8.681627	2675.223	16.67968	30.26474	0.065853
Observations	52	52	52	52	52	52

Compared to the ADF test, the PP unit root test is able to apply the unit root test validly in time series containing serial correlation and heteroskedasticity. In this respect, the PP unit root test is more robust than the ADF unit root test [49]. The ADF and PP tests do not include structural breaks in the model. Therefore, considering the 1970-2021 sample period in this study, it is expected that structural breaks have occurred in Türkiye. Consequently, excluding structural breaks from the model in the presence of time series makes it difficult to reject the null hypothesis of a unit root [51]. From a theoretical perspective, to identify structural breaks that may occur in the Turkish economy, break dates were determined using the Bai and Peron [52] method. The break date is determined by the statistical significance of the F statistic obtained from the Bai and Perron [52] test, which rejects the null hypothesis of no structural break. This test can detect structural breaks up to five breaks. Accurately identifying the unit root process and determining the degree of stationarity of variables are important for measuring long-term relationships. In this context, the empirical analysis continues with the unit root test with structural breaks, as proposed by Bai and Perron [52]. Accordingly, the single-break ADF unit root test can be preferred [53], which can yield more effective results in this context [54].

The ARDL bounds test, proposed by Pesaran et al. [55], is used to determine the long-term association between variables. The ARDL bounds test can be applied with a limited sample size. Furthermore, this test does not require the same degree of integration as in conventional cointegration tests. The ARDL approach proposed by Pesaran et al. [55] can be used to estimate both short-term and long-term relationships. In this test, the dependent variable must be stationary in the first difference, while the explanatory variables can be stationary at either the level or first difference. The ARDL bounds test differs from other cointegration tests by providing reliable and unbiased results in small samples. One of the most important advantages of the ARDL bounds test is that it allows variables with different degrees of integration to be included in the model [56, 57]. The ARDL bounds test is preferred in this study due to the limited sample period, the ability to obtain short- and long-term results, and the large number of explanatory variables included in the model. The ARDL bounds test is defined in Equation 2.

$$\Delta ILCF_t = a_0 + \sum_{j=1}^{p-1} a_{1j} \Delta ILCF_{t-j} + \sum_{j=0}^{p-1} a_{2j} \Delta GDP_{t-j} + \sum_{j=0}^{p-1} a_{3j} \Delta GDP2_{t-j} +$$
$$\sum_{j=0}^{p-1} a_{4j} \Delta NRR_{t-j} + \sum_{j=0}^{p-1} a_{5j} \Delta REN_{t-j} + \sum_{j=0}^{p-1} a_{6j} \Delta NREN_{t-j} + a_7 ILCF_{t-1} +$$
$$a_8 GDP_{t-1} + a_9 GDP2_{t-1} + a_{10} NRR_{t-1} + a_{11} REN_{t-1} + a_{12} NREN_{t-1} + \varepsilon_t \tag{2}$$

The F-statistics are obtained by imposing restrictions on the coefficients of the lagged values of both the dependent and independent variables. The corresponding hypotheses, derived from Equation 2, are presented in Equation 3.

$$H_0: a_7 = a_8 = a_9 = a_{10} = a_{11} = a_{12} = 0$$
$$H_1: a_6 \neq a_7 \neq a_8 \neq a_9 \neq a_{10} \neq 0 \tag{3}$$

The null hypothesis in Equation 3 states that there is no cointegration, while the alternative hypothesis states that there is. If the F-statistics calculated in the ARDL bounds test approach are greater than the upper critical value in Pesaran et al. [55], it indicates the existence of a cointegration relationship. In the ARDL bounds test, short-term and long-term coefficients can be obtained if the assumptions of normality, no autocorrelation, no heteroscedasticity, and model stability are satisfied. In this study, considering the existence of structural breaks, the ARDL test is performed by incorporating structural breaks into the model through dummy variables. For methodological robustness of the obtained findings, the DOLS method proposed by Tsong et al. [58] is applied. According to the DOLS method of Stock and Watson [59], each variable must be first-degree stationary. The DOLS method is asymptotically efficient and eliminates the

feedback effect in the cointegration equation. The DOLS approach allows explanatory variables that are stationary in their first differences and allows for the inclusion of lags in the estimation process. Finally, the study investigates the short-term causality relationship among the determinants of environmental sustainability. The TY [60] test is based on a lagged VAR model that allows for varying degrees of integration or stationarity of variables. In this approach, the null hypothesis is set as no causality. The Wald test statistic is used to test this hypothesis. If the test statistic exceeds the critical value, the existence of causality is concluded. In this test, in accordance with the previous methodology, the causal relationship is tested by including the structural break date in the model.

4. Findings

This section presents the empirical findings. Table 3 presents the results of the traditional ADF and PP unit root tests. According to the results inTable 3, all variables are stationary at first differences according to both the ADF and PP unit root tests. Consequently, all variables are determined to be I(1).

Table 4 shows the results of the Bai-Perron test to determine the structural break date. The results in Table 4 indicate that one structural break is statistically significant. According to the results, 1995 was identified as the structural break date. This result may indicate that the results of traditional unit root tests may be biased. In other words, performing a unit root test in the presence of a structural break is important for accurately identifying the unit root processes of the variables in the model.

Table 5 presents the findings of the ADF unit root test with one break. Based on the results in Table 5, all variables were determined to be I(1). Break dates vary by variable. However, based on both the Bai-Perron method and the one-break ADF test, the consensus decision was to use 1995 as the structural break year. Furthermore, the fact that the structural break period of the dependent variable in the empirical model occurred in 1995 also influenced this decision.

Table 3. ADF and PP unit root results.

Series	t-Stat	Prob.	Series	t-Stat***	Prob.	Decision
ADF						
ILCF	-0.9425	0.7662	D(ILCF)	-7.1408	0.000	I(1)
GDP	0.7057	0.9912	D(GDP)	-6.6755	0.000	I(1)
GDP2	0.9602	0.9956	D(GDP2)	-6.5730	0.000	I(1)
NRR	-1.9829	0.2932	D(NRR)	-7.3468	0.000	I(1)
REN	-1.4932	0.5291	D(REN)	-8.2288	0.000	I(1)
NREN	-2.4242	0.1403	D(NREN)	-8.5209	0.000	I(1)
PP						
ILCF	-0.8309	0.8016	D(ILCF)	-9.9485	0.000	I(1)
GDP	0.9419	0.9953	D(GDP)	-6.6564	0.000	I(1)
GDP2	1.4557	0.9990	D(GDP2)	-6.5498	0.000	I(1)
NRR	-1.9829	0.2932	D(NRR)	-7.3550	0.000	I(1)
REN	-1.4372	0.5569	D(REN)	-8.7964	0.000	I(1)
NREN	-2.2661	0.1866	D(NREN)	-9.5398	0.000	I(1)

("D" denotes the difference operator. Results significant at the 1% level are marked with ***.)

Table 6 presents the findings of the ARDL bounds test. According to the results in Table 6, the F-statistic was found to be higher than the upper critical value at the 1% significance level according to the ARDL (2,4,4,0,4,3) model. This indicates the existence of a cointegration relationship at the 1% significance level. However, to validate this result and obtain short- and long-term dynamics, assumptions regarding diagnostic tests must be satisfied.

Table 4. Bai-Perron test results.

Break Number	Break Date	F-statistic	Critical Value
1	1995	63.40880***	20.08
2	1995,2001	8.690138	22.11
3	1995,2001,2013	15.53675	23.04
4	1983,1995,2001,2013	19.99459	23.77
5	1983,1995,2000,2007,2015	0.000000	24.43

(Results significant at the 1% level are marked with ***.)

Table 5. ADF unit root test with a single break results.

Series	t-Stat	P-valuea	Break Date	Series	t-Stat	P-valuea	Break Date	Decision
ILCF	-1.946688 (2)	0.9850	1993	**D(ILCF)**	-9.684269*** (0)	0.0000	1995	I(1)
GDP	-1.633722 (0)	0.9948	2002	**D(GDP)**	-7.368645*** (0)	0.0000	2009	I(1)
GDP2	-1.499352 (0)	0.9968	2009	**D(GDP2)**	-7.379497*** (0)	0.0000	2009	I(1)
NRR	-2.876532 (0)	0.7498	1985	**D(NRR)**	-8.048621*** (0)	0.0000	1998	I(1)
REN	-3.290131 (0)	0.5088	1974	**D(REN)**	-9.313641*** (0)	0.0000	1988	I(1)
NREN	-2.490348 (0)	0.9053	1973	**D(NREN)**	-8.913222*** (0)	0.0000	1988	I(1)

(Break Selection: Minimize Dickey-Fuller t-statistic, Schwarz information criterion, maxlag=10). "D" denotes the difference operator. Results significant at the 1% level are marked with ***. a: Vogelsang [61] asymptotic one-sided p-values. Values in parentheses are lag length values.)

Table 6. ARDL bounds test results.

Test statistics	F-stats.	K	Decision
ARDL (2,4,4,0,4,3)	5.734630***	5	Cointegrated
	I(0)		I(1)
10%	2.08		3
5%	2.39		3.38
1%	3.06		4.15

(Results significant at the 1% level are marked with ***.)

Table 7 shows the diagnostic test findings. Based on the findings in Table 7, it was concluded that the error terms of the ARDL (2,4,4,0,4,3) model showed a normal distribution, there were no autocorrelation or heteroskedasticity problems, and the model was stable.

Table 7. The results diagnostic tests of ARDL (2,4,4,0,4,3) model.

Test	Calculated Statistics	Probability
Breusch-Godfrey Autocorrelation	0.085162	0.9583
Breusch-Pagan-Godfrey Test	20.96867	0.5830
Jargue-Bera Test of Normality	5.678686	0.0585
Ramsey RESET Test	1.286215	0.2684
CUSUM[x]	Stable	
CUSUMQ[x]	Stable	

(In the relevant model, the variance-covariance matrix was corrected with the Newey-West approach.)

Cumulative Sum (CUSUM) and Cumulative Sum of Squares (CUSUMQ) graphs for model stability are shown in Figure 1. According to Figure 1, the ARDL model was found to be stable at the 5% significance level.

Table 8 shows temporal dynamics at different time scales of the relevant ARDL model. According to the long-term results in Table 8, the coefficients of GDP and GDP2 are positive and negative, respectively. This result indicates that the ILCC hypothesis is confirmed. Accordingly, an increase in economic growth first increases the ILCF and then decreases it. As a result, an inverted-U relationship is reached between GDP and ILCF. A 1% increase in NRR increases the ILCF by approximately 0.02% at the 5% significance level. A 1% increase in REN decreases the ILCF by approximately 0.76% at the 10% significance level. A 1% increase in NREN increases the ILCF by approximately 2.54% at the 10% significance level. When the short-term results in Table 8 are examined, it is seen that the error correction term CointEq(-1) lies between 0 and -1. Furthermore, the relevant term is statistically significant at the 1% significance level. This coefficient indicates that a shock occurring in the short term will be corrected after approximately three years.
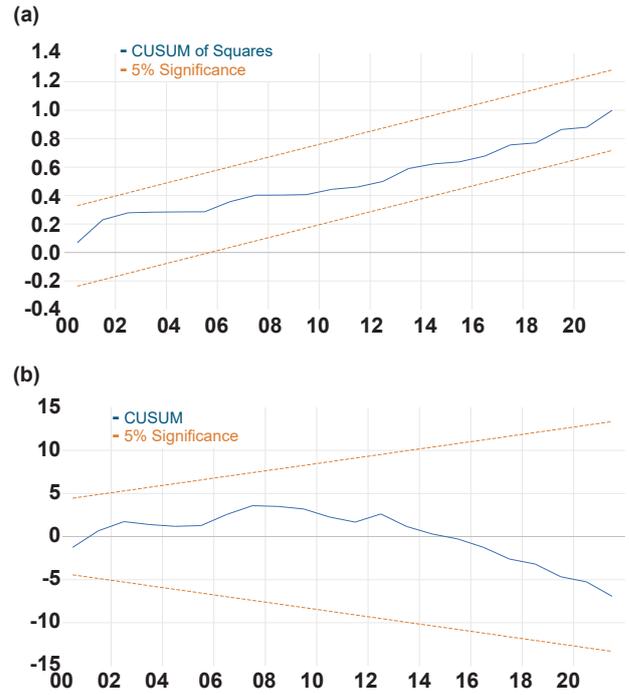
Figure 1. CUSUM (a) and CUSUMQ (b) charts.

An examination of other short-term results reveals that the ILCC hypothesis is valid, similar to the long-term findings. In other words, there is an inverted-U association between GDP and ILCF in the short term. NRR is statistically insignificant. In the short term, a 1% increase in REN decreases ILCF by approximately 0.17% at the 1% level of significance. A 1% increase in NREN increases ILCF by approximately 1.88% at the 1% level of significance. Furthermore, the dummy variable for the structural break date, D1995, is statistically significant.

Table 8. Short-term and long-term coefficients with error correction model.

Var.	Coef.	Std. Err.	t-stat.	Prob.
Long-Run				
GDP	6.971447***	1.669585	4.175556	0.0003
GDP2	-0.352776***	0.089505	-3.941397	0.0006
NRR	0.018701**	0.008949	2.089626	0.0474
REN	-0.756998*	0.438640	-1.725784	0.0984
NREN	2.542510*	1.348057	1.886055	0.0710
Short-Run and Error Correction Model				
D(GDP)	10.43840***	1.958455	5.329914	0.0000
D(GDP2)	-0.561249***	0.111954	-5.013217	0.0000
D(NRR)	0.023245	0.015077	1.541732	0.1388
D(REN)	-0.168090***	0.056053	-2.998744	0.0062
D(NREN)	1.876919***	0.462466	4.058499	0.0005
D1995	0.069331***	0.012940	5.357794	0.0000
CointEq(-1)	-0.371460***	0.088934	-4.176796	0.0005

(The symbols ***, **, and * correspond to the 1%, 5%, and 10% significance levels, respectively.)

Table 9 presents the results of the DOLS method as a robustness test. According to the results in Table 9, the D1995 term, the variable indicating the structural break date, is statistically significant. An examination of the association between GDP and ILCF reveals that the ILCC hypothesis is valid at the 1% significance level. This result is consistent with the ARDL long-term result. Examining other variables, a 1% increase in NRR increases ILCF by approximately 0.03% at the 5% significance level. The effect of REN on ILCF is not statistically significant. Finally, a 1% increase in NREN increases ILCF by approximately 3.15% at the 5% significance level. The results obtained from the DOLS test largely confirm the previous results.

Table 9. Robustness analysis DOLS.

Var.	DOLS			
	Coef.	Std. Err.	t-stat.	Prob.
GDP	7.989804***	1.795063	4.450988	0.0001
GDP2	-0.416461***	0.096478	-4.316650	0.0002
NRR	0.031812**	0.013174	2.414783	0.0231
REN	-0.172870	0.103326	-1.673062	0.1063
NREN	3.154324**	1.410847	2.235767	0.0335
D1995	0.067882***	0.016424	4.133079	0.0003

(The symbols ***, and ** correspond to the 1% and 5% significance levels, respectively.)

According to the Granger representation theorem, there must be at least unidirectional causality in the short term among variables determined to have a long-term equilibrium relationship [62, 63]. Causal relationships between the ILCF and other variables are determined using the TY causality test under structural breaks. First, the diagnostic test findings for the Vector autoregression (VAR) system for the TY causality test are presented in Table 10. According to the results in Table 10, it is observed that the error terms of the estimated VAR system are not first-degree autocorrelated and that the variance of the error terms is not homoskedastic. It is also observed from the table that the estimated VAR systems satisfies the stationarity condition.

Table 10. Diagnostic test results of the TY causality test.

k	dmax	LM	White	Jargue-Bera	AR roots	
					Min	Max
2	1	30.08521 (0.7521)	483.9573 (0.2318)	15.87231 (0.1972)	0.14	0.98

(Probabilities are shown in parentheses.)

Table 11 shows the TY test results. According to the causality test findings in Table 11, causality from GDP, GDP2, and NRR to ILCF was found. On the other hand, causality from ILCF to GDP, GDP2, and NRR was found.

Table 11. TY Causality test results with structural break.

Series	t-Stat	P-valuea	Break Date	Series
GDP → ILCF	2	17.10565***	0.0000	✓
GDP2 → ILCF	2	15.67940***	0.0000	✓
NRR → ILCF	2	6.463996**	0.0110	✓
REN → ILCF	2	1.173263	0.2787	✗
NREN → ILCF	2	1.059628	0.3033	✗
ILCF → GDP	2	3.380170*	0.0660	✓
ILCF → GDP2	2	3.546481	0.0597	✓
ILCF → NRR	2	4.974191**	0.0257	✓
ILCF → REN	2	0.915814	0.3386	✗
ILCF → NREN	2	1.017929	0.3130	✗

(The symbols ***, **, and * correspond to the 1%, 5%, and 10% significance levels, respectively. ✓: There is causality. ✗: There is no causality. The test statistics were obtained using the SUR-Seemingly Unrelated Regression method proposed by Zelner [64]. The structural break date was determined as 1995.)

5. Discussion

This study explores the association between energy transformation, natural resources, economic growth, and the environment over the sample period of 1970-2021. The study emphasizes the importance of natural resources in the Turkish economy and specifically addresses boron. The fact that Türkiye holds a significant portion of the world's boron reserves is a key focus of this study. Sustainability is a frequently discussed multidisciplinary concept, both globally and in Türkiye. Reducing ED is an important component within sustainability discussions. CO_2 emissions have frequently been used as an indicator of ED in the literature. However, the ILCF variable, which has recently become popular as a broader indicator of ED, offers a more comprehensive perspective. This study examines on the association between ILCF and natural resource rents, renewable energy, fossil fuels, and economic growth through empirical analysis. In the empirical analysis, unit root tests with various power characteristics were first utilized. The analysis period, which covers the oil crisis of the 1970s, extends to 2021. Various structural breaks/transformations have occurred in Türkiye during this 50-year period. Indeed, theoretical expectations were supported by empirical tests, and analyses were conducted with 1995 as the break date. In the empirical model established to determine environmental sustainability, the existence of a cointegration association between the variables was investigated using the ARDL bounds test. The ILCF method revealed that the explanatory variables move together in the long run. Short- and long-term dynamics and causal relationships were then investigated. The findings indicated that natural resource rents increase ED, renewable energy reduces ED, and fossil fuel use increases environmental pollution. Furthermore, the ILCC hypothesis was concluded to be valid in the association between economic growth and ED.

These findings are consistent with the literature [19, 65, 66]. These results highlight the importance of energy transformation and natural resource utilization in the Turkish economy. First, due to the validity of the ILCC hypothesis, ensuring the sustainability of economic growth appears crucial. For Türkiye to achieve sustainable economic growth, it is essential to ensure energy supply security and natural resource efficiency. In this context, shifting toward green resources and reducing the proportion of fossil fuels should be identified as urgent areas requiring action. With the slow transition to clean energy sources, the environmental efficiency of economic structures based on fossil fuel revenues will continue to be negatively impacted. Furthermore, the effective and efficient use of natural resources can also play an important role in improving environmental quality. The study's findings highlight the importance of renewable energy, necessitating policy restructuring. Türkiye, particularly where the environmental resource curse prevails, requires urgent institutional measures for sustainability. In this context, boron resources in Türkiye stand out as a significant strategic resource. This is underscored by the fact that boron minerals are a critical input in clean energy technologies. Boron can be used particularly in wind turbines and solar panels. Furthermore, boron, in addition to being a natural resource, has the potential to play a critical role in the green energy transition. Considering that Türkiye holds a significant share of the world's boron reserves, strategic advantages can be achieved. In this context, boron emphasizes the need to reassess natural resources within the framework of energy supply security and environmental sustainability.

6. Conclusion

This study focuses on environmental sustainability in the Turkish economy. In this context, the association between Türkiye's energy structure, natural resources, economic structure, and environmental pollution was examined in depth. Robustness tests and empirical analyses were conducted in the study. The study findings suggest an inverted-U association between economic growth and environmental degradation. Accordingly, environmental pollution increases in the initial stages of economic growth, but declines after a certain turning point. On the other hand, it is concluded that natural resource rents increase environmental pollution. Energy derived from renewable sources reduces environmental pollution, while fossil fuel energy increases it. This study emphasizes the importance of natural resource use in achieving Türkiye's environmental sustainability goals. Furthermore, renewable energy use plays a significant role in improving environmental quality. Fossil fuel use is one of the biggest obstacles to environmental sustainability. In this context, boron, one of Türkiye's most strategic natural resources, is expected to contribute to the sustainability of energy technologies. Furthermore, the widespread use of boron is expected to transform Türkiye into an environmentally sound system that enhances environmental quality and efficiency. The most significant limitation of this study is the absence of a direct variable representing boron. Therefore, the study was conducted using indirect representation. If this data constraint is overcome, a study directly representing boron could be conducted in the future. Furthermore, it is considered that future studies could explore the relationship between environmental quality and boron by using the load capacity factor as an environmental variable. It is also anticipated that panel data techniques could be utilized to more effectively overcome the data constraint with these variables. This would allow for the expansion of the relevant literature.

7. Author Contribution Statement

Sefa Özbek: Conceptualization, data analysis, data curation, methodology, original draft writing.

Serkan Şahin: Conceptualization, visualization, original draft writing, review writing and editing, supervision, validation.

Bahar Özbek: Conceptualization, visualization, original draft writing, review writing and editing, supervision, validation.

8. Conflict of Interest

Authors have no conflict of interest.

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