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THE IMPACT OF RENEWABLE ENERGY SOURCES ON SUSTAINABLE ECONOMIC GROWTH

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ABSTRACT

This study examines the impact of renewable energy sources on sustainable economic growth in Türkiye for the period 2000-2024. Gross Domestic Product (GDP) is used as an indicator of economic growth, while hydraulic, geothermal, and wind energy production represent renewable energy sources. The stationarity of the variables was examined using ADF, PP, and KPSS unit root tests, and all tests showed that the series are first-order together (I (1)). After determining the optimal lag length, a Vector Autoregressive (VAR) model was estimated, followed by impulse response functions, variance decomposition, and Granger causality analyses. The empirical findings reveal that shocks in geothermal energy production have a strong and lasting positive effect on economic growth in both the medium and long term. Hydraulic energy exhibits a negative effect in the short term, but this effect diminishes and becomes insignificant in the long term. On the other hand, wind energy has a limited and short-term effect on GDP. Variance decomposition results show that a significant portion of long-term fluctuations in GDP can be explained by changes in geothermal energy production. Granger causality analysis also shows a bidirectional causal relationship between geothermal energy and economic growth. The results highlight the critical role of renewable energy, particularly geothermal energy, in supporting sustainable economic growth in Türkiye. These findings indicate the importance of prioritizing geothermal energy investments within the framework of long-term energy policies and sustainable development goals.

KEYWORDS: Renewable Energy, Economic Growth, VAR Model, Geothermal Energy, Hydraulic Energy, Wind Energy.

1. INTRODUCTION

Energy, an essential input in production and most consumption activities, is a fundamental source of economic growth. This is because it is a crucial input in industrial production. Energy is needed in manufacturing, communication, transportation, homes – in short, in every area of life for its sustainability. Energy is one of the most important factors determining the level of development of countries. Energy indicates a country's strong position. As a fundamental input for production, energy is important for increasing the welfare of societies and is used in almost every aspect of daily life (Koç and Kaya, 2015, p. 37). Globally, energy resources and the proportion of energy in the political power balance and economy are high. Countries that have a say in world politics and are economically powerful are often those that control energy resources or can process these resources with high added value (Çepik, 2015, p. 44).

Table 1: Categorization of Energy Sources.

Energy Sources According to Their Availability	**Energy sources according to their convertibility.**
1. Non-renewable Energy Sources	1. Primary Energy Sources
Fossil-derived Coal Oil Natural gas Nuclear Origin Uranium Thorium	Coal Oil Natural gas Nuclear Biomass Hydraulic Sun Wind Wave, Tide
2. Renewable Energy Sources	2. Secondary Energy Sources
Solar energy Wind Energy Geothermal Energy Hydrogen Energy Hydroelectric Energy Biomass Energy Wave and Tidal Energies	Electricity, Gasoline, Diesel, Motor Oil Secondary Coal Coke, Petrocoke Air Gas Liquefied Petroleum Gas (LPG)
Source: Koç and Kaya, 2015, 37	

Generally, energy sources are classified according to their convertibility and usage patterns. When classified according to usage patterns, energy is divided into two categories: renewable and non-renewable energy. Non-renewable energy is energy obtained from resources that are not sustainable, are depleted with use, and require a long time to replace. Examples include fossil fuels, uranium, and thorium. Renewable energy sources, on the other hand, are energy obtained from resources that constantly renew themselves in nature and are limitless. Examples include biomass, hydraulic, wind, solar, and geothermal (Koç and Kaya, 2015, p. 37). Energy sources are further divided into primary and secondary energy sources according to their convertibility (Table 1). Primary energy is the form of energy that has not undergone any transformation or change (OECD/IEA, 2005). In other words, it is energy sources obtained directly from nature that have not yet undergone transformation. Secondary energy is the type of energy obtained by transforming primary energy sources (Koç and Kaya, 2015, p. 37).

Energy is a force inherent in matter and manifesting itself in various physical forms. Economic growth, in turn, refers to the increase in a country's income volume and per capita income over time (Aydın, 2010, p. 318). Renewable energy is classified as energy obtained from inexhaustible resources that can regenerate naturally over time, and is also known as clean energy (Günay and Yıldırım, 2024, p. 62). It is also called green energy. Green energy has positive effects on public health because it does not create air, water, or soil pollution during energy production. The increasing world population, industrialization activities, rising living standards, technological innovations, and increased consumer spending are all contributing to the growing demand for energy. The rapid increase in energy demand has led to the long-term use of fossil fuels, which have relatively low costs, as the primary source of energy production. However, due to the environmental damage caused by the excessive use of fossil fuels, particularly in developing and developed countries, the United Nations Framework Convention on Climate Change gained legal validity in 1994. Policies supporting the use of renewable energy sources have gained momentum in order to meet increasing energy demand and prevent global warming. This is because renewable energy sources are environmentally friendly and an unlimited resource, therefore they are supported by environmental organizations, and because their costs are higher than fossil fuels, they are used more by developed countries (Şengelen, 2016, pp. 1-2).

The 1997 Kyoto Protocol, which entered into force in 2005, aimed to reduce greenhouse gas emissions by 5.2% between 2008 and 2012 compared to 1990 levels. However, the Protocol concluded that carbon dioxide (CO2) is the most polluting greenhouse gas causing climate change , and that it is responsible for 58.8% of global emissions (Pao, Fu & Tseng, 2012, p. 400; Büyükyılmaz and Mert, 2015, p. 104; Çepik, 2015, p. 29; Çetin and Sezen, 2018, p. 137). The concept of "Sustainable Development" was first brought together by the UN Conference on the Human Environment in 1972. The 1987 Brundland Report introduced this concept (Biresselioğlu, 2022, p. 2).

The definition of "sustainability" used in this report draws attention to three points: firstly, it explains the concept of development from a broader perspective, without limiting needs from an economic standpoint; secondly, it emphasizes intergenerational equality; and thirdly, it addresses intergenerational equality both within and between countries (Batı, 2013, pp. 1-2). The 1992 Rio Conference established an international regime for combating the climate crisis. The 2005 Kyoto Protocol aimed to reduce greenhouse gas emissions by developed countries. The 2016 Paris Climate Agreement is the first international agreement on the climate crisis aimed at reducing greenhouse gas emissions by both developed and developing countries. In Turkey, the Paris Climate Agreement entered into force on October 7, 2021 (Biresselli̇oğlu, 2022, p. 2).

The oil crisis of the 1970s first exposed industrialized countries to an energy crisis, making energy security a focal point for nations on the international stage. Many countries have turned to the use of renewable energy for sustainable development and have begun implementing renewable energy development plans (Xu, 2016, p. 310). While energy has long been a key variable in competition and economic growth for countries, in the modern economic climate, growth has become increasingly dependent on energy, and the demand for energy is growing day by day. Therefore, energy and the economy are considered as a whole (Alptürk, 2025, p. 15).

Greenhouse gases refer to gaseous formations in the atmosphere, whether spontaneous or human-caused, that trap and re-emit infrared radiation (UN, 2002, p. 5). The goal of the 2002 UN report is to achieve a level of halting greenhouse gas accumulations in the atmosphere, based on the provisions of the convention outlined in the report, that will prevent the dangerous human-caused impact on climate change. Countries should cooperate to promote a clear and supportive international economic integration that will lead to sustainable economic growth and development, especially in developing countries, and to address climate change problems more thoroughly (UN, 2002, p. 7). A 2018 report by the Intergovernmental Panel on Climate Change demonstrated that the risks posed by a global warming of 1.5°C are significantly less than those posed by a warming of 2°C. If the temperature increase is limited to 1.5°C, by 2050 hundreds of millions of people will be spared from climate-related disasters and biodiversity loss will decrease (Jelley, 2024, p. 23). Energy use is the most important input for all sectors of a country's social and economic growth. Therefore, energy use is increasing in developing countries. Most energy production on Earth comes from fossil fuel power plants. The rapid depletion of these fossil fuels and the release of greenhouse gases into the atmosphere are causing an energy crisis and an environmental crisis.

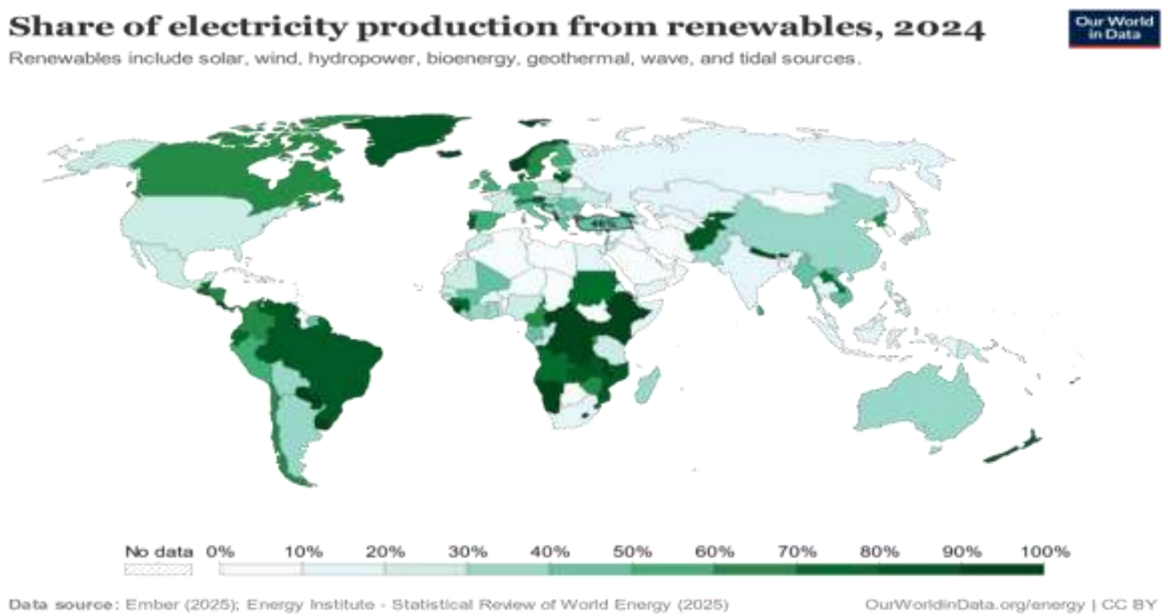

Figure 1: Share of Electricity Generation from Renewable Sources, 2024.
Source: (Ember 2025; Our World in Data, 2025).

Therefore, countries are shifting to renewable energy. Renewable energy sources, which have limited negative impacts on human and environmental health, include natural and sustainable energy types as an alternative to fossil fuels. The environmental impacts of traditional energy sources, fossil fuels, are triggering the climate crisis and threatening natural life. Therefore, the importance of renewable energy sources is increasing and they are one of the fundamental dynamics of sustainable economic growth.

Figure 1 shows the share of renewable energy sources in electricity production in 2024. According to the data, while the use of renewable energy continues its upward trend globally, there are significant differences between countries. Rates are high in European countries and especially in Scandinavia, while they are low in regions dependent on fossil fuels. Turkey's share of renewable energy is above the world average. Hydroelectric, wind, and solar investments in Turkey have made a significant contribution to this development. Nevertheless, coal and natural gas still hold a decisive position in energy supply. This is because the speed of transition to renewable energy is related to national energy policies and investment strategies. For Turkey, the use of renewable energy sources reduces the use of imported fossil fuels, thus reducing both environmental impacts and imports, which positively impacts economic growth (Turkish Electricity Transmission Corporation [TEİAŞ], 2024). Energy is the lifeblood of the modern economy, the foundation of development, and the catalyst for growth. Globally, 675 million people lack electricity; 450 million people have unreliable power. More than one billion people worldwide live in energy poverty (World Bank, 2025).

As stated in the bulletin published by TSKB Economic Research (2025), 40% of global electricity production in 2024 was obtained from clean energy sources. In 2024, electricity generated from clean energy sources reached 12,609 terawatt-hours (TWh), with a significant contribution from renewable energy sources. Hydroelectric power accounted for the highest percentage at 14.3%, followed by wind at 8.1% and solar at 6.9%. Nuclear power accounted for 9.0% of electricity production. Looking at the proportion of renewable sources in Türkiye's energy production, this rate is lower compared to the EU. In 2024, the main sources of electricity production in Türkiye were coal with 35.2% and natural gas with 18.9%, while 21.5% of electricity was obtained from hydroelectric energy, 10.5% from wind, 7.5% from solar, 3.2% from geothermal energy and 3.2% from other sources (Turkish Ministry of Energy and Natural Resources, 2025).

Renewable energy sources make significant contributions to economic growth. They create employment by offering new job opportunities. For example, according to the International Renewable Energy Agency (IRENA), as of 2023, the renewable energy sector provided employment for more than 13 million people worldwide. Examples include wind turbine manufacturing and solar panel installation. They ensure energy independence. By reducing dependence on fossil fuel imports from other countries, they contribute to the foreign trade balance of countries. Investments in renewable energy (e.g., new technologies and R&D) increase economic growth. While economic growth includes elements such as GDP growth, job creation, and energy independence, sustainability addresses environmental and social balance alongside economic growth.

In conclusion, renewable energy sources offer a wide range of benefits, including energy supply security, increased employment, reduced dependence on foreign sources, and lower environmental costs. Therefore, renewable energy sources should be central to economic strategies. For the economy of the future, alongside growth, the sustainability of that growth must also be prioritized. Overall, renewable energy sources not only contribute to economic growth but also to environmental sustainability and the mitigation of climate change.

The aim of this study is to examine the relationship between renewable energy sources (hydroelectric, geothermal, and wind energy) and sustainable economic growth in Turkey for the period 2000-2024 through multivariate time series analysis. In this context, the stationarity properties of the variables were considered, a VAR model was estimated after selecting an appropriate lag length, and variance decomposition, Granger causality tests, and impulse-response functions were applied. These findings demonstrate that the effects of renewable energy types on economic growth differ and offer important implications for Türkiye's energy policies. Due to data limitations, the analysis was conducted using data from 2000-2024. This study will include four variables, making it an important contribution to the literature. The introduction provides information on renewable energy sources and sustainable economic growth. The second part presents a literature review. The third part includes the econometric analysis and findings. The final part presents the results of the applied analysis.

2. LITERATURE REVIEW

When examining research analyzing the relationship between renewable energy sources and sustainable economic growth, it becomes clear that this has been a subject of much research, especially in recent years. Studies have heavily focused on the relationship between renewable energy sources and economic growth. Academic research revealing the relationship between renewable energy sources and economic growth is summarized in Table 2.

Table 2: Literature Review.

Reference	Aim	Variables	APPLICATION Period and Method	Conclusion
Özşahin, Mucuk and Gerçeker (2016)	This study econometrically validated the relationship between economic growth and renewable energy consumption in BRICS-T countries (including Türkiye).	Dependent Variable: GDP Independent Variables: Renewable Energy Consumption, Total Workforce, Fixed Capital Investment	2000-2013 Panel ARDL. Pedroni, Westerlund Panel CUSUM Cointegration Test Homogeneity Tests with Cross-Sectional Dependence	The findings reveal a positive long-term cointegration relationship between economic growth and renewable energy consumption.
Acaravci and Erdogan (2018)	To identify the long-term relationships between renewable energy production, environmental pollution, and income in the top five renewable energy-producing countries globally.	Dependent Variable: Environmental Pollution (Carbon Emissions Per Capita) Independent Variables: Renewable Energy Production, Real GDP Per Capita	1992-2013 Panel Data Analysis Cross-Sectional Dependency Test	Long-term parameter estimations show that the variables move together in the long term. Applied findings confirm that the increase in renewable energy production has a mitigating effect on environmental pollution. Long-term analysis indicates that economic growth (per capita income) has a positive effect on environmental pollution.
Alper (2018)	is to determine the long-term relationship between renewable energy use and economic growth in Turkey using econometric methods.	Dependent Variable: Real GDP per capita Independent Variables: Labor Force Participation Rate, Total Fixed Capital, Renewable Energy Use	1990-2017 Toda-Yamamoto Causality Test, Bayer-Hank Cointegration Test FMOLS Method TY Causality Test	Long-term FMOLS estimation results indicate that a 1% increase in renewable energy use has a positive and statistically significant impact of 0.19% on economic growth. Findings from causality analyses point to a unidirectional causal relationship from economic growth to renewable energy use, confirming the validity of the conservation hypothesis for Turkey. Furthermore, it was concluded that all coefficients for the independent variables included in the model were statistically significant.
Singh, Nyuur and Richmond (2019)	This study aims to reveal the relationships between renewable energy production and economic growth, and their differing effects on the economies of developed and developing countries.	Total Renewable Electricity Consumption, GDP, Total Workforce, Gross Fixed Capital, Total Fossil Fuel Electricity Consumption	1995-2016 Fully Modified Least Squares(FMOLS) Regression Model	Renewable energy production has a positive and significant impact on economic growth in 20 developed and developing countries. However, this effect has been found to be greater in developing economies than in developed economies. While an increase in renewable energy production in developed countries leads to a 0.07% increase in overall production, this increase is only 0.05% in developing countries.
Akusta and Cergibozan (2020)	Analyzing the environmental impact of economic growth and renewable energy use in Türkiye.	Dependent Variable: Real Pressure on Nature Per Capita Independent Variables: GDP Per Capita Squared, Financial Development, Openness to Trade, Real GDP Per Capita, Renewable Energy Sources	1972-2015 Variance Decomposition Analysis ARDL and Johansen Cointegration Tests	Long-term forecast results show that real GDP per capita, openness to the outside world, and financial development increase environmental degradation; while the square of real GDP per capita and the use of renewable energy reduce environmental damage. Furthermore, it was concluded that real GDP per capita is the strongest predictor of environmental pressure.
Unuvar and Keskinkilic (2020)	is to reveal the relationship between economic growth and renewable energy	Dependent Variable: GDP Independent Variable:	2000-2016 Cross-Sectional Dependence and Homogeneity Tests in	The analysis results revealed a positive and statistically significant relationship between renewable energy production and economic growth in G20 countries.

Reference	Aim	Variables	APPLICATION Period and Method	Conclusion
	production by analyzing 19 countries (G20 members) using econometric methods	Renewable Energy Production	Panel Data Analysis ADF and PP Fisher Unit Root Tests Kao and Johansen Fisher Cointegration Tests FMOLS and DOLS Test	
Dinçer and Karakuş (2020)	To investigate the impact of renewable energy use on sustainable economic development through a comparative analysis of BRICS and MINT countries.	Sustainable Economic Development, Renewable Energy	1990-2015 (Annual) Toda Yamamoto Causality Analysis Engle-Granger cointegration	The results indicate a stable long-term link between renewable energy and economic development in BRICS and MINT countries. In particular, the use of renewable energy has proven to be a key driver of sustainable economic development in Brazil and China.
Candarli and Unakıtan (2021)	To reveal the relationship between renewable energy use and economic growth in Türkiye.	GDP (at constant prices) The share of renewable energy use in total energy use, external variables: Gross capital stock (at constant prices), and a puppet chart representing the economic crises of 1994, 2001, and 2009.	1990-2019 (Dataset Covering the Years) Vector Error Correction Model (VECM) Granger Causality Analysis	The analysis results show a unidirectional causal relationship from renewable energy use to economic growth.
Yurtkuran (2021)	The study aims to reveal the link between economic growth, primary energy consumption, and logistics in Türkiye.	Primary Energy Resources Consumption, Logistics, Economic Growth	1974-2019 Bayer-Hank Method, Least Squares, Dynamic Least Squares, Canonical Cointegration Regression	In conclusion, the study reveals that primary energy sources and logistics have an enhancing effect on economic growth; economic growth positively influences primary energy consumption, while logistics has a negative impact. These findings support the feedback hypothesis for Turkey.
Eyüboğlu, Akdağ and Özçelik (2021)	The study examines the link between energy efficiency and renewable energy consumption and economic growth within a multi-country framework.	Dependent Variable: Economic Growth Independent Variables: Energy Efficiency, Renewable Energy Consumption	1990-2014 Westerlund (2007) Cointegration, Dumitrescu Hurline (2012) Causality Tests	The findings indicate that energy efficiency and renewable energy consumption do not show a stable long-term relationship with economic growth, but in the short term, bidirectional causal links emerge between both variables and economic growth.
Lightning and Rock (2021)	This study analyzes the factors determining renewable energy use in selected OECD countries and reveals their impacts. The main objective is to explain the macroeconomic structures of OECD countries that are advanced in renewable energy technology.	Renewable Energy Consumption, Carbon Dioxide Emissions, Current Account Balance, Budget Balance, Economic Growth, Inflation Rate, Crude Oil Prices, Unemployment Rate	1996-2017 Panel ARDL Method Using six different models	Carbon dioxide emissions have been identified as the strongest indicator of renewable energy use. Economic growth, inflation, oil prices, and the current account balance all have an impact on renewable energy use. However, renewable energy use does not significantly influence other variables.
Cetintas and Aydin (2022)	This research aims to analyze the interaction between renewable energy use, environmental pollution, and economic growth, specifically in OECD countries.	Environmental Pollution, Use of Renewable Energy, Economic Growth	1995-2018 Smooth Transition Panel Regression (SPR) Model	Findings from the threshold model reveal that the threshold value for the share of renewable energy use in total energy consumption is 7.825%. When this share is below the threshold, economic growth increases environmental degradation, while exceeding the threshold reverses this trend, turning the impact of economic growth on environmental quality positive and reducing environmental pollution.

Reference	Aim	Variables	APPLICATION Period and Method	Conclusion
Birol and Demirgil (2022)	The aim of this study is to determine the relationship between wind energy production, which is considered within the scope of renewable energy sources, and economic growth using econometric methods and annual data from the EU-15 countries.	Real GDP, Wind Energy Production	1995-2019 Panel Data Analysis Cointegration and Panel Causality Tests	Empirical findings indicate that economic growth has a limited but positive long-term impact on wind energy production; causality analyses reveal a unidirectional relationship from economic growth to wind energy production.
Cetinbakis and Sahin Kutlu (2022)	This study analyzes the causality, short-term and long-term effects of renewable energy consumption and environmental sustainability variables on economic growth in Türkiye using an ARDL approach econometric model with time series data.	GDP, Renewable Energy Consumption, Carbon Dioxide Emissions, Final Consumer Expenditures, Foreign Direct Investments	1988-2019 ARDL Bounds Test Approach	The analysis results show that final consumption expenditures, foreign direct investment, and renewable energy consumption support economic growth in both the short and long term. In contrast, the impact of carbon dioxide emissions on economic growth was found to be temporary and only apparent in the short term.
Eygu (2022)	The aim of this study is to determine the impact of renewable energy consumption on economic growth in Türkiye by including key macroeconomic variables such as labor and capital in the model, and to obtain findings that will contribute to energy policies.	Dependent Variable: GDP Independent Variables: Fixed Capital, Labor, Electricity Consumption from Renewable Energy Sources	1995-2020 ADF and PP unit root tests, Ziot-Andrews structural fracture unit root tests, ARDL boundary test, Toda-Yamamoto causality analysis	The analysis results show a unidirectional causal relationship from renewable energy consumption to economic growth.
Enough (2023)	To determine per capita carbon emissions as an indicator of environmental quality in Türkiye, considering renewable energy and economic globalization.	Dependent Variable: Per capita carbon emissions Independent Variables: Renewable Energy Production, Economic Globalization, GDP Per Capita, Agricultural Production	1980-2020 Unit Root based on Fourier Functions, Cointegration and Causality Analysis	There is no short-term causal relationship between GDP per capita, agricultural production, renewable energy, and globalization and carbon emissions. In the long term, per capita income levels and agricultural activities negatively impact environmental quality. Economic globalization and renewable energy, however, have been found to have a positive impact on environmental quality.
Kuskaya (2023)	The aim is to investigate the impact of renewable energy production on economic growth.	Dependent Variables: GDP Independent Variables: Solar Energy Production, Wind Energy Production, Biomass Energy Production	1990-2020 (Quarterly Periods) Quantile Regression Model	This study shows that increased renewable energy production has a positive impact on economic growth.
Caner and Yaşar (2024)	This study aims to demonstrate the impact of renewable energy production on economic growth through a practical example in Türkiye.	Dependent Variable: GDP Independent Variable: Renewable Energy Production Controlling Variables: Labor and Capital	1990-2019 ARDL Bounds Test, Toda-Yamamoto Causality Analysis, Cobb-Douglas Production Function	The long-term analysis results show that renewable energy production has a positive effect on economic growth. However, in the specific case of the Turkish economy, the study revealed no statistically significant causal relationship between renewable energy production and economic growth during the examined period.

Reference	Aim	Variables	APPLICATION Period and Method	Conclusion
Inn (2024)	The study aims to reveal the relationships between renewable energy and macroeconomic and environmental indicators specifically in OECD countries (38 countries).	Carbon Emissions, Unemployment, Renewable Energy Consumption, GDP, Foreign Trade	1990-2022 Panel Causality, CADF-CIPS Test, and Köse Causality Analysis	The analysis results indicate that the use of renewable energy has positive effects on economic growth, environmental sustainability, and employment. Causality tests suggest a bidirectional relationship between renewable energy and carbon emissions and economic growth; a unidirectional causal relationship from exports to renewable energy, and a bidirectional causal relationship between imports and renewable energy were identified. Furthermore, a unidirectional causal relationship was found between renewable energy and unemployment.
Ozkaya (2025)	This study investigates the effects of environmental sustainability, digitalization, and energy consumption variables on economic growth in developing countries.	Environmental Sustainability, Digitalization, Economic Growth, Energy Consumption	Literature and Archival Studies	This strongly demonstrates that energy policies supporting economic growth in developing countries must be compatible with environmental sustainability and digitalization processes. Addressing energy consumption, environmental protection, and digitalization policies together plays a strategic role in helping these countries achieve their economic development goals.

3. ECONOMETRIC AND MODEL DATA SET

3.1. Analysis with the VAR Model

3.1.1. Vector Autoregression (VAR) Analysis

VAR models are systems of equations in which each endogenous variable in a system of equations includes both its own lagged value and the lagged values of other variables in the system. Although the variables are expressed as endogenous variables in this model, exogenous variables can also be included in the system of equations (Sevüktekin and Çınar, 2017, p. 495). According to Sims (1980) and Sims, Stock, and Watson (1990), the purpose of a VAR model is not to determine parameter estimates but to determine the interaction between variables. The rationale for this is that the variables used in this model must be stationary. If the variables are not stationary, the difference is taken, and the covariation between the data is wasted (Sevüktekin and Çınar, 2017, p. 496).

The aim of this study is to examine the dynamic relationships between electricity generation from renewable energy sources (hydroelectric, geothermal, and wind) and GDP. A VAR model within the framework of multivariate time series analysis was used to reveal how the variables influence each other over time. This model is suitable for analyzing the causal relationships between energy production and economic growth because it considers all variables simultaneously as both dependent and independent.

3.1.2. Mathematical Formula of the VAR Model.

A VAR model with a delay of p generally:

$$Y_t = c + A_1 Y_{t-1} + A_2 Y_{t-2} + \cdots + A_p Y_{t-p} + u_t$$

It is in this form.

This study's 4-variable VAR(p) model:

$$Y_t = \begin{bmatrix} GDPt \\ HDt \\ JEOt \\ RUZt \end{bmatrix}$$

$$Y_t = c + \sum_{i=1}^{p} A_i Y_{t-i} + u_t$$

Each equation includes all the lags for all four variables.

3.2. Impulse-Response Analysis

In VAR models, impulse response functions are one of the fundamental tools for analyzing the dynamic structure of the system and the time-dependent interaction between variables. The impulse response approach reveals the time-spread effects of a one-unit change, normalized by the standard error applied to structural or reduced error terms, on all endogenous variables in the model (Sims, 1980). This method allows for analytical monitoring of how shocks propagate within the system through direct and indirect pathways, and what dynamic characteristics dominate in terms of magnitude, direction, and duration (Yıldırım, 2021,

p. 218). However, it is important to note that the variables in the system must satisfy the stationarity condition. Because if the variable(s) are stationary, the effect of the shock will disappear after a certain period. If the variable(s) are not stationary, the effect of the shocks applied to the system will continue indefinitely, making it impossible to accurately calculate the relationships between the relevant variables (Sevüktekin and Çınar, 2017, p. 510). The impulse response function provides a complementary analytical framework that enhances the interpretability of results obtained from VAR models by revealing the intrinsic structural relationships, causality mechanisms, and interaction processes of the model (Stock & Watson, 2001, pp. 104-109).

3.3. Data Set and Variables

This study uses annual data from 2000-2024 to analyze the impact of renewable energy sources on sustainable economic growth in Türkiye. The dependent variable is real Gross Domestic Product (DGDP) in dollar terms, while the independent variables are annual data on electricity production from hydraulic (DHD), geothermal (DJEO), and wind (DRUZ) sources. The data used in the article were obtained from the GDP Trading Economics and World Bank databases, while the data on electricity production from renewable energy sources (hydraulic, geothermal, and wind) were obtained from the TEİAŞ database. The 2000-2024 data and descriptive statistics for the variables used in the study are shown in Table 3 below.

Table 3: Descriptive Statistics for Variables.

Variable	Variable Definition	Avg.	Min.	Max.	Standard Deviation
DGDP	(Billion USD) Real Gross Domestic Product	7.2077	20.175	13.2325	27.5596
DHD	Hydroelectric power generation (GWh)	5.2078	24.009	8.8822	16.6845
DJEO	Geothermal electricity generation (GWh)	3.6927	7.5500	11.139	4.3991
DRUZ	Wind power generation (GWh)	11.2642	33.4000	36,826	12.8103

The descriptive statistics presented in Table 3 show that the variables exhibit different levels of volatility throughout the period. The high standard deviation values of the DGDP and DHD variables reveal that hydroelectric production exhibits significant fluctuations with economic growth. The low standard deviation of the DJEO variable indicates that geothermal production has a more stable structure. The DRUZ variable, on the other hand, indicates a moderate level of volatility in wind energy. These findings reveal that the series have a heterogeneous volatility structure and that the dynamic relationships of the VAR model should be evaluated within the framework of these statistical differences.

4. FINDINGS

In this study, to check for data stationarity, the Augmented Dickey-Fuller (ADF), Phillips-Perron (PP) Unit Root Test, and Kwiatkowski-Philips-Schmidt-Shin (KPSS) Unit Root Test were used. Then, a VAR (Vector Autoregressive) model was applied to examine the short-term and long-term relationships between the variables. Finally, a VAR Granger N causality analysis was performed to determine the causal relationship between the variables. The analyses and tests used in the study were performed using the E-Views 13 software package. The findings obtained from the tests and analyses are presented under the following subheadings .

4.1. Unit Root Test

The VAR (Vector Autoregressive) model is tested for the stationarity of the series being analyzed before application. In this context, the Augmented Dickey-Fuller (ADF), Phillips-Perron (PP) Unit Root Test and Kwiatkowski-Philips-Schmidt-Shin (KPSS) Unit Root Test were used to check whether the series are stationary. The purpose of these tests is to determine whether the series change over time and whether they contain a unit root. If there is a unit root, the series is not stationary and is usually made stationary by taking the difference. According to the results in Table 4, the variables became stationary after taking the first difference (I (1)).

Table 4: Unit Root Test Results.

At the level	Variables	ADF	PP	KPSS
Fixed	DGDP	-0.0066	-0.3513	0.0462

		0.9490	0.902	0.216000
	DHD	-1.8453 0.5508	1.666 0.4347	0.6183 0.739000
	DJEO	-2.4983 0.1288	0.6780 0.9889	0.6324 0.739000
	DRUZ	-1.1176 0.6863	2.6254 1.0000	0.6324 0.739000
Fixed and Trending	DGDP	-2.9081 0.1797	-1.5159 0.7953	0.0462 0.216000
	DHD	-4.2689 0.0313	-4.3120 0.0119	0.0851 0.216000
	DJEO	-3.6935 0.0435	-1.6481 0.724	0.178487 0.216000
	DRUZ	-2.096466 0.0515	-1.4066 0.8326	0.1931 0.216000
First Awareness	**Variables**	**ADF**	**PP**	**KPSS**
Fixed	DGDP	-3.954* 0.0545	-3.9396 * 0.056	0.2081* 0.739000
	DHD	-5.5587 0.0002	-17.2557* 0.0000	0.1282 0.21600
	DJEO	-1.5642 0.4356	-3.0945* 0.0418	0.3338 0.7390
	DRUZ	0.83986 0.9543	-7.3321* 0.0000	0.6516 0.73900
Fixed and Trending	DGDP	-2.95440* 0.0000	-7.8660* 0.0001	0.1282* 0.21600
	DHD	-5.5887*	-16.6641*	0.3550*
		0.0002	00000	0.2160
	DJEO	0.0477 * - 0.0110	-3.1761 * 0.1147	0.1122 * 0.2160
	DRUZ	0.01561* -4.34371	-6.9443* 0.0001	0.1933* 0.21600

Table 4 shows that the stationarity tests of the variables were examined using the ADF (Augmented Dickey-Fuller), PP (Phillips-Perron), and KPSS (Kwaiatkowski-Philips-Schmidt-Shin) unit root tests. When the findings from the three tests are evaluated together, it is understood that the variables have unit roots at the level values, in other words, the series do not satisfy the stationarity condition. According to the results obtained from the three tests, it is seen that the variables contain unit roots at the level and are not stationary. This means that the series do not show a tendency to return to the mean over time and the variance is not constant. Therefore, it was determined that the variables became stationary after taking their first differences (I(1)). In other words, it can be said that the variables were made stationary by taking their differences and making them stationary at the first order. This finding indicates that although the variables are not stationary at the level, they acquire the property of reverting to the mean when differences are taken, making them suitable for econometric analyses (cointegration test, VAR/VECM models, etc.).

4.2. VAR (Vector Autoregressive) Model

Dynamics of financial and economic time series Its structure can be explained and predicted using VAR (Vector Autoregressive) models (Çil, 2018, p. 323). Therefore, in this study, a VAR (Vector Autoregressive) model was applied to contribute to the literature in order to obtain the effect of renewable energy sources on GDP. The appropriate lag length is determined before using the VAR model. The LR, FPE, AIC, and HQ criteria in Table 5 are important statistics used to determine the optimal lag length of the model. Each of these criteria is a statistical tool evaluated from different perspectives to best optimize the accuracy and predictive capacity of the model. According to the analyses performed, all four criteria move in the same direction, and the lag length of 3, which shows the lowest value, is determined to be the most suitable. This indicates that the lag length of 3 should be used to increase the predictive accuracy of the model and obtain valid results.

Table 5: VAR Delay Length Determination Criteria.

Lag	LogL	LR	FPE	AIC	SC	HQ
0	-688.5806	NA	5.20e+23	65.96006	66.15901	66.00324
1	-663.3333	38.47202*	2.24e+23	65.07937	66.07415	65.29526
2	-646.8067	18.88761	2.60e+23	65.02921	66.81982	65.41782
3	-613.9348	25.04528	9.48e+22*	63.42236*	66.00879*	63.98368*

Table 6: Results of the VAR Model.

	DGDP	DHD	DJEO	DRUZ
DGDP(-1)	-0.477585	-54.19751	0.270557	-1.079966
	(0.31003)	(54.3685)	(1.13159)	(5.97183)
	[-1.54043]	[-0.99686]	[0.23910]	[-0.18084]
DGDP(-2)	-0.397973	-39.86253	1.760305	0.002157
	(0.31967)	(56.0577)	(1.16675)	(6.15738)
	[-1.24496]	[-0.71110]	[1.50873]	[0.00035]
DHD(-1)	0.000560	-0.623237	0.002421	-0.014016
	(0.00149)	(0.26121)	(0.00544)	(0.02869)
	[0.37618]	[-2.38595]	[0.44539]	[-0.48851]
DHD(-2)	0.001432	-0.486606	-0.001350	0.031481
	(0.00139)	(0.24361)	(0.00507)	(0.02676)
	[1.03048]	[-1.99749]	[-0.26616]	[1.17651]
DJEO(-1)	-0.267973	3.307161	1.355910	-0.211123
	(0.08060)	(14.1346)	(0.29419)	(1.55255)
	[-3.32463]	[0.23398]	[4.60898]	[-0.13598]
DJEO(-2)	0.080619	-7.570749	-0.269091	2.549579
	(0.07934)	(13.9131)	(0.28958)	(1.52821)
	[1.01614]	[-0.54415]	[-0.92925]	[1.66834]
DRUZ(-1)	-0.000554	-3.538052	-0.002478	0.106424
	(0.01423)	(2.49585)	(0.05195)	(0.27414)
	[-0.03896]	[-1.41758]	[-0.04770]	[0.38821]
DRUZ(-2)	0.032964	2.302072	-0.043119	-0.324671
	(0.01485)	(2.60490)	(0.05422)	(0.28612)
	[2.21911]	[0.88375]	[-0.79532]	[-1.13473]
C	119.4403	11171.19	-33.89300	867.1619
	(42.6311)	(7475.91)	(155,598)	(821.154)
	[2.80171]	[1.49429]	[-0.21782]	[1.05603]
R-squared	0.616855	0.436801	0.876237	0.633134
Adj. R-squared	0.381074	0.090217	0.800076	0.407370
Sum sq. residences	60398.61	1.86E+09	804606.1	22408984
SE equation	68.16192	11953.06	248.7826	1312.923
F-statistic	2.616215	1.260305	11.50499	2.804410
Log likelihood	-118.3111	-231.9820	-146.7944	-183.3899
Akaike AIC	11.57374	21.90745	14.16312	17.48999
Schwarz SC	12/2007	22.35379	14.60946	17.93632
Mean dependent	49.22727	1871.336	501.6045	1671.745
SD dependent	86.64077	12531.70	556.4004	1705.484

4.3. Impulse Response Analysis

Figure 2 visualizes the impulse-response functions used to analyze the short-term and long-term effects of shocks on the system. This approach was used to provide insight into the effects of shocks over time and to better understand the dynamic relationships between the series.

Therefore, it is based on a VAR analysis examining the hydroelectric energy response of Gross Domestic Product over 10 periods. A standard deviation of the hydroelectric energy variable shows the effect of a negative shock in the first period. This reflects the temporary negative effects of fluctuations in energy supply. However, the response quickly returns to equilibrium and converges to zero in the long term. This shows that hydroelectricity has a stable but not permanent effect on growth , and that the economy can adapt to such shocks.

The study's analysis reveals the dynamic responses of Gross Domestic Product to different renewable energy shocks. The overall assessment is that these energy types have different effects on economic growth.

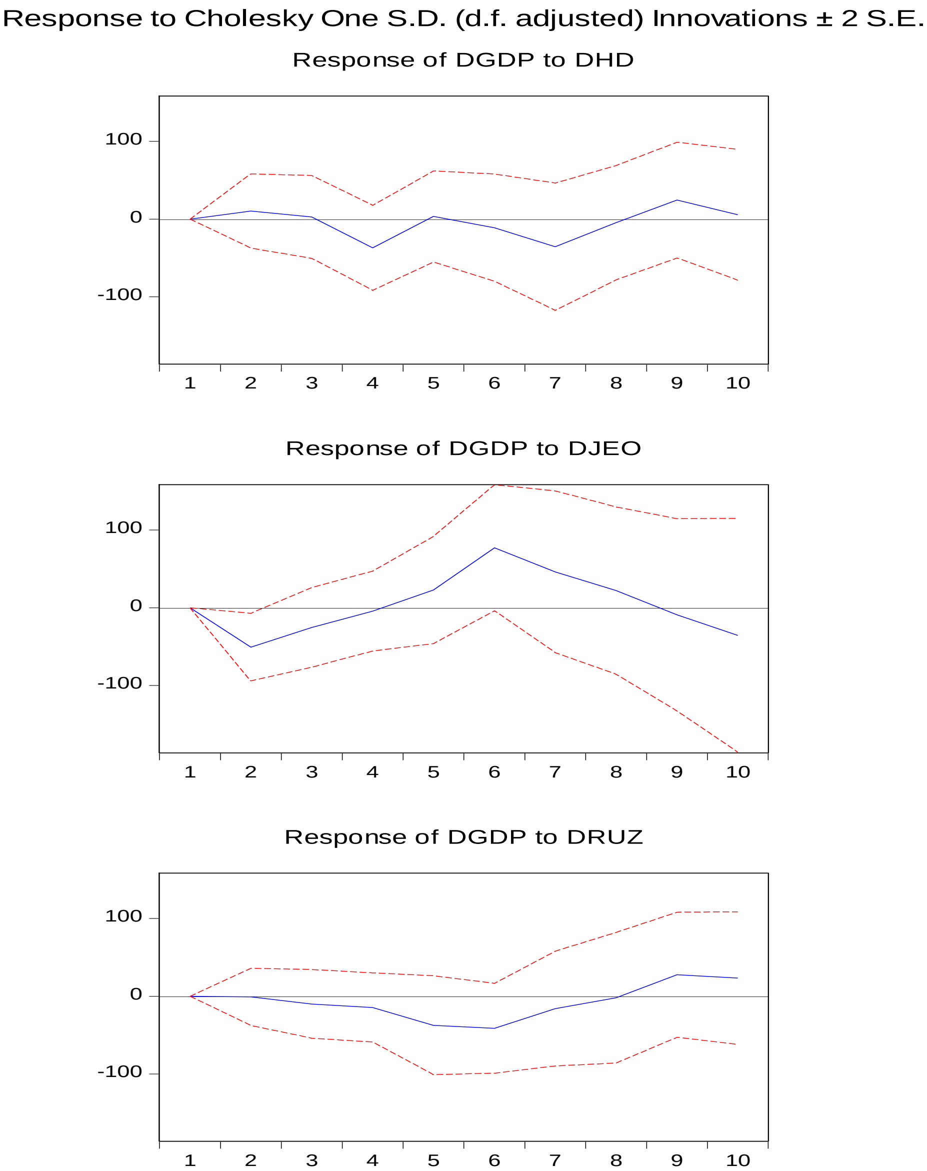

Figure 2: Demonstrating the Effect of a Standard Error Shock Occurring in Direct Renewable Energy Sources on GDP.

The response to a shock in hydroelectric energy initially shows a mild negative impact, indicating that fluctuations in energy supply can lead to short-term temporary contractions. However, this negative effect is not permanent; the economy quickly adapts, the response reaches equilibrium, and it dissipates in the long term. This shows that hydroelectric energy does not have a stable but profound effect on growth.

Geothermal energy, however, has yielded the most remarkable results. A shock in this energy type initially creates significant negative pressure on the economy due to investment costs and adjustment periods. However, this situation quickly reverses, and the response becomes distinctly positive and significant from the third period onwards. This finding clearly demonstrates that geothermal energy investments strongly support economic growth in the medium and long term.

Similarly, no significant or statistically significant impact of wind energy shocks on economic growth has been observed. The response fluctuates around zero, and it appears that the sector does not significantly affect short-term growth dynamics due to its relatively limited share of total energy or its long-term investment character. Consequently, the most important finding that can be drawn for shaping energy policies is the lagged but strong positive impact of geothermal energy. This suggests that geothermal energy, as a domestic and sustainable resource, can play a central role in long-term growth strategies.

Table 7: Variance Decomposition.

Period	SE	DGDP	DHD	DJEO	DRUZ
1	68.98686	100.0000	0.000000	0.000000	0.000000
2	87.56199	65.12594	1.384067	33.47923	0.010763
3	92.17001	59.74152	1.340946	37.74972	1.167813
4	102.8018	52.45734	14.06.19	30.52358	2.957143
5	112.3944	44.96664	11.85469	29.64887	13.52979
6	143.4097	28.60168	7.880798	46.95371	16.56381
7	156.2537	24.93675	11.82037	48.25020	14.99268
8	158.0173	24.54987	11.64329	49.13006	14.67678
9	162.5142	23.21372	13.25768	46.76889	16.75970
10	168.0684	21.71409	12.50321	48.20314	17.57956
11	170.5528	21.27312	12.46077	49.19328	17.07282
12	174.6132	21.08785	12.12444	50.10646	16.68125
13	178.0532	20.47332	12.06176	51.42160	16.04331
14	182.2496	19.54741	11.53248	50.11115	18.80897
15	188.9761	18.24026	10.96937	51.63768	19.15269
16	194.1245	17.55913	12.46101	51.24452	18.73534
17	197.6050	17.14616	12.03484	52.23871	18.58029
18	198.7653	16.97230	12.16053	52.04001	18.82716
19	200.3193	16.72460	11.99248	52.04463	19.23828
20	201.5898	16.56356	12.25689	52.11821	19.06133
21	205.3434	16.27270	12.17794	52.34271	19.20665
22	208.3366	15.90158	11.91966	53.47085	18.70790
23	209.5195	15.74025	11.80405	52.90847	19.54723
24	210.6850	15.56836	11.74897	53.03626	19.64642

According to the variance decomposition results, significant findings are presented in terms of explaining the source of dollar-based fluctuations in Gross Domestic Product (DGDP). Accordingly, only 21.71% of the total variability in DGDP in the 10th period is explained by the internal dynamics of the series itself. This rate indicates that the exogenous energy variables included in the model have a strong effect on DGDP. Indeed, the fact that changes in geothermal energy production (DGDP) explain 48.20% of the DGDP variance reveals that geothermal energy is a dominant determinant of economic growth. The fact that fluctuations in wind energy production (DJEO) affect GDP by 17.57% shows that wind energy also plays a significant and complementary role in economic performance. In contrast, the effect of hydroelectric power production (DRUZ) remains more limited at 12.50%. These results show that among energy sources, geothermal and wind energy make a stronger contribution to explaining macroeconomic fluctuations. Impulse-response functions also support the variance decomposition, showing that a shock in geothermal energy production, in particular, creates an increasingly significant and persistent positive effect on DGDP over time. As the time horizon widens, the explanatory power of geothermal energy production on DGDP reaches 53%, becoming the most dominant exogenous variable. This increase confirms that geothermal energy resources have strategic importance for economic growth in the long term. The impact of wind energy on DGDP also maintains its significance across periods, showing that the economy's response to renewable energy continues consistently. In contrast, the decrease in the self-explanatory power of DGDP over time reveals that economic growth is increasingly determined by renewable energy dynamics.

4.4. Analysis of Model Assumptions

In order to demonstrate that the VAR(3) model estimated in the study is a suitable model, the stability analysis (Figure 3), autocorrelation test (Table 8), heteroskedasticity test (Table 9) and normality distribution test of error terms (Table 10) are given in this section.

In the stationarity analysis of a VAR (Vector Autoregressive) model, the inverse roots of the AR (Autoregressive) characteristic polynomial play a significant role. These roots determine the model's behavior over time and the system's equilibrium. For a VAR model to be stationary, the inverse roots of the AR characteristic polynomial must lie within the unit circle. To evaluate the reliability of the obtained results and to determine whether the model contains a structural problem, several important tests have been applied. These tests include Autocorrelation . test , LM (Lagrange Multiplier) test , White Variable Variance These tests are critical for ensuring the reliability and validity of the VAR model. The inverse roots of the AR characteristic polynomial, the autocorrelation LM test, and the White Heteroskedasticity test are the main methods used to check the stationarity and structural validity of the model.

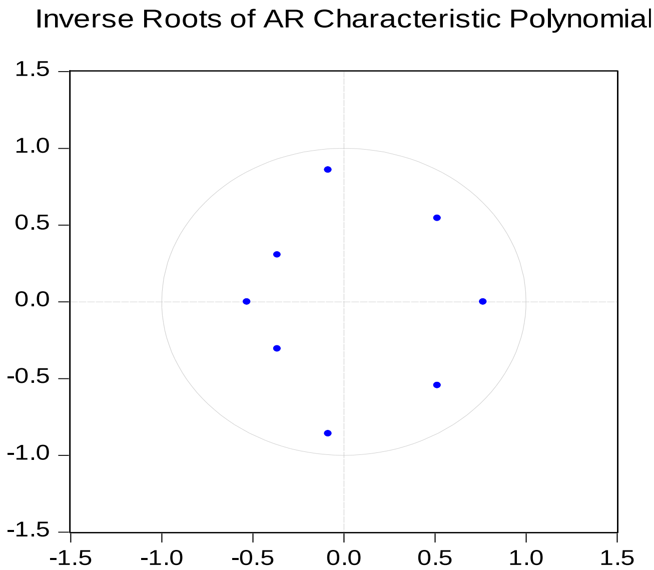

Figure 3: Representation of the Roots of the Characteristic Equation Using the Unit Circle.

The results of these tests provide important information in determining whether the model is working correctly and whether the predictions are reliable. The test results are presented in Table 8.

4.4.1. Autocorrelation

Table 8: Autocorrelation Test.

Lag	LRE* stat	df	Prob.	Rao F-stat	df	Prob.
1	25.51097	16	0.0613	2.277492	(16, 3.7)	0.2351
2	18.89174	16	0.2743	1.119817	(16, 3.7)	0.5160
3	25.44876	16	0.0623	2.262940	(16, 3.7)	0.2370

According to Table 8, the model does not have autocorrelation problems.

4.4.2. Heteroskedasticity

Table 9: Results of Heteroskedasticity Tests.

Test Method	Statistics	Value	Probability
White Test	F-statistic	0.611817	0.7685
	Chi-Square (Obs*R²)	6.774843	0.6605
	Scaled Explained SS	7.259307	0.6101
Breusch-Pagan-Godfrey	F-statistic	0.673952	0.5781
	Obs*R-squared	2.203472	0.5313
	Scaled Explained SS	2.361040	0.5009
Glejser Test	F-statistic	0.580348	0.6347
	Obs*R-squared	1.921943	0.5888
	Scaled Explained SS	2.045152	0.5631

Three different tests of heteroskedasticity (White, Breusch-Pagan-Godfrey and Glejser) According to the test results, the estimated model does not have a heteroskedasticity problem. In other words, the variance of the error terms remains constant for all observations. This finding increases the reliability of the model and indicates that there are no potential problems arising from variability in the variance of the error terms.

4.4.3. Normal Distribution of Error Terms.

Table 10. Normality Distribution Test Results.

Component	Jarque-Bera	df	Prob.
1	14.89109	2	0.0006
2	2 1.774861	2	0.0049
3	23.126480	2	0.0038
4	21.270116	2	0.0003
Joint	18.06255	8	0.0208

Table 10 shows that the error terms are normally distributed.

4.4.4. Granger Causality Test

Short-term relationships were examined using the Granger causality test. This test is a method for analyzing whether one variable has a causal effect on another. It was used to determine the direction of causality between renewable energy sources and economic growth in the short term. Thus, the short-term effects of renewable energy sources on economic growth were revealed in more detail.

Table 11: VAR Granger Causality Test Results.

Dependent Variable	Independent Variable	Chi-sq	df	Prob.
DGDP	DHD	1.7156	3	0.6335
	DJEO	14.6649	3	0.0021
	DRUZ	1.9155	3	0.0590
	All of them	19.6197	9	0.0204
DHD	DGDP	5.6002	3	0.1328
	DJEO	4.4697	3	0.2150
	DRUZ	5.7553	3	0.1241
	All of them	9.4409	9	0.3976
DJEO	DGDP	5.5392	3	0.1363
	DHD	0.5901	3	0.8987
	DRUZ	9.6672	3	0.0216
	All of them	14.9128	9	0.0934
DRUZ	DGDP	2.6045	3	0.4567
	DHD	5.6131	3	0.1320
	DJEO	2.1754	3	0.5368
	All	10.6387	9	0.3013

According to the Granger causality test results, a unidirectional causal relationship was found between the ratio of Gross Domestic Product DGDP to hydraulic and geothermal energy DJOE. Furthermore, it is emphasized that no causal relationship was found between DGDP and wind energy DRUZ.

5. CONCLUSION

This study analyzes the effects of renewable energy sources on sustainable economic growth in Turkey using data from the 2000-2024 period. When the VAR model, impulse response functions, and variance decomposition results are evaluated together, it is seen that renewable energy types affect economic growth at different levels.

Geothermal energy stands out as the renewable energy type with the strongest and most lasting effect on economic growth. This result is consistent with geothermal energy's high capacity factor, its nature as a domestic resource, and its role in providing economic stability. While hydroelectric energy creates a negative effect in the short term, it quickly returns to equilibrium and does not show a significant lasting effect on economic growth in the long term. The effect of wind energy is limited and is not a strong determinant of economic growth. The variance decomposition findings revealed that a significant portion of the change in DGDP is explained by fluctuations, particularly in geothermal energy production. This result indicates that geothermal resources should have a priority position in Turkey's energy investments. Overall, the study reveals that investments in renewable energy contribute to sustainable economic growth, but this effect varies depending on the type of energy. For policymakers, the findings include:

Improving the quality of education and developing vocational programs to enhance human capital, increase the efficiency of human resources, and boost productivity across various sectors, thereby meeting labor market demands and strengthening competitiveness. The study highlights the need to improve sustainable development indicators, given their direct roles in supporting economic growth and positively contributing to DGDP growth. It also emphasizes the importance of adopting effective environmental policies aimed at reducing harmful emissions and conserving natural resources; ensuring the achievement of sustainable development goals in the countries studied and striking a balance between economic growth and environmental sustainability.

The most important policy is to establish innovative economic projects with the capacity for production and sustainable growth without harming the environment or contributing to climate change, by promoting green investment, supporting sustainable trade, and using resources efficiently. Adopting modern industrial technologies with high production efficiency, establishing advanced infrastructure, and promoting a transition to circular production based on recycling and waste reduction contributes to a shift towards a more sustainable and innovative development model.

Furthermore, the adoption of modern industrial technologies that provide high production efficiency will enhance economic performance by strengthening energy savings and resource optimization. In this context, greater integration of renewable energy sources into production processes is critical for a low-carbon economy. Simultaneously, promoting a transition to a circular economy model based on waste reduction and recycling supports both the reduction of the environmental burden and the sustainable use of resources, while also lowering costs and creating new employment opportunities.

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