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Araştırma Makalesi / Research Article

The Energy Trilemma as a Driver of Economic Growth: Empirical Findings from Türkiye

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Abstract

The energy trilemma requires a balance between three key dimensions - energy security, energy access and environmental sustainability - to support a sustainable energy system. These three dimensions have a central role in shaping global energy policies. Therefore, this study investigates the impacts of the energy trilemma on economic growth in Turkiye. Using annual data for the period 2000-2022, ARDL method was preferred in this study. The results show that the Energy Trilemma Index has a positive and strong impact on the Gross Domestic Product in the short-run with a coefficient of 0.243, and in the long-run, this impact is even stronger with a coefficient of 0.346. Moreover, the other explanatory variables, i.e., Foreign Direct Investment, Transition to Sustainable Energy, Financial Development, and Gross Fixed Capital Formation, also positively impact economic growth in both the short - and long-run. Therefore, energy policies harmonize economic growth, energy security, environmental sustainability, and social welfare are recommended for economic stability in Turkiye.

Keywords: *Energy Trilemma, Economic Growth, Energy Security, Environmental Sustainability, ARDL.*

Ekonomik Büyümenin İtici Gücü Olarak Enerji Trilemması: Türkiye'den Ampirik Bulgular

Öz

Enerji trilemması, sürdürülebilir enerji sistemini desteklemek için enerji güvenliği, enerjiye erişim ve çevresel sürdürülebilirlik olmak üzere üç temel boyut arasında bir denge kurulmasını gerektirir. Bu üç boyut, küresel enerji politikalarının şekillendirilmesinde merkezi bir role sahiptir. Bu nedenle, bu çalışmada Türkiye'de enerji trilemmasının ekonomik büyüme üzerindeki etkileri araştırılmıştır. 2000-2022 dönemi yıllık verilerinin kullanıldığı bu çalışmada ARDL yöntemi tercih edilmiştir. Çalışmada Enerji Trilemma Endeksi'nin kısa dönemde Gayri Safi Yurtiçi Hasıla üzerinde 0.243'lük bir katsayı ile pozitif ve güçlü bir etkiye sahip olduğu, uzun dönemde ise bu etkinin 0.346'ya yükselerek daha da güçlendiği tespit edildi. Aynı zamanda, diğer açıklayıcı değişkenler olan Yabancı Doğrudan Yatırım, Sürdürülebilir Enerjiye Geçiş, Finansal Gelişmişlik ve Gayrisafi Sabit Sermaye Oluşumu da ekonomik büyümeyi hem kısa hem de uzun dönemde pozitif yönde etkilemektedir. Bu nedenle, Türkiye'de ekonomik istikrar için ekonomik büyüme, enerji güvenliği, çevresel sürdürülebilirlik ve sosyal refahı uyumlaştıran enerji politikaları önerilmektedir.

Anahtar Kelimeler: *Enerji Trilemması, Ekonomik Büyüme, Enerji Güvenliği, Çevresel Sürdürülebilirlik, ARDL.*

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INTRODUCTION

Energy is considered one of the most crucial and indispensable needs throughout human history. The growing global population, urbanization, and technological advancements are continually driving up the energy demand. Consequently, the sustainability, security, and accessibility of energy systems are gaining increasing importance worldwide in the face of rising global populations and economic growth. According to estimates by the International Energy Agency (IEA), global energy demand is expected to double from its current level by 2050 (Khan et al., 2021a). This surge necessitates establishing reliable, equitable, and environmentally sustainable energy systems.

Investments required in energy infrastructure by 2050 are estimated to be around 50 trillion US dollars (Marti & Puertas, 2022). These investments are critical for managing the challenges of energy security, sustainability, and accessibility in a balanced manner. The energy trilemma is a framework used to understand the relationship and interaction between these three challenges. Addressing all three dimensions simultaneously allows for a sustainable and inclusive energy transition. As global energy demand is expected to double, the energy sector is developing new methods to meet this demand through decentralization, decarbonization, and digitalization. These new methods enhance the capacity to balance energy security, energy equity, and environmental sustainability (Khan et al., 2021b; Luciani, 2020).

Energy security refers to a country's capacity to reliably meet current and future energy demands and the resilience of its energy infrastructure. Energy equity (accessibility) encompasses the ability to provide reliable, affordable, and abundant energy. Environmental sustainability in energy systems involves reducing carbon emissions and addressing climate change within its framework (World Energy Council [WEC], 2020). The World Energy Council's (WEC) energy trilemma index measures countries' performance in these three dimensions and the accessibility of their energy policies.

The energy trilemma is tightly integrated with economic growth. When energy security is ensured, industries can operate without interruptions, and economic activities can expand. Energy equity is directly linked to providing access to energy across all economic layers, enabling a broad population to benefit from economic opportunities. Environmental sustainability supports a greener and more sustainable growth path in the long-run by reducing the environmental impacts of economic activities. Conclusively, the energy trilemma plays a central role in addressing our global challenges. Developing all three dimensions of the energy system equitably is a priority for policymakers and planners. The trilemma index is a key indicator in achieving this balance and advancing the global energy sector. This framework must continuously evolve in terms of energy policies and regulations to adapt to increasing changes and manage decarbonization processes effectively. Studies and policies on the energy trilemma are crucial for meeting future energy demands sustainably, reliably, and equitably. Therefore, this study investigates the impacts of the energy trilemma on economic growth in Turkiye.

This study contributes to the literature in at least three ways. First, there is no empirical study analyzing the impact of the energy trilemma on economic growth in Turkiye. This study aims to fill this gap in the literature. Second, it presents a study with methodological depth using various statistical methods such as principal component analysis, unit root tests, ARDL bounds test, and ARDL estimator. Third, the findings obtained through econometric methods are supported with policy recommendations. In this way, the theoretical results of the study are supported from a practical perspective.

The rest of the paper is organized as follows: Section 1 is a literature review, Section 2 discusses the energy trilemma and the situation in Turkiye, Section 3 describes the data and methodology, Section 4 presents the empirical findings and finally Section 5 concludes.

1. LITERATURE REVIEW

The energy trilemma consists of three main dimensions: energy security, energy equity and environmental sustainability. These dimensions have a strong relationship with economic growth. They are also of strategic importance for international policy makers. In the literature, the impacts of different dimensions of the energy trilemma on economic growth have been extensively analyzed. Therefore, in this section, studies investigating the impacts of these three dimensions of the energy trilemma on economic growth will be presented.

Energy security is a critical component for economic development and social welfare. In developing countries, imbalances in energy supply can have negative impacts on economic growth (Nawaz & Alvi, 2018). Similarly, Prado et al. (2016) found a positive relationship between energy security and economic growth in Brazil. Gasparatos and Gadda (2016) examined the impacts of energy imports and tariff barriers on economic sustainability. Le and Nguyen (2019) emphasize the importance of energy security for macroeconomic stability by assessing this link in terms of economic perceptions. These findings suggest that energy security is a supportive factor for economic growth.

Access to energy is a critical issue for both economic and social sustainability. Ullah et al. (2021) examined the energy equity index and found that access to energy supports economic growth. Hu et al. (2019) find a positive relationship between energy efficiency and economic growth in China, while Rajbhandari and Zhang (2018) analyze how energy efficiency policies can support growth in middle-income countries. Ziolo et al. (2020) argue that energy consumption boosts economic growth, but without proper fiscal support, environmental impacts can be negative. Dell'Anna (2021) argued that efficient use of energy should be supported by government policies. These studies show that access to energy has a direct impact on economic growth.

The relationship between environmental sustainability and economic growth is complex. Ekins (2002) discussed the impacts of environmental factors such as natural resource use and deforestation on economic growth. Drews et al. (2018) showed that economic growth can be compatible with environmental sustainability by examining European and US cases. Kurniawan et al. (2021), in a study covering 140 countries, identified factors that distinguish economic growth from environmental degradation. These findings suggest that environmental sustainability does not necessarily conflict with economic growth, but can be harmonized with appropriate policies. Overall, all three dimensions of the energy trilemma are associated with economic growth. While energy security and access to energy stand out as factors that support economic growth, environmental sustainability can also be harmonized with economic growth through appropriate policies. In this respect, it is of great importance that energy policies are designed to support sustainable growth.

The relationship between the energy trilemma and economic growth is complex and multidimensional. In the literature, energy security, energy access, and environmental sustainability dimensions are usually considered separately. However, studies evaluating these dimensions together are quite limited. Therefore, studies that address the energy trilemma with a holistic approach are of great importance.

The impact of energy trilemma on economic growth has been investigated in different countries and periods. Chi et al. (2023) demonstrated the balanced impact of energy use and population growth on economic growth in North African countries. The study emphasizes that energy efficiency and low-carbon energy transition policies play a critical role in the growth process. Meanwhile, Khan et al. (2022a) argue that the energy trilemma promotes economic growth within the framework of sustainable development goals but poses risks to environmental sustainability. These findings suggest that energy policies need to balance growth and environmental impacts.

The environmental impacts of the energy trilemma have also been widely discussed. Liu et al. (2022) examined the energy trilemma and sustainable energy transitions in countries with high CO_2 emissions and discussed the trade-off between economic growth and environmental quality. The results show that energy use and fixed asset investments contribute to economic growth, but negatively affect environmental quality. Khan et al. (2022b) find that clean energy transitions promote economic growth and reduce environmental footprint. Similarly, Kang (2022) analyzed 109 countries and found that the trade-off between energy security, energy access and environmental sustainability varies by region and income level. These findings suggest that energy policies should be designed considering regional and economic conditions.

The impact of energy policies on economic growth has also been analyzed in terms of long and short-run dynamics. Khan et al. (2021c) examined the impact of the World Energy Trilemma Index on economic growth. The study found that energy use and financial development can affect growth in the short - and long-run. The study also suggested taxation and policy adjustments regarding energy security and accessibility. Ang et al. (2015) analyzed how definitions and methodologies of energy security have changed over time and noted that energy policies increasingly take environmental sustainability and energy efficiency into account.

Studies in the Turkiye context have generally focused on the relationship between renewable energy use, energy consumption and economic growth. For instance, Boluk and Mert (2015) showed that renewable energy consumption reduces CO_2 emissions in Turkiye. Similarly, Acaravci and Erdogan (2018) find that renewable energy generation supports environmental sustainability. Studies on the relationship between renewable energy and economic growth reveal a positive long-run relationship between these two variables (Ozturk & Acaravci, 2010). Halicioglu (2009) found that economic growth increases CO_2 emissions and creates environmental costs. Cetin and Sezen (2018) find that renewable energy consumption in Turkiye has a supportive impact on both environmental and economic sustainability.

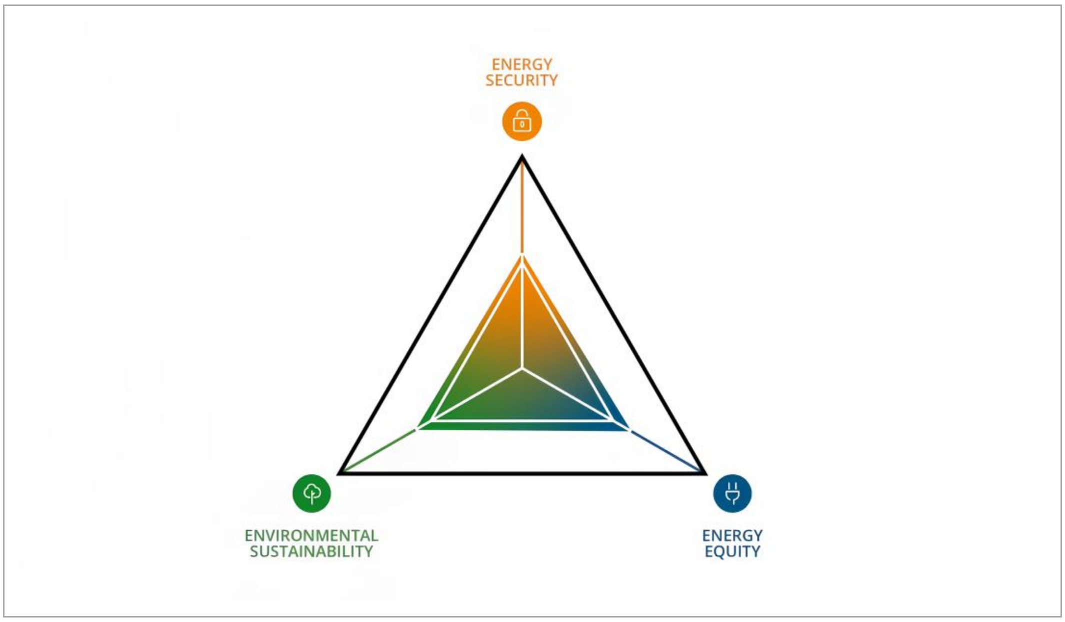
Overall, the literature has widely discussed the relationship of the energy trilemma with economic growth, environmental sustainability, and energy policies. However, studies evaluating all dimensions of the energy trilemma together are limited. Existing evidence points to the need for a balanced energy policy between energy security, accessibility, and environmental sustainability. In particular, it is emphasized that the transition to renewable energy should be designed to support economic growth and promote environmental sustainability.

Studies conducted in Turkiye generally reveal that energy consumption supports economic growth, and using renewable energy can potentially reduce CO_2 emissions. However, no direct study in the literature examines the impacts of the energy trilemma on economic growth in all its dimensions. Therefore, this study aims to fill this gap in the literature by addressing the energy trilemma in a holistic framework in the context of Turkiye. For this purpose, this study empirically examines the relationship between the energy trilemma and economic growth using data from 2000-2022 for Turkiye. In this regard, the role of energy policies in achieving the balance between economic growth and sustainability objectives is emphasized. The study results provide new perspectives on how energy policies can be aligned with economic growth and sustainability goals.

2. ENERGY TRILEMMA AND TURKIYE'S POSITION

The energy trilemma concept necessitates balancing three fundamental dimensions to support a sustainable energy system: energy security, energy equity, and environmental sustainability. These dimensions are pivotal in shaping global energy policies and offer a comprehensive assessment of energy systems. The World Energy Trilemma Index, developed by the World Energy Council (WEC), ranks the performance of energy systems in 127 countries across these dimensions (WEC, 2018).

Figure 1: Dimensions of the Energy Trilemma



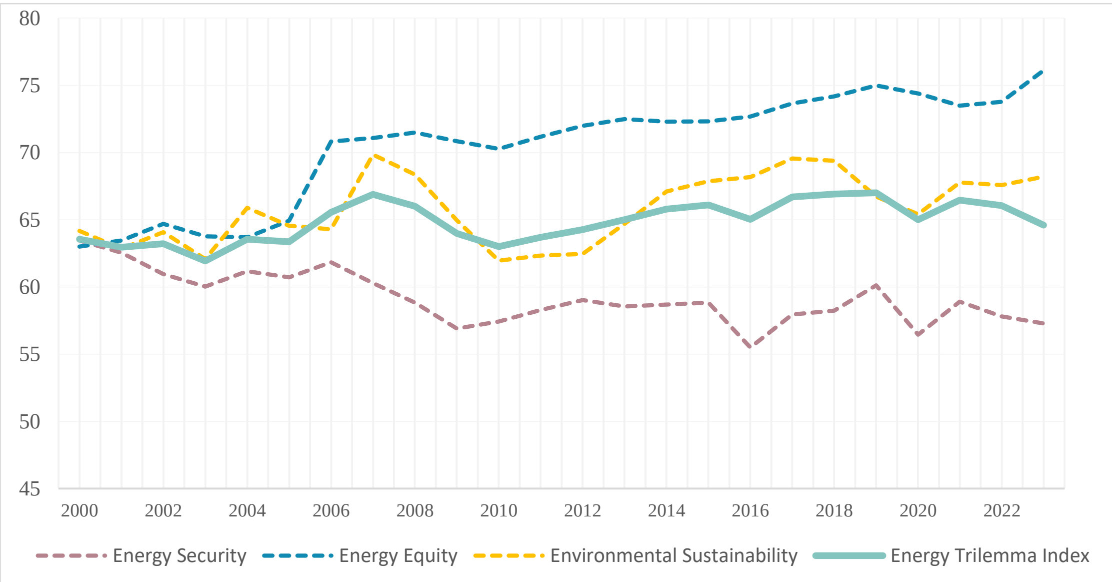
Source: World Energy Council (2023).

As depicted in Figure 1, the dimension of energy security evaluates a country's capacity to meet its growing energy demand and its resilience against supply shocks. This dimension, constituting 30% of the energy trilemma index, considers various sub-indicators including the management effectiveness of internal and external energy resources, and the reliability and resilience of the energy infrastructure. Energy security encompasses the capabilities of countries to maintain consistent access to energy resources and to respond swiftly to potential disruptions in energy supply. This is typically achieved through the diversification of energy sources, investments in renewable energy, and modernization of infrastructure (WEC, 2023).

The energy equity dimension measures the performance of providing reliable and affordable access to energy. This dimension, also accounting for 30% of the energy trilemma index, includes two asynchronous inputs to consider: reliability and affordability. Reliable energy access is a fundamental metric assessed in alignment with the UN Sustainable Development Goal 7 (SDG7). Energy equity further includes the actual affordability of energy, determined by energy prices and widespread socioeconomic improvements. This dimension aims to provide fair and affordable energy to all consumers (WEC, 2023).

The environmental sustainability dimension evaluates a country's performance in mitigating environmental harm and reducing the impacts of climate change on its energy systems. Also weighted at 30% in the energy trilemma index, this dimension assesses the efficiency of energy use, production, transmission, and distribution; pollution in the form of carbon dioxide, methane, and particulate matter; and the performance in decarbonization. This dimension also covers radical emission reductions needed to limit global warming to 1.5°C and evaluates the countries' capacities to meet these targets. The national context is also incorporated into the energy trilemma index, accounting for 10% of the weight, and measures macroeconomic and governance conditions, the stability of the economy and government, and the attractiveness and innovation capacity of the country (WEC, 2023).

Figure 2. Turkiye's Energy Trilemma Index



Source: Constructed with data from World Energy Council (2024).

Figure 2 illustrates the development of Turkiye's Energy Trilemma Index and its sub-dimensions from 2000 to 2023. The energy security index started at 63.5 in 2000 and has generally shown a decline, reaching its lowest level of 56.5 in 2020. This indicates a decrease in Turkiye's capability to provide energy reliably and stably. The environmental sustainability index has generally followed an increasing trend, peaking at 65.9 in 2004, but showed a decline towards 2020, suggesting that the management of environmental impacts from energy sources was not sufficiently effective. On the other hand, the energy equity index started at 63.0 in 2000 and increased to 76.1 by 2023, indicating either a more equitable distribution of energy or an increase in the number of people having access to energy. Overall, the energy trilemma index has fluctuated, maintaining values between 63 and 67, which reflects the overall balance and performance of energy policies. The highest values were recorded in 2007 and 2018, and the lowest in 2023 at 64.6.

In the 2023 World Energy Trilemma Index, Turkiye scored an overall 64.6, placing it 46th among the ranked countries. Within the dimensions of the energy trilemma, it scored 57.3 for energy security, 76.1 for energy equity, and 68.2 for environmental sustainability (WEC, 2024).

3. DATA AND METHODOLOGY

3.1. Model Specification and Data

This study's empirical research investigates the impacts of the energy trilemma on economic growth in Turkiye. The study utilizes annual data for the period from 2000 to 2022. The period of the study was determined based on the availability of data. The research model can be expressed in functional form as shown in Equation (1):

$$GDP_{(M\text{-}D)} = f(ETI, FDI, FD, GFC, TSE) \tag{1}$$

In Equation 1, GDP represents the dependent variable of the research model. In this equation, economic growth is depicted by GDP per capita. Our study utilizes the ratio of private sector loans to GDP, as recorded by the World Bank, to represent financial development, denoted as FD (Khan et al., 2021c). Additionally, we have formulated a variable represented as TSE (Toward Sustainable Energy). The TSE variable was developed using the method proposed by Liu et al. (2022), incorporating the variables of Energy Intensity and Renewable Energy Consumption. Principal Component Analysis (PCA) was used to construct the TSE variable. Other explanatory variables used in the study were compiled from the literature (see Agbanyo et al., 2023; Chi et al., 2023; Liu et al., 2022). The model for the empirical research is presented in Equation 2.

$$\mathrm{GDP}_{(\mathrm{M-D})} = \alpha_0 + \beta_1 ETI_{\mathrm{t}} + \beta_2 FDI_{\mathrm{t}} + \beta_3 FD_{\mathrm{t}} + \beta_4 GFC_{\mathrm{t}} + \beta_5 TSE_{\mathrm{t}} + \mu_{\mathrm{t}} \tag{2}$$

In econometric models, α_0 represents the constant terms of the models and denotes the intercept. β_1, β_2, ..., β_5 are the slope coefficients for each variable written alongside them. μ_t is assumed to be the error term of the models, which has a zero mean and constant variance, and the symbol t under the variables denotes the period. The indicators used in our study and their descriptive statistics are shown in Table 1.

Table 1: Variable Description and Data Sources

Variables	Symbol	Description	Mean	S. D.	Min.	Max	Source
GDP per capita	GDP	Constant 2015 US$	9515	2362	5994	14055	WB
Energy Trilemma Index	ETI	Index (from 0 to 100)	64.87	1.49	61.94	67.00	WEC
Foreign direct investment	FDI	Net inflows (% of GDP)	1.57	0.78	0.36	3.62	WB
Credit to private sector	FD	% of GDP	42.31	19.87	14.01	70.90	WB
Gross fixed capital formation	GFC	Constant 2015 US$	11.23	0.21	10.78	11.46	WB
Toward Sustainable energy	TSE	Index (from 0 to 100)	50.49	22.62	17.91	93.70	AU
Energy intensity	INT	MJ/$2017 PPP GDP	2.86	0.23	2.49	3.27	WB
Renewable energy consumption	REN	% of total energy	28.63	6.38	18.18	44.03	EIA

Note: The abbreviations WB, WEC, EIA, and AU refer to the World Bank - World Development Indicators, the World Energy Council - Energy Trilemma Database, the U.S. Energy Information Administration - Electricity Data Browser, and data calculated by the author, respectively.

3.2. Index Techniques

Principal Component Analysis (PCA) is a well-established technique used in multivariate statistical analyses. PCA not only identifies relationships among variables but also reduces the number of variables, enhancing the quality and comprehensibility of the analysis (Jolliffe, 2002). Initially proposed by Pearson (1901) and later refined by Hotelling (1933), PCA is extensively employed across various disciplines.

The first step in the analysis involves normalizing the data related to the variables. Normalization is the process of converting variations in the range of each attribute into a standard format. This procedure is particularly crucial for preventing distortions in variables with smaller ranges when compared with others. In our study, the Min-Max normalization method is used, which scales the data between 0 and 1, ensuring that each variable contributes equally to the analysis (OECD, 2008).

The implementation of PCA involves reducing the p variables in the dataset to k independent principal components, where k is less than or equal to p ($k \leq p$). During this process, PCA creates new axes by maximizing the variance represented in the dataset. These components are defined as linear combinations of the original variables, and each explains a portion of the total variance in the dataset. The first principal component accounts for the maximum variance, followed by the second principal component, which explains the maximum of the remaining variance, and so on (Jolliffe, 2002).

Determining the principal components involves calculating the eigenvalues and eigenvectors of the covariance matrix of the data matrix. The covariance matrix displays the linear relationships between the variables, where the eigenvalues are the new axes aligned with the direction that maximizes the variance, and the eigenvectors determine the directions of the new principal components. The eigenvalues indicate the significance of these components in the dataset (Jolliffe, 2002). As a result of this process, *p* variables are reduced to *k* statistically significant independent principal components, thereby minimizing information loss while enhancing the interpretability of the analysis results.

3.3. Unit Root Analysis

During the analysis of time series data, stationarity is critically important for making reliable forecasts. Studies like Johansen and Juselius (1990) have indicated that economic time series frequently exhibit non-stationary characteristics. Granger and Newbold (1974) have noted that using non-stationary variables in time series analyses can lead to the problem of spurious regression, which could skew forecasts and render them unreliable and inconsistent. Therefore, as a first step in the analysis process, the stationarity statuses of the series should be checked using unit root tests.

In this study, the ARDL (Autoregressive Distributed Lag) model has been adopted. The ARDL model allows for different levels of integration (stationarity) among the explanatory variables. However, it requires the dependent variable to be stationary at level I(0) and/or any of the explanatory variables to not be stationary at the second difference I(2). For this purpose, the stationarity levels of the series have been determined using the Augmented Dickey-Fuller (ADF) and Phillips-Perron (PP) unit root tests at the initial stage of the analysis process. The fundamental hypothesis of both tests is that the series has a unit root. Thus, when the computed test statistics exceed the critical values, the null hypothesis is rejected.

3.4. ARDL Bounds Test

In the second phase of the analysis, the ARDL bounds test developed by Pesaran, Shin, and Smith (Pesaran et al., 2001) was utilized to determine the presence of a cointegration relationship among the variables. This test provides flexibility in the application even when the series' stationarity statuses may differ, such as I(0) or I(1). Moreover, it features the capacity to incorporate variables with different lag lengths within the model. This method allows for the estimation of both short-run and long-run dynamics through a single equation, enabling reliable predictions even in studies with small sample sizes.

The ARDL bounds test is conducted by estimating the model's error correction term using the Ordinary Least Squares (OLS) method. During the test's application, the regression model is constructed with the dependent variable's first difference, the independent variables' first differences, and their lagged values. The lag lengths are denoted as p and q for the dependent and independent variables, respectively. This setup represents the ARDL (p, q) model structure and allows for the use of various lag values for both dependent and independent variables (Narayan & Smith, 2005).

The fundamental hypothesis of the cointegration test is whether the coefficients of the variables' first lags are zero. Rejection of this hypothesis indicates a long-run relationship among the variables. The hypothesis is tested using an F-test. The F-test statistic is calculated by dividing the difference in the sums of squared residuals of the model's restricted and unrestricted forms by their degrees of freedom. The obtained F-test statistic is evaluated by comparing it with the I(0) and I(1) limits. A statistically significant F-value (usually at the 10% significance level) above the upper I(1) limit indicates the presence of cointegration. However, if the F-value is below the lower I(0) limit, the cointegration hypothesis cannot be rejected. This methodology provides assistance in identifying long-run stable relationships between variables and holds significant importance in economic modeling. The ARDL bounds test is widely used, particularly in macroeconomic time series data analysis (Narayan & Smith, 2005).

3.5. ARDL Coefficient Estimator

The F-test has been used to verify the presence of a long-run cointegration relationship within the model. The ARDL bounds test test results indicate a significant long-run relationship among the examined variables, fulfilling the prerequisite for estimating long-run coefficients. After this step, the estimation of long-run relationships has been performed based on the determined lag lengths within the ARDL model framework. Optimal lag lengths have been selected using the Akaike Information Criterion (AIC) and Schwarz Information Criterion (SIC) as suggested by Pesaran et al. (2001). Additionally, the criterion for the lag length should not exceed two for annual data has been considered. Various diagnostic tests have been conducted to evaluate the model's accuracy, including tests to determine whether the error term is normally distributed, contains autocorrelation, and has constant variance. Moreover, the model's functional form has been verified, and the stability of the estimated parameters has been tested.

4. EMPIRICAL FINDINGS

In the initial phase of analysis, the Augmented Dickey-Fuller (ADF) and Phillips-Perron (PP) unit root tests were applied to the series of variables found in the research models to determine their levels of stationarity. The estimation results for the unit root models, which include both the constant term and the terms for constant and trend, are presented in Table 2.

Table 2: Unit Root Test Results

Variable		ADF unit root test		PP unit root test	
		t-statistic (level)	t-statistic (frst difference)	t-statistic (level)	t-statistic (frst difference)
GDP	Constant	-1.335	-4.546***	-1.843	-4.933***
ETI		-2.736*	-4.682***	-2.736*	-4.681***
FDI		-3.688*	-6.637***	-3.605**	-6.303***
TSE		-1.176	-4.050***	-1.084	-6.862***
FD		-3.910***	-4.554***	-1.237	-5.417***
GFC		-1.073	-4.910***	-1.070	-4.821***
GDP	Constant and Trend	-3.534	-4.629***	-3.204	-4.775***
ETI		-1.596	-5.479***	-2.171	-5.479***
FDI		-3.344*	-6.380***	-3.348*	-6.087***
TSE		-3.691***	-5.355***	-3.219	-7.019***
FD		-1.806	-2.425***	-1.516	-3.587***
GFC		-1.760	-5.441***	-1.760	-5.454***

Note: The superscripts ***, **, and * denote the significance at a 1%, 5%, and 10% level, respectively.

The results in Table 2 reveal that the null hypothesis of the existence of a unit root is rejected for variables such as Energy Transition Index (ETI), Foreign Direct Investment (FDI), and Gross Fixed Capital Formation (GFC) in both the models with and without trend. However, the unit root hypothesis has not been rejected for other variables. Additionally, according to the outcomes of these tests, it has been determined that the first differences of all series are stationary. Moreover, under both tests and models, the GDP (M-D) series is not stationary at level, but becomes stationary upon first differencing - hence, it is integrated of order one, I(1). Consequently, considering that the dependent variable is I(1) and the explanatory variables are either I(1) or I(0), it is concluded that the use of the Autoregressive Distributed Lag (ARDL) bounds testing approach is more appropriate for investigating the cointegration relationship than traditional cointegration tests.

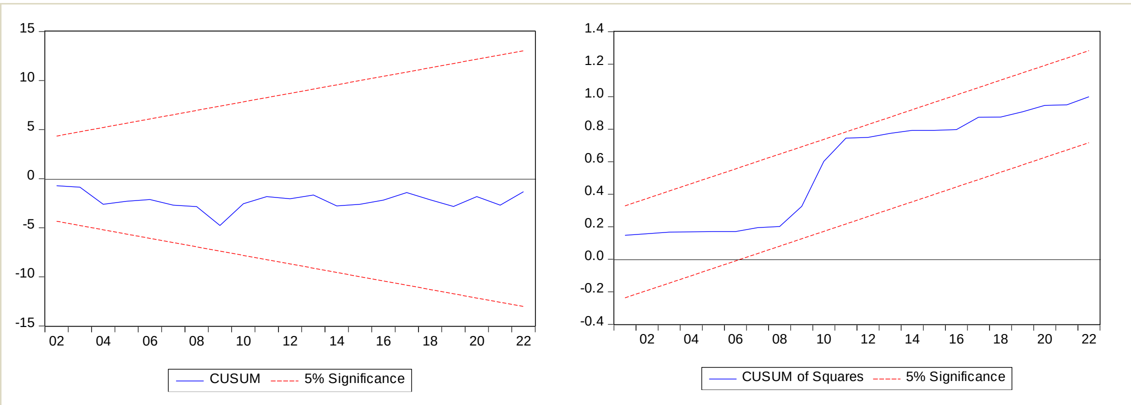
Table 3: The Results of the ARDL Bounds Test

Model	Optimal Lag Length	F-Statistics	Critical Values %5		Critical Values %1	
			I(0)	*I*(I)	*I*(0)	*I*(I)
F(GDP ∣ ETI, FDI, TSE, FD, GFC)	(2,1,2,2,2,1)	11.076***	2.39	3.38	3.06	4.15

Note: The superscripts ***, **, and * denote the significance at a 1%, 5%, and 10% level, respectively.

In the second phase of the analyses, the ARDL bounds test was employed to examine the presence of long-run relationships among the variables. The results of this test are presented in Table 3, which includes the functional structures of the cointegration models, the optimal lag lengths selected based on the Akaike Information Criterion (AIC), the F-statistic values used to evaluate the hypothesis that suggests the absence of cointegration, and the critical values at 5% and 1% significance levels. The F-test values exceeded the critical bounds, indicating that there are statistically significant long-run relationships among the variables. The findings from the ARDL bounds test demonstrated a long-run relationship between the dependent variable and the explanatory variables, leading to the estimation of long-run coefficients in the final stage of the analysis. The results of these long-run estimations can be seen in Table 5.

Figure 2: Plots of CUSUMSQ and CUSUM Statistics



Following the ARDL bounds test, specification tests for the ARDL model were conducted. To detect the presence of autocorrelation, varying variance, specification errors, and issues with normality distribution, several tests were implemented: the Serial Correlation LM Test, Histogram-Normality Test, Heteroskedasticity Test, and the Ramsey RESET Test. Additionally, the CUSUM and CUSUM of Squares Tests were performed to examine structural breaks. The results of these tests indicated no specification errors in the model, and the estimated models' F-statistics and slope coefficients were consistent. The outcomes of these tests are presented in Table 5. Graphs for the CUSUM and CUSUMSQ tests conducted for the research model are shown in Figure 2.

Table 4: Short-run and Long-run Results

Dependent variable: $GDP_{(M-D)}$	Short-run coefficients	Long-run coefficients
Regressors		
ETI	0.243***	0.346***
FDI	0.016*	0.136***
TSE	-0.199	0.515***
FD	0.218***	0.170***
GFC	0.728***	0.540**
ECT(-1)	-0.475***	
C		9.297***
Diagnostic tests		*P value*
χ^2 *(Serial correlation)*		0.23
χ^2 *(Heteroskedasticity)*		0.59
χ^2 *(Normality)*		0.68
χ^2 *(Functional form)*		0.17
CUSUM		Stable
CUSUMSQ		Stable

Note: The superscripts ***, **, and * denote the significance at a 1%, 5%, and 10%, respectively.

Table 4 shows that the research model's error correction coefficient is negative and statistically significant. These findings indicate the presence of a long-run relationship among the variables and suggest that equilibrium will be restored in case of any imbalances. Furthermore, the error correction coefficient specified in the table implies that approximately 48% of the short-run and long-run deviations will be corrected in the following period. Both short-run and long-run coefficients have generally been found to be significant.

The results demonstrate that the Energy Trilemma Index has a positive and strong impact on GDP in the short-run with a coefficient of 0.243, while in the long-run, this impact is strengthened with a coefficient of 0.346. This implies that urgent policy interventions or changes in the energy sector can significantly influence economic growth in the short-run. Particularly in situations like energy crises or policy innovations, the impacts of the Energy Trilemma Index on the economy can manifest swiftly. Moreover, the impact of the Energy Trilemma Index on economic growth is stronger in the long-run. This outcome emphasizes that energy policies should be designed to support long-run economic and environmental sustainability goals. Notably, technological innovations in the energy sector and improvements in energy efficiency are fundamental factors supporting economic growth. These results are consistent with the findings of Ang et al. (2015), Khan et al. (2022b), and Kang (2022).

Foreign Direct Investments (FDIs) have positive impacts on economic growth both in the short - and long-runs. While creating an immediate impact in the short-run with a coefficient of 0.016 is limited, in the long-run, they significantly boost economic growth with a coefficient of 0.136. FDIs facilitate capital flow to local economies, introduce new technologies and business management skills, and contribute to increasing technological capacity. This is strategically important, particularly in terms of high technology transfer and workforce skill development, requiring a competitive business environment and stable political structure. Although the impacts of foreign investments are limited in the short-run, their long-run potential contributions should not be overlooked. It takes time for foreign investments to become fully integrated into the economy, but once this process is complete, their impacts on economic growth become more pronounced and powerful.

Transitioning Toward Sustainable Energy, although not showing a statistically significant relationship in the short-run, exerts a significant positive impact on economic growth in the long-run with a high coefficient of 0.515. The high and positive coefficient of Transitioning Toward Sustainable Energy in the long-run indicates that increasing the use of renewable energy sources and reducing the use of fossil fuels not only supports environmental sustainability but also promotes economic growth. This situation underscores the economic benefits of developing sustainable energy technologies, energy efficiency projects, and environmentally friendly practices. Particularly, reducing energy intensity, i.e., the amount of energy consumed per unit of product, enables industries to produce more with less energy consumption. This not only helps lower energy costs but also minimizes environmental impacts. Additionally, increasing the consumption of renewable energy reduces the carbon footprint and enhances sustainability criteria in energy production. These findings are similar to those of Liu et al. (2022).

Financial Development, with the expansion of financial infrastructure and services, positively influences economic growth with coefficients of 0.218 in the short-run and 0.170 in the long-run. In the short-run, the development of the financial sector and increased availability of credit accelerate the capital flow necessary for economic activities, rapidly reflecting positive impacts on the GDP. The development of the financial sector, especially during times of crisis or economic slowdowns, supports economic recovery. In the long-run, financial deepening and diversified financial services contribute to macroeconomic stability, thereby supporting sustainable economic growth. In this way, financial development enables both individuals and businesses to expand their economic activities, thus promoting overall economic growth.

Gross Fixed Capital Formation, with a relatively high coefficient of 0.728 in the short-run, demonstrates that fixed investments, particularly in infrastructure and industrial machinery and equipment, have a direct and rapid impact on economic growth. These investments increase production capacity, stimulate labor demand and economic production in the short-run, and help revitalize overall economic activity. In the long-run, with a coefficient of 0.540, the continued impact of fixed capital investments and the expansion of economic infrastructures and technological capacity strengthen growth potential. The strong and positive impact of fixed investments is especially critical during periods of economic slowdown or when acceleration of growth processes is needed. This highlights the need for governments and the private sector to prioritize infrastructure projects and capital development.

5. CONCLUSION

The energy trilemma has three main dimensions: energy security, energy equity and environmental sustainability. These dimensions are directly related to economic growth and are critical for sustainable development policies. Although the impacts of the different components of the energy trilemma on economic growth have been extensively discussed in the literature, studies that evaluate all dimensions together are limited. This study aims to fill this gap. To this end, this study analyzes the impacts of the energy trilemma on economic growth in Turkiye. First, the stationarity levels of the variables are analyzed. ADF and PP unit root tests were applied in the stationarity analysis. The ARDL bounds test is used to test the existence of long-run relationships between variables. Short-run and long-run coefficient estimates are calculated using the ARDL coefficient estimator.

ARDL estimation results show that the Energy Trilemma Index has a positive and strong impact on GDP with a coefficient of 0.243 in the short-run, and this impact increases to 0.346 in the long-run. Furthermore, Foreign Direct Investments exert a minimal impact in the short-run with a coefficient of 0.016, yet significantly bolster economic growth in the long-run with a coefficient of 0.136. The transition to sustainable energy shows a substantial positive impact on economic growth in the long-run with a high coefficient of 0.515, while it does not display a significant short-term relationship. Financial Development positively influences economic growth in both the short and long-runs with coefficients of 0.218 and 0.170, respectively, as the expansion of financial infrastructure and services supports growth. Lastly, Gross Fixed Capital Formation rapidly and directly impacts economic growth through infrastructure and industrial machinery and equipment investments in the short-run with a very high coefficient of 0.728, with its influence persisting in the long-run indicated by a coefficient of 0.540.

The results show that the energy trilemma supports economic growth. In this direction, several policy recommendations have been suggested: (1) In order for Turkiye to achieve balance in the energy trilemma, energy policies need to be structured in a comprehensive manner. Diversifying energy resources and reducing external dependence is a critical step. Integration of domestic and renewable energy sources should be accelerated to ensure energy supply security. (2) Renewable energy investments supporting long-term economic growth should be increased. The government should establish financial support mechanisms to encourage private sector investments. Renewable energy projects should be supported through tax breaks, low-interest loans, and grant programs. In addition, public-private partnership models should be implemented to develop renewable energy infrastructure. (3) Energy intensity in Turkiye is high. Incentive policies should be implemented in industry, housing and transportation sectors to increase energy efficiency. The use of energy-saving technologies in the industrial sector should be expanded. Energy management systems should be made mandatory. Awareness campaigns and incentive programs should be organized to reduce energy consumption. (4) Financial development is an important factor supporting economic growth. Financial infrastructure needs to be expanded and investment climate needs to be improved. Credit mechanisms in the banking system should be strengthened and financing options for small and medium-sized enterprises (SMEs) should be increased. Supporting financial innovation will facilitate investment in renewable energy and infrastructure projects. (5) Increasing foreign investment is crucial for technology transfer and employment capacity building. Turkiye should develop investor-friendly policies to attract FDI. Bureaucratic processes should be simplified, legal safeguards should be increased and investment incentives should be expanded. (6) Gross fixed capital formation directly and rapidly impacts economic growth. Therefore, infrastructure investments especially in transportation, energy transmission lines and industrial production should be increased. High-technology-based industrial machinery and equipment investments should be encouraged. In addition, public investments should be planned in harmony with the private sector. (7) To strengthen environmental sustainability, policies to reduce the use of fossil fuels should be developed. Technologies that reduce carbon emissions should be supported. Regulations such as a carbon tax can be implemented to accelerate green energy transformation. (8) Energy policies should be addressed within long-term strategies rather than short-term solutions. National and international energy planning and coordination should be ensured. A sustainable, reliable and fair energy supply plan should be prepared considering future energy demand. Technological developments and innovative energy solutions should be considered in this process. These policy recommendations support Turkiye's transition to a more sustainable growth model within the framework of the energy trilemma. A balanced energy policy can harmonize economic growth, environmental sustainability, and social welfare.

Despite its significant findings, this study has limitations, and future research could address these. Firstly, separate model estimations could be conducted for energy security, energy equity, and environmental sustainability to examine the impacts of each dimension of the energy trilemma more broadly. Such an expansion would allow for a more comprehensive assessment of these impacts. Secondly, subsequent studies could include samples from both developed and developing countries to explore if the impacts of the energy trilemma on economic growth differ by level of economic development. Lastly, the reliability of this study's findings could be tested with larger data sets and various analysis techniques, which would provide deeper insights into factors affecting energy security risks and help develop effective policies. Future research following these directions could enhance understanding of the relationship between the energy trilemma and economic growth and assist in policy formulation.

AUTHOR STATEMENT

Statement of Research and Publication Ethics

This study has been prepared in accordance with scientific research and publication ethics.

Author Contributions

Contribution rate (100%)

Conflict of Interest

There is no conflict of interest for the authors or third parties arising from the study.

REFERENCES

Acaravci, A., & Erdogan, S. (2018). Yenilenebilir enerji, çevre ve ekonomik büyüme ilişkisi: Seçilmiş ülkeler için ampirik bir analiz. *Eskişehir Osmangazi Üniversitesi İktisadi ve İdari Bilimler Dergisi*, *13*(1), 53-64. https://doi.org/10.17153/oguiibf.359419

Agbanyo, G. K., Ofori, C., Prah, G. J., & Chin, T. (2023). Exploring the energy-economy-environment paradox through Yin-Yang harmony cognition. *Heliyon*, *9*(9). https://doi.org/10.1016/j.heliyon.2023.e19864

Ang, B. W., Choong, W. L., & Ng, T. S. (2015). Energy security: Definitions, dimensions and indexes. *Renewable and Sustainable Energy Reviews*, *42*, 1077-1093. https://doi.org/10.1016/j.rser.2014.10.064

Boluk, G., & Mert, M. (2015). The renewable energy, growth and environmental Kuznets curve in Turkey: An ARDL approach. *Renewable and Sustainable Energy Reviews*, *52*, 587-595. https://doi.org/10.1016/j.rser.2015.07.138

Cetin, M., & Sezen, S. (2018). Türkiye'de yenilenebilir ve yenilenemeyen enerji tüketimi, ekonomik büyüme ve karbondioksit salinimi arasindaki ilişki: Bir SVAR (yapisal var) analizi. *Journal of Management and Economics Research*, *16*(1), 136-157. https://doi.org/10.11611/yead.385401

Chi, Y., Esily, R. R., Ibrahiem, D. M., Houssam, N., Chen, Y., Jia, X., & Zhang, X. (2023). Is North Africa region on track to energy trilemma for enhancing economic progress? The role of population growth and energy usage. *Energy Strategy Reviews*, *50*, 101245. https://doi.org/10.1016/j.esr.2023.101245

Dell'Anna, F. (2021). Green jobs and energy efficiency as strategies for economic growth and the reduction of environmental impacts. *Energy Policy*, *149*, 112031. https://doi.org/10.1016/j.enpol.2020.112031

Drews, S., Antal, M., & van den Bergh, J. C. (2018). Challenges in assessing public opinion on economic growth versus environment: Considering European and US data. *Ecological Economics*, *146*, 265-272. https://doi.org/10.1016/j.ecolecon.2017.11.006

Ekins, P. (2002). *Economic growth and environmental sustainability: The prospects for green growth*. Routledge. https://doi.org/10.4324/9780203011751

Gasparatos, A., & Gadda, T. (2009). Environmental support, energy security and economic growth in Japan. *Energy Policy*, *37*(10), 4038-4048. https://doi.org/10.1016/j.enpol.2009.05.011

Granger, C. W. J., & Newbold, P. (1974). Spurious regressions in econometrics. *Journal of Econometrics*, 2, 111-120. https://doi.org/10.1016/0304-4076(74)90034-7

Halicioglu, F. (2009). An econometric study of CO2 emissions, energy consumption, income and foreign trade in Türkiye. *Energy Policy*, *37*(3), 1156-1164. https://doi.org/10.1016/j.enpol.2008.11.012

Hotelling, H. (1933). Analysis of a complex of statistical variables into principal components. *Journal of Educational Psychology*, *24*(6), 417. https://doi.org/10.1037/h0071325

Hu, B., Li, Z., & Zhang, L. (2019). Long-run dynamics of sulphur dioxide emissions, economic growth, and energy efficiency in China. *Journal of Cleaner Production*, *227*, 942-949. https://doi.org/10.1016/j.jclepro.2019.04.170

Johansen, S., & K. Juselius (1990). Maximum likelihood estimation and inference on cointegration with applications to the demand for money. *Oxford Bulletin of Economics and Statistics*, 52, 169-210. https://doi.org/10.1111/j.1468-0084.1990.mp52002003.x

Jolliffe, I. T. (2002). *Principal component analysis for special types of data*. In the *Principal Component Analysis*. Springer Series in Statistics. Springer. https://doi.org/10.1007/0-387-22440-8_13

Kang, H. (2022). An analysis of the relationship between energy trilemma and economic growth. *Sustainability*, *14*(7), 3863. https://doi.org/10.3390/su14073863

Khan, I., Hou, F., & Le, H. P. (2021a). 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*, *754*, 142222. https://doi.org/10.1016/j.scitotenv.2020.142222

Khan, I., Hou, F., Irfan, M., Zakari, A., & Le, H. P. (2021c). Does energy trilemma a driver of economic growth? The roles of energy use, population growth, and financial development. *Renewable and Sustainable Energy Reviews*, *146*, 111157. https://doi.org/10.1016/j.rser.2021.111157

Khan, I., Hou, F., Zakari, A., & Tawiah, V. K. (2021b). The dynamic links among energy transitions, energy consumption, and sustainable economic growth: A novel framework for IEA countries. *Energy*, *222*, 119935. https://doi.org/10.1016/j.energy.2021.119935

Khan, I., Zakari, A., Dagar, V., & Singh, S. (2022a). World energy trilemma and transformative energy developments as determinants of economic growth amid environmental sustainability. *Energy Economics*, *108*, 105884. https://doi.org/10.1016/j.eneco.2022.105884

Khan, I., Zakari, A., Zhang, J., Dagar, V., & Singh, S. (2022b). A study of trilemma energy balance, clean energy transitions, and economic expansion in the midst of environmental sustainability: New insights from three trilemma leadership. *Energy*, *248*, 123619. https://doi.org/10.1016/j.energy.2022.123619

Kurniawan, R., Sugiawan, Y., & Managi, S. (2021). Economic growth-environment nexus: An analysis based on natural capital component of inclusive wealth. *Ecological Indicators*, *120*, 106982. https://doi.org/10.1016/j.ecolind.2020.106982

Le, T. H., & Nguyen, C. P. (2019). Is energy security a driver for economic growth? Evidence from a global sample. *Energy Policy*, *129*, 436-451. https://doi.org/10.1016/j.enpol.2019.02.038

Liu, H., Khan, I., Zakari, A., & Alharthi, M. (2022). Roles of trilemma in the world energy sector and transition towards sustainable energy: A study of economic growth and the environment. *Energy Policy*, *170*, 113238. https://doi.org/10.1016/j.enpol.2022.113238

Luciani, G. (2020). The impacts of the energy transition on growth and income distribution. *The Geopolitics of the Global Energy Transition*, 305-318. https://doi.org/10.1007/978-3-030-39066-2_13

Marti, L., & Puertas, R. (2022). Sustainable energy development analysis: Energy Trilemma. *Sustainable Technology and Entrepreneurship*, *1*(1), 100007. https://doi.org/10.1016/j.stae.2022.100007

Narayan, P. K., & R. P. Smith (2005). Trade liberalization and economic growth in Fiji: An empirical assessment using the ARDL approach, *Journal of the Asia Pacific Economy*, 10(1), 96-115. https://doi.org/10.1080/1354786042000309099

Nawaz, S. M. N., & Alvi, S. (2018). Energy security for socio-economic and environmental sustainability in Pakistan. *Heliyon*, *4*(10). https://doi.org/10.1016/j.heliyon.2018.e00854

OECD. (2008). Joint Research Centre-European Commission. (2008). Handbook on constructing composite indicators: Methodology and user guide. OECD publishing. https://doi.org/10.1787/9789264043466-en

Ozturk, I., & Acaravci, A. (2010). CO2 emissions, energy consumption and economic growth in Türkiye. *Renewable and Sustainable Energy Reviews*, *14*(9), 3220-3225. https://doi.org/10.1016/j.rser.2010.07.005

Pearson, K. (1901). LIII. On lines and planes of closest fit to systems of points in space. *The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science*, *2*(11), 559-572. https://doi.org/10.1080/14786440109462720

Pesaran, M. H., Shin, Y., & Smith, R. J. (2001). Bounds testing approaches to the analysis of level relationships. *Journal of Applied Econometrics*, *16*(3), 289-326. https://doi.org/10.1002/jae.616

Prado Jr, F. A., Athayde, S., Mossa, J., Bohlman, S., Leite, F., & Oliver-Smith, A. (2016). How much is enough? An integrated examination of energy security, economic growth and climate change related to hydropower expansion in Brazil. *Renewable and Sustainable Energy Reviews*, *53*, 1132-1136. https://doi.org/10.1016/j.rser.2015.09.050

Rajbhandari, A., & Zhang, F. (2018). Does energy efficiency promote economic growth? Evidence from a multicountry and multisectoral panel dataset. *Energy Economics*, *69*, 128-139. https://doi.org/10.1016/j.eneco.2017.11.007

Ullah, S., Khan, M., & Yoon, S. M. (2021). Measuring energy poverty and its impact on economic growth in Pakistan. *Sustainability*, *13*(19), 10969. https://doi.org/10.3390/su131910969

World Energy Council (WEC) (2018). World Energy Trilemma Index 2018. Retrieved on 22.04.2024 from https://www.worldenergy.org/assets/downloads/World-Energy-Trilemma-Index-2018.pdf

World Energy Council (WEC) (2019). World Energy Trilemma Index 2019. Retrieved on 10.04.2024 from https://www.worldenergy.org/assets/downloads/1.-World-Energy-Issues-Monitor-2019-Interactive-Full-Report.pdf

World Energy Council (WEC) (2020). World Energy Trilemma Index 2020. Retrieved on 15.04.2024 from https://www.worldenergy.org/assets/downloads/World_Energy_Trilemma_Index_2020_-_REPORT.pdf?v=1602261628

World Energy Council (WEC) (2023). World Energy Trilemma Index 2024. Retrieved on 18.04.2024 from https://www.worldenergy.org/assets/downloads/World_Energy_Trilemma_Index_2022.pdf?v=1669839605

World Energy Council (WEC) (2024). World Energy Trilemma Index 2024. Retrieved on 18.04.2024 from https://www.worldenergy.org/assets/downloads/World_Energy_Trilemma_2024_Full_Report.pdf?v=1713253987

Ziolo, M., Jednak, S., Savić, G., & Kragulj, D. (2020). Link between energy efficiency and sustainable economic and financial development in OECD countries. *Energies*, *13*(22), 5898. https://doi.org/10.3390/en13225898