

Unraveling the impact of non-renewable energy, green innovation and institutional quality on economic welfare in Türkiye

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Abstract

Purpose – This study examines the impact of non-renewable energy consumption, green innovation and institutional quality on economic welfare in Türkiye, using data from 1990 to 2021.

Design/methodology/approach – The dynamic autoregressive distributed lag (DARDL) model is employed for the analysis. Additionally, the frequency domain causality (FDC) is used to assess the direction of causality and check the robustness of the study. Economic welfare is measured using principal component analysis (PCA).

Findings – The results indicate that non-renewable energy positively affects economic welfare in the short run and long run, although only the long-run effect is statistically significant. Similarly, green innovation significantly promotes economic welfare in the long run, but its short-run impact is statistically insignificant. Conversely, institutional quality has a detrimental effect on economic welfare, exhibiting a negative and significant impact in the short and long run. The FDC test results reveal that all variables Granger-cause economic welfare, with a unidirectional causality between non-renewable energy, institutional quality and economic welfare. However, a bidirectional causal relationship exists between green innovation and economic welfare.

Practical implications – The study provides policymakers with insights into balancing energy use, green innovation and institutional quality for sustainable welfare. Accordingly, policymakers in Türkiye should prioritize green patents. In addition, reducing the permit-process time for renewable energy projects is imperative to incentivize investors, while ensuring institutional reforms are aligned with sound macroeconomic policies for sustainable welfare.

Originality/value – This is the first study to simultaneously analyze the effect of non-renewable energy, green innovation and institutional quality on economic welfare in Türkiye.

Keywords Non-renewable energy, Green innovation, Institutional quality, Economic welfare, Türkiye

Paper type Research article

1. Introduction

The sustainable development goals (SDGs) aim to eradicate poverty and protect the environment by 2030, ensuring greater economic welfare for peace and prosperity (UNDP, 2024a, b). Achieving these goals requires a more comprehensive understanding of economic welfare that extends beyond traditional economic indicators. While GDP has long been used as the primary measure of economic welfare, its flaws in capturing overall well-being and social progress are increasingly recognized (Fitoussi *et al.*, 2011; Reinsdorf, 2020). In response to these limitations, some scholars argue that economic welfare should go beyond GDP to include non-market activities like leisure, human capital development and digital engagement (Nordhaus, 2000; Suliswanto, 2024). The OECD (2011) further integrates income, health,

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education, political voice and environmental factors as vital components of economic welfare. Thus, a comprehensive assessment of economic welfare in countries requires multidimensional indicators.

The dynamics between energy consumption, green innovation and institutions are central to economic growth, employment and overall economic welfare. However, the relationship between these factors and economic welfare varies between industrialized and developing nations. Developing countries often grapple with weak institutions and rely heavily on non-renewable energy to meet industrial demand and drive growth, leading to environmental issues. In contrast, developed countries are more likely to embrace green innovation and stronger institutions, having transitioned into knowledge-driven economies. [JinRu and Qamruzzaman \(2022\)](#) affirm that institutional quality and green innovation positively influence environmental sustainability and ecological balance in G7 countries. For emerging countries like Türkiye, where industrialization continues to be a key driver of growth, balancing energy use, green innovation and institutional quality is vital for achieving sustainable economic welfare.

Energy is considered the lifeline of the contemporary economy and is crucial for basic needs such as healthcare, food, education and work ([World Bank, 2024a, b](#)). In Türkiye, it drives industrialization and significantly impacts economic outputs and livelihoods. In 2023, Türkiye’s industrial sector accounted for 28.4% of GDP ([World Bank, 2024a, b](#)) and is characterized by high material demand. The [IEA \(2024\)](#) reports that Türkiye’s rapid economic and demographic growth over the past 2 decades has led to a sharp rise in energy demand. For instance, electricity consumption per capita in Türkiye increased by 117% between 2000 and 2023 ([IEA, 2024](#)). However, non-renewable energy sources, such as fossil fuels, dominate the energy mix, accounting for 81.6% of total consumption ([IEA, 2024](#)). The country’s economic dependence on imported fossil fuels, particularly oil and gas, increases its energy security risks and exacerbates its material footprint and environmental degradation. In response, Türkiye has been diversifying its energy mix, investing in green technologies to reduce environmental impact and meet international standards.

Green innovation improves resource efficiency by introducing new organizational strategies, technologies and processes that maximize resource utilization across industries ([Sun et al., 2023](#)). For example, advancements in solar panels and wind turbines exemplify how green innovation enhances renewable energy technologies, improving efficiency and sustainability. Reflecting this global shift, Türkiye has significantly invested in renewable energy. Between 2019 and 2023, the country invested USD24 billion toward achieving its sustainable energy efficiency targets ([Bloomberg Finance, 2024](#)). While progress has been made in renewable energy adoption, non-renewable sources still accounted for 57.87% of Türkiye’s electricity generation in 2023 ([Figure 1](#)), underscoring the ongoing need for further

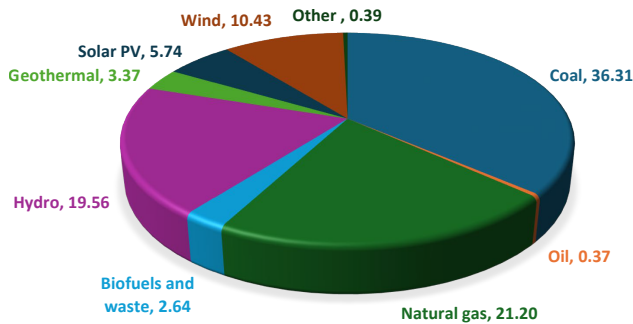


Figure 1. Electricity generation mix 2023 (%). Source(s): Authors’ computation based on data from [IEA \(2024\)](#)

expansion of green energy. Green energy is essential for sustainable development and advancing the United Nations' SDGs, particularly SDG 7 on Affordable and Clean Energy (Wang *et al.*, 2022). To advance its sustainable development goals, Türkiye aims to accelerate its transition to clean energy by increasing green energy investment to USD 80 billion by 2035 (Anadolu Agency, 2024).

Institutional dynamics are crucial in shaping energy policies and influencing economic welfare by affecting investment, governance and regulatory stability. Empirical studies on EU countries and candidates indicate that institutional quality improves economic performance, with government effectiveness and accountability playing key roles (Eurofound, 2022). However, Türkiye's economic trajectory presents a different picture. Acemoglu and Üçer (2020) argued that Türkiye's economic growth since 2007 has been of low quality, marked by minimal productivity growth and limited technological upgrading, owing to weakening economic and political institutions. Table 1 presents Türkiye's governance scores based on the World Bank's Worldwide Governance Indicators (WGIs), where values range from -2.5 (weak institutions) to $+2.5$ (high institutions). The data indicate that, on average, Türkiye scored low in five governance dimensions between 2015 and 2021, except for regulatory quality, which recorded a positive value of 0.05. These data suggest that most institutions are weak, posing challenges to Türkiye's economic development.

Against this background, it is vital to understand how non-renewable energy use, green innovation and institutional quality impact sustainable economic welfare in Türkiye. A thorough examination of these factors' short- and long-term effects on economic welfare can provide policymakers with informed strategies for sustainable development. While previous studies have explored the impact of some of these factors on economic or green growth in Türkiye (Pata and Terzi, 2017; Kechagia and Metaxas, 2020; Naimoğlu *et al.*, 2025), to the best of our knowledge, no single study has simultaneously analyzed the effect of non-renewable energy, green innovation and institutional quality on the economic welfare index, while accounting for key variables such as inflation and foreign direct investment in Türkiye. Our study also fills this gap by providing a more comprehensive perspective integrating key economic welfare determinants beyond the gross domestic product (GDP)-based assessment. Furthermore, we employ innovative methodological approaches, including dynamic autoregressive distributed lag (DARDL) and the frequency domain causality (FDC), to examine these interconnections. This is the first study to apply these advanced techniques to this topic, offering a more nuanced and rigorous analysis.

The remainder of the paper is organized as follows: Section 2 reviews the theoretical and empirical literature. Sections 3 and 4 present the materials, methodology, report the results and discuss them. Finally, Section 5 concludes with policy implications and directions for future research.

Table 1. Worldwide governance indicators for Türkiye (2015–2021)

Year	Voice and accountability	Political stability	Government effectiveness	Regulatory quality	Rule of law	Control of corruption
2015	-0.37	-1.50	0.20	0.27	-0.23	-0.16
2016	-0.61	-2.01	-0.01	0.19	-0.34	-0.20
2017	-0.71	-1.79	0.01	0.04	-0.32	-0.21
2018	-0.85	-1.32	-0.07	0.02	-0.39	-0.35
2019	-0.83	-1.38	-0.02	-0.02	-0.35	-0.33
2020	-0.86	-1.14	-0.16	-0.02	-0.42	-0.36
2021	-0.86	-1.14	-0.12	-0.10	-0.43	-0.41

Source(s): Authors' computation based on World Bank Data (2024a, b)

2. Theoretical and empirical literature review

2.1 Theoretical review

Energy plays a pivotal role in economic development, with various theoretical perspectives that analyze its impacts on growth and welfare. The energy-led growth hypothesis (ELGH) posits that energy use is a fundamental driver of economic growth and welfare, serving as a key input for industrialization and production (Stern, 2004). In many developing economies, coal, oil and natural gas remain essential for economic expansion. The theory further asserts that energy scarcity constrains economic growth, though this constraint diminishes as energy becomes more abundant (Stern, 2011). Although non-renewable energy has traditionally driven economic growth, the role of renewable energy varies across countries (Fareed and Pata, 2022). However, excessive reliance on non-renewable energy can undermine long-term economic welfare because of environmental and economic costs (Le et al., 2020; Gradinarii et al., 2023). As many emerging countries transition to green energy, ELGH remains a useful lens for analyzing energy consumption and its relationship to economic welfare.

Another foundational theoretical framework relevant to this study is Romer's (1990) endogenous growth theory, which emphasizes technology transfer and human capital as key drivers of long-term economic growth. The theory has been extended to incorporate green innovation, research and development (R&D) and environmental concerns, highlighting how technological progress can foster cleaner energy solutions without sacrificing economic growth (Acemoglu et al., 2023). This theoretical framework aligns with green innovation policies, which promote the deployment of renewable energy and clean technologies to enhance economic welfare by lowering environmental costs and improving energy efficiency. It underscores the importance of innovation, particularly in knowledge production, which is often considered cleaner than the production of material goods (Chen and Sun, 2018). While the theory offers valuable insights into regional growth patterns, it also faces criticism, particularly in accounting for empirical realities in developing countries (Wijayanto, 2019). Despite these criticisms, the theory remains central to the case of continued investment in innovation to achieve long-term welfare.

North's (1990) institutional economics theory holds that strong institutions are essential for economic development. North (1990) defines institutions as the formal and informal rules that govern human interaction, shaping social, economic and political incentives. Institutions establish the environment within which economic activities occur, influencing government policies and household decisions that shape sustained economic well-being. High institutional quality boosts total factor productivity and firm value, with political and governance effectiveness playing vital roles in promoting technological progress and long-term economic welfare (Chang, 2023). Conversely, weak institutions hinder innovation, undermine property rights, erode investors' confidence, restrict remittance flows, limit economic freedom and raise the cost of capital for development (Alquist et al., 2022; Mohammed and Karagöl, 2023). The theory provides a framework for understanding how institutional quality shapes economic welfare, emphasizing the importance of strong institutions in fostering sustainable development.

2.2 Empirical literature review

2.2.1 Economic welfare and non-renewable energy consumption. Existing studies have predominantly examined the relationship between energy consumption and economic growth rather than economic welfare. For instance, Rahman and Velayutham (2020) analyzed the effects of renewable and non-renewable energy use on economic growth in five South Asian countries from 1990 to 2014, finding that non-renewable energy raised economic growth by 0.10%. Similarly, Ali et al. (2024) used a DARDL model and revealed that non-renewable energy supports both short- and long-term economic growth in Canada. However, the assumption that non-renewable energy always promotes economic growth has been contested. Some scholars argued that while energy is a critical input for production, over-reliance on

fossil fuels generates environmental challenges (Jeon, 2022). Evidence has suggested that non-renewable energy use may undermine long-term sustainability by increasing pollution and climate-related risks (Chaudhry *et al.*, 2021; Saliminezhad *et al.*, 2024). These concerns have shifted attention toward measures of economic welfare that encompass broader well-being.

Unlike the energy-growth literature, studies exploring energy use and economic welfare are limited. Azami and Almasi (2020) examined energy consumption and sustainable economic welfare in energy-exporting countries using the Index of Sustainable Economic Welfare (ISEW). Their results showed a positive long-term relationship, with unidirectional causality from economic welfare to energy consumption, suggesting that improved welfare levels drove energy demand. Similarly, Menegaki and Tugcu (2018) applied ISEW in selected Asian countries and found a bidirectional relationship, implying that economic welfare and energy reinforced each other. Further empirical contribution came from Subhan *et al.* (2024), who applied a DARDL model to investigate the impact of energy on economic welfare in India, constructing an index with seven variables. Their findings confirmed that non-renewable energy use significantly affected economic welfare, though the short-run impact was insignificant.

Some studies also used GDP or income per capita as a proxy for economic welfare. For instance, Noorani *et al.* (2022) found that non-renewable energy positively impacts economic welfare in Iran using a traditional ARDL and cointegration approach. Similarly, Olubiyi (2020) confirmed unidirectional causality from coal and fuel to per capita income as a measure of well-being. These outcomes underline the need for a multidimensional approach to measuring economic welfare rather than relying solely on GDP-based indicators.

The existing studies primarily focus on the energy-growth nexus, yielding mixed results. This study aims to expand the literature by examining the energy-welfare nexus in the context of Türkiye, an area that remains relatively unexplored.

2.2.2 Economic welfare and green innovation. Green innovation (GI) creates public environmental benefits, drives industrial transformation and enhances productivity, making it vital for long-term economic growth (Li *et al.*, 2024). Guo *et al.* (2024) argued that GI capabilities, including exploitative and exploratory innovations, can drive high-quality economic growth while tackling environmental concerns.

Empirical studies have examined the impact of GI on economic welfare, primarily focusing on environmental performance or economic growth. For example, using meta-analysis, Rahmani *et al.* (2024) established that green product and process innovations positively affect ecological performance. Similar conclusions were reported by Hu *et al.* (2022) and Gao and Li (2021), reinforcing the positive link between GI and environmental sustainability. Sun *et al.* (2023) also found that GI significantly improves resource efficiency and economic growth. Supporting this, Zhou *et al.* (2024) integrated the Schumpeterian endogenous growth model and found that GI fosters strong economic expansion and environmental protection, a conclusion also echoed by Chen *et al.* (2023) and Guo *et al.* (2024).

While most studies indicate that GI contributes to economic development, its effect may depend on institutional roles. Wang (2023) argued that institutions supporting environmental regulations, specifically market-driven incentives, can effectively encourage businesses to adopt GI, thereby promoting growth. Equally, Li *et al.* (2021) found that addressing GI-related institutional constraints can significantly impact China's economic development at the regional and national levels. Qamruzzaman and Karim (2024) analyzed the determinants of green growth in OECD countries, emphasizing the role of environmental innovation and political stability, among other variables. Their study confirmed that environmental innovation positively impacts green growth, while political stability fosters investor confidence, long-term sustainable development and effective green strategies.

Conversely, certain studies highlight the limitations of GI. Li *et al.* (2024) observed that GI significantly reduced green economic efficiency among enterprises in China, suggesting a potential trade-off. Similarly, Wang *et al.* (2025) detected a bidirectional relationship between

economic growth and GI in China, where GI negatively impacted economic growth. These outcomes suggest a complex and context-dependent relationship between GI and EW. Our study provides a more nuanced understanding of the green innovation–welfare nexus by employing a holistic welfare measure.

2.2.3 Economic welfare and institutional quality. Strong institutions are vital in addressing market failures, reducing transaction costs and fostering both environmental and economic growth. They also facilitate GI by providing financial support, shaping supportive policies and promoting collaboration between research and businesses (Li and Li, 2021). Empirical studies have explored the effect of institutional quality on EW, although many rely on GDP or GDP per capita as a proxy for welfare. For instance, Kunawotor *et al.* (2024) examined the effect of institutional quality on economic welfare in Africa, using GDP per capita as a proxy for welfare. The findings indicated that institutions positively affect economic welfare. Similarly, Şentürk and Ali (2022) investigated the institution–welfare nexus in BRIC-T countries using the Panel – seemingly unrelated regressions (SUR) method and proxied welfare with GDP. They confirmed a positive relationship between institutional quality and welfare, particularly in Türkiye. Other studies have focused on economic growth. For example, Azam *et al.* (2023) showed that institutional quality positively impacts sustainable development, particularly in lower-middle-income countries. Parsa and Datta (2023) further confirmed the positive impact and unidirectional causality from institutions to economic growth in middle-income countries, with the gains increasing as institutions improve. Additionally, high institutional quality fosters green growth and sustainable development, while weak institutions hinder these outcomes (Qamruzzaman and Karim, 2024; Kafka, 2024).

While much of the literature shows evidence of the positive effect of strong institutions, some studies suggest that institutional quality does not always result in positive outcomes. For instance, Beyene (2024) found that corruption control and government effectiveness had a negative association with economic growth in 22 sub-Saharan African (SSA) countries. Narita and Sudo (2021) similarly demonstrated that democracy, as a measure of institutional quality, negatively affected economic growth during 2001–2020 across five instrumental-variable strategies. Furthermore, institutional weakness can significantly hinder economic performance. Fomba *et al.* (2023) found that corruption and weak governance reduced education quality and the effectiveness of public spending, limiting human capital development. Similar results were reported by Jungo (2024).

In short, the literature shows mixed results, and most studies fail to employ a broader measurement of economic welfare in their analyses. This calls for a more holistic welfare-institutional framework analysis, which our study seeks to provide.

3. Material and methodology

3.1 Variables definition and data sources

The analysis uses annual time-series data for Türkiye from 1990 to 2021. Economic welfare (EW) refers to the overall standard of living or level of prosperity of individuals or society at a given time. The variables used in our computation of EW include the human development index (HDI) (sourced from UNDP), GDP, life expectancy at birth (in years), carbon dioxide emissions (CO₂) and household final consumption expenditure, all sourced from the World Bank. We constructed the EW index (Table 2) using principal component analysis (PCA) to reduce dimensionality.

The PCA transforms correlated variables into uncorrelated principal components, with the first few components capturing the most information in the data (Weaving *et al.*, 2019). The first principal component forms the index because it explains the largest share of variance. PC1 explains 96.45% of the variation and has an eigenvalue of 5.7 (Table 3). Given this outcome, we conclude that a single factor dominates the EW measure employed in our study.

Our independent variables (Table 2) include non-renewable energy (NRE), derived from gas, oil and coal, and measured as final energy consumption (sourced from OECD). Green

Table 2. Variables, measurements and sources

Variables	Measurements	Sources
<i>Dependent variable</i>		
Economic welfare	Index	PCA
<i>Independent variables</i>		
Non-renewable energy	Million toe	OECD (2024)
Green innovation	Environmental technologies (% of total)	OECD (2024)
Institutional quality	Economic Freedom Index	Fraser Institute (2024)
<i>Control variables</i>		
Inflation	Consumer prices (annual %)	World Bank (2024a, b)
Foreign direct investment	Net inflow (% of GDP)	World Bank (2024a, b)
Source(s): Authors' computation		

Table 3. Correlation matrix of the eigenvalues

	Eigenvalue	Variance (%)	Cumulative (%)
1	5.78695	96.45	96.45
2	0.161978	2.7	99.15
3	0.0303508	0.15	99.65
4	0.0103127	0.17	99.83
5	0.00721047	0.12	99.95
6	0.00319616	0.05	100
Source(s): Authors' computation			

innovation (GI) comprises innovations in products, services, or processes that reduce environmental harm while optimizing the use of natural resources. GI is measured as environment-related technologies (% of total; sourced from OECD). Institutional quality (INS) is proxied by the Fraser Institute's Economic Freedom Index, which evaluates government size; legal system and property rights; sound money; freedom to trade internationally; credit markets; and labor and business regulation.

The control variables (Table 2) include inflation (INF), sourced from the World Bank and measured as the annual percent change in the consumer price index (CPI). Foreign direct investment (FDI) net inflows, defined as the sum of equity capital, reinvested earnings, other long-term capital and short-term capital in the balance of payments, are measured as a percentage of GDP (sourced from the World Bank).

3.2 Model specification

This study uses the Dynamic ARDL (DARDL) approach by Jordan and Philips (2018) to investigate the effect of NRE, GI and INS on EW. Unlike the traditional ARDL models (Pesaran *et al.*, 2001), which analyze short and long-run relationships but do not directly model asymmetric shocks, the DARDL simulates counterfactual shocks while holding other parameters constant. This method also assesses whether shocks to the regressors have positive or negative effects on the dependent variable and provides a visual analysis of potential shocks, *ceteris paribus* (Sarkodie and Owusu, 2020). The DARDL offers advantages over methods like 2SLS and system GMM because it can test cointegration and both short- and long-run relationships without relying on strong instruments. However, it does not inherently account for nonlinearity or threshold effects. Figure 2 provides a schematic representation of the test procedures.

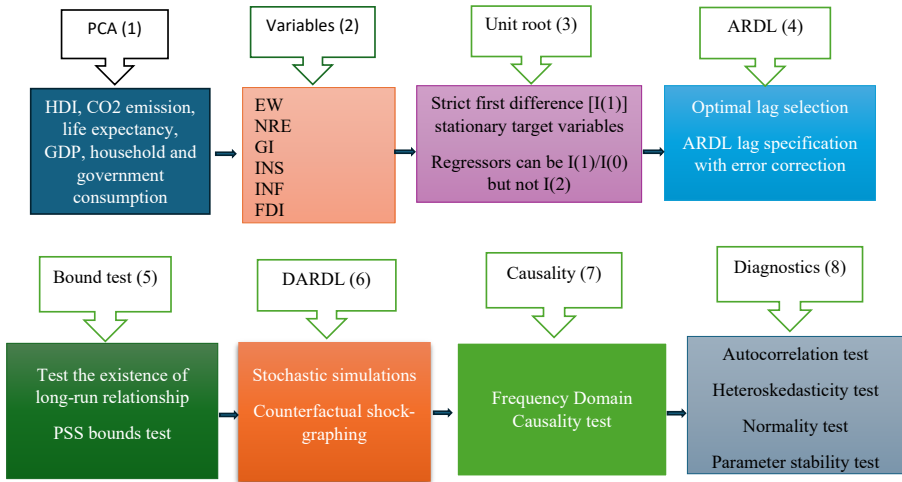


Figure 2. Graphical illustration of the test processes. Source(s): Authors’ computation

To examine the correlations between the parameters studied, the following general equation is used:

$$EW = f (NRE, GI, INS, INF, FDI) \tag{1}$$

EW denotes economic welfare, NRE represents non-renewable energy, GI indicates green innovation, INS is institutional quality, INF denotes inflation and FDI represents foreign direct investment. Equation (2) shows a transformation of Equation (1) to derive direct elasticities and is expressed as:

$$EW = \alpha_0 + \beta_1 NRE_t + \beta_2 GI_t + \beta_3 INS_t + \beta_4 INF_t + \beta_5 FDI_t + \mu_t \tag{2}$$

Here, t denotes time, α_0 is the constant; $\beta_1 - \beta_5$ represent the coefficients; and μ_t depicts the error term.

3.3 Stationarity test

Before running the DARDL simulations, we conduct unit root tests to determine the order of integration and avoid spurious regression. The DARDL technique requires the dependent variable to be strictly I(1) (i.e. stationary in first differences) (Jordan and Philips, 2018). To ensure that no variables are I(2), we use the Augmented Dickey-Fuller (ADF) and the Phillips-Perron (PP) tests. The null hypothesis posits a unit root, while the alternative indicates stationarity. Since structural breaks can bias traditional unit root tests and lead to inaccurate results, we apply the Zivot and Andrews (1992) test. Çamalan et al. (2024) identified the ZA test as one of the most effective for detecting single breaks in stationary series, thereby enhancing economic interpretation, model specification and forecasting.

3.4 PSS bound test

After fulfilling the strict I(1) requirement for the dependent variable in first differences, we apply the modified Pesaran–Shin–Smith (PSS) bounds test to analyze cointegration dynamics. We present the ARDL bounds model in the following form:

$$\begin{aligned} \Delta EW_t = & \alpha_0 + \alpha_1 EW_{t-i} + \alpha_2 NRE_{t-i} + \alpha_3 GI_{t-i} + \alpha_4 INS_{t-i} + \alpha_5 INF_{t-i} + \alpha_6 FDI_{t-i} \\ & + \sum_{i=1}^m \beta_1 \Delta EW_{t-i} + \sum_{i=1}^m \beta_2 \Delta NRE_{t-i} + \sum_{i=1}^m \beta_3 \Delta GI_{t-i} + \sum_{i=1}^m \beta_4 \Delta INS_{t-i} \\ & + \sum_{i=1}^m \beta_5 \Delta INF_{t-i} + \sum_{i=1}^m \beta_6 \Delta FDI_{t-i} + \mu_t \end{aligned} \quad (3)$$

where Δ denotes the first difference of EW, NRE, GI, INS, INF and FDI, and μ_t is the white noise term. The selected lag lengths are denoted by $t - i$ and α and β are the coefficients to be estimated for the long run and short run, respectively. If the variables exhibit a long-run relationship, we construct an ARDL model approximation for the short and long runs. The hypotheses for the bounds test, the H_0 and H_1 are as follows:

($H_0 = \alpha_1 = \alpha_2 = \alpha_3 = \alpha_4 = \alpha_5 = \alpha_6 = 0$) against the alternative hypothesis

$$(H_1 \neq \alpha_1 \neq \alpha_2 \neq \alpha_3 \neq \alpha_4 \neq \alpha_5 \neq \alpha_6 \neq 0)$$

The computed F-statistic determines whether to accept or reject the null hypothesis. If the F-statistic exceeds the upper critical bound, the null hypothesis is rejected, indicating that the variables are cointegrated. The test result is inconclusive if the F-statistic falls between the lower and upper critical bounds. If it falls below the lower critical bound, we accept the null hypothesis, concluding that no cointegration exists among the variables. The ARDL bounds test results suggest the presence of cointegration.

The long-run ARDL model is as follows:

$$\begin{aligned} EW_{t-1} = & \rho_0 + \sum_{i=1}^m \gamma_1 EW_{t-i} + \sum_{i=1}^m \gamma_2 NRE_{t-i} + \sum_{i=1}^m \gamma_3 GI_{t-i} + \sum_{i=1}^m \gamma_4 INS_{t-i} \\ & + \sum_{i=1}^m \gamma_5 INF_{t-i} + \sum_{i=1}^m \gamma_6 FDI_{t-i} + \mu_t \end{aligned} \quad (4)$$

The long-run coefficients of the variables are represented by γ in Equation (4). The error correction model for the short-run ARDL model is presented as follows:

$$\begin{aligned} \Delta EW_{t-1} = & \rho_0 + \sum_{i=1}^m \theta_1 \Delta EW_{t-i} + \sum_{i=1}^m \theta_2 \Delta NRE_{t-i} + \sum_{i=1}^m \theta_3 \Delta GI_{t-i} + \sum_{i=1}^m \theta_4 \Delta INS_{t-i} \\ & + \sum_{i=1}^m \theta_5 \Delta INF_{t-i} + \sum_{i=1}^m \theta_6 \Delta FDI_{t-i} + \text{ECT}_{t-1} + \mu_t \end{aligned} \quad (5)$$

In Eq. (5), θ represents the short-run coefficients of the parameters, while the error-correction term (ECT) captures the speed of adjustment for imbalances. The model's reliability is assessed through several diagnostic tests: the Breusch–Godfrey test for serial correlation, the Autoregressive Conditional Heteroskedasticity (ARCH) and Breusch–Pagan–Godfrey tests for heteroscedasticity, the Ramsey RESET (Regression Specification Error Test) for specification accuracy and the Jarque–Bera test for normality of residuals. Structural stability is evaluated using the ordinary least square (OLS) cumulative sum of recursive residuals (CUSUM) plot for parameter stability.

3.5 Dynamic autoregressive distributed lag simulations

This study uses the novel DARDL model. This model evaluates shocks to a single regressor at a time to compute and forecast the dependent variable, holding other variables constant, and

employs an error correction term to simulate the parameter vector. We present the baseline framework as follows:

$$\begin{aligned} \Delta EW_t = & \alpha_0 + \varphi_0 EW_{t-1} + \tau_1 \Delta NRE_t + \varphi_1 NRE_{t-1} + \tau_2 \Delta GI_t + \varphi_2 GI_{t-1} + \tau_3 \Delta INS_t \\ & + \varphi_3 INS_{t-1} + \tau_4 \Delta INF_t + \varphi_4 INF_{t-2} + \tau_5 \Delta FDI_t + \varphi_5 FDI_{t-1} + \varnothing ECT_{t-1} + \mu_t \end{aligned} \tag{6}$$

In Equation (6), the difference operator (Δ) captures the short-term dynamic relationship, while the intercept term α_0 represents the constant, indicating the starting point of this relationship. The long-term coefficients are denoted by $(\varphi_1, \varphi_2, \varphi_3, \varphi_4, \varphi_5)$ and the short-term coefficients are denoted by $(\tau_1, \tau_2, \tau_3, \tau_4, \tau_5)$. The white noise error term μ_t captures random fluctuations in the model.

3.6 Frequency domain causality test

We analyze the causality using the FDC test to assess the robustness and stability of the model. The FDC evaluates the time series fluctuations and the statistical significance of each frequency, offering an alternative to the traditional Granger causality test (Breitung and Candelon, 2006). Unlike methods such as the Kernel Regularized Least Squares (KRLS), which provide only overall measures, FDC captures dynamic causal structures across short-, medium- and long-term horizons. It also detects causal shifts due to structural breaks or cyclical patterns that time-domain methods like DARDL may overlook, offering a more nuanced analysis (Shadaydeh et al., 2018). The test is illustrated as follows:

$$x_t = \theta_t X_{t-1} + \dots + \theta_\delta X_{t-\delta} + \rho_1 Y_{t-1} + \dots + \rho_\delta Y_{t-\delta} + \mu_t \tag{7}$$

The linear restriction in Equation (7) is equivalent to $H_0 = M_{Y \rightarrow X} \omega = 0$. However, θ and ρ are the parameters to be estimated; δ denotes the lag order; and μ_t is the error term.

4. Empirical results and discussions

4.1 Summary statistics

Table 4 presents summary statistics, including the mean, maximum, minimum and standard deviations. The ranges for EW, NRE, GI, INS, INF and FDI indicate the sample’s diversity. NRE has the highest mean value (82.05), followed by INF (35.32). The standard deviations show that INF has the highest dispersion, followed by NRE. Skewness statistics describe the shape of the distributions, and all variables are right-skewed. According to the kurtosis statistics, each variable has a platykurtic (lower peak and short-tailed) distribution. Overall, these moments suggest non-normality but no extreme tail risk.

Table 4. Description and summary statistics of variables

Variable	Mean	Stat dv	min	max	Skewness	Kurtosis
Economic Welfare	-5.94e-	1.00	-1.2	1.96	0.142	0.159
Non-renewable energy	82.05	29.26	41.0	133.58	0.579	0.004
Green innovation	8.09	2.96	5.11	7.08	0.00	0.00
Institutions quality	6.22	0.67	5.1	7.08	0.393	0.018
Inflation	35.32	32.16	6.3	105.21	0.085	0.049
Foreign direct investment	1.22	0.86	0.31	3.62	0.086	0.195
Observations	32	32	32	32	32	32

Source(s): Authors’ computation

Table 5. Unit root analysis

Variables	Phillips–Perron (PP)	Augmented Dickey–fuller (ADF)	Z. Andrews Structural break	Breaking year
<i>Level</i>				
EW	3.839	0.377	−2.774	2005
NRE	0.868	0.930	−3.908	2003
GI	−5.517***	−5.485***	−5.734***	1996
INS	−1.668	−1.689	−3.078	2013
INF	−1.038	−0.991	−3.214	2007
FDI	−2.175	−2.203	−3.271	2007
<i>First difference</i>				
ΔEW	−3.915**	−3.870**	−5.519***	2016
ΔNRE	−5.216***	−5.147***	−5.262***	2008
ΔGI	−10.371***	−8.194***	−6.942***	1999
ΔINS	−4.405***	−4.385***	−5.448***	2009
ΔINF	−5.355***	−5.352***	−6.782***	2000
ΔFDI	−5.072***	−5.060***	−4.487**	2006

Note(s): *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$ indicate significance at 1%, 5 and 10% respectively
Source(s): Authors' computation

4.2 Order of integration of the respective variables

Following the descriptive statistics, we examine the variables' unit root properties using three stationarity tests: ADF, PP and Zivot–Andrews. As shown in Table 5, the PP, ADF and Zivot–Andrews tests indicate that all variables (EW, NRE, GI, INS, INF and FDI) are stationary at the first difference, $I(1)$. Furthermore, GI is stationary at level $I(0)$ across all tests. The results indicate that none of the variables are integrated of order $I(2)$; they are either $I(0)$ or $I(1)$. This confirms that all variables meet the stationarity requirements for the DARDL framework.

4.3 Lag length selection results

Determining lag length is key in autoregressive models to capture dynamics and address serial correlation. Standard criteria like LR, AIC, HQIC, SIC and FPE guide this selection. As shown in Table 6, while most criteria suggest a lag of 3, FPE-yielding the lowest value-points to a lag of 4, which we adopt as the optimal choice for our analysis.

4.4 PSS bounds testing in ARDL

The Pesaran–Shin–Smith (PSS) bounds test is significant at the 5% level (Table 7). Based on the F -statistic of 5.015 and associated p -values, we conclude that the variables are cointegrated and exhibit a long-run relationship.

Table 6. Lag length selection results

Lags	LL	LR	FPE	AIC	HQIC	SIC
0	−337.741		1855.4	24.5529	24.6402	24.8384
1	−193.512	288.46	0.8693	16.8223	17.4332	18.8206
2	−144.495	98.035	0.51014	15.8925	17.027	19.6036
3	−61.822	165.34*	0.0676	12.5588*	14.2169*	17.9827*
4			−3.6e−50*			

Note(s): * indicates lag order selected by the criterion
Source(s): Authors' computation

Table 7. ARDL bounds testing for co-integration

	Value			
F stats	5.015**			
Critical values	<i>F-statistics</i>			
	<i>I (0)</i>	<i>I (1)</i>	<i>t-statistics</i>	
	<i>I (0)</i>	<i>I (1)</i>	<i>I (0)</i>	<i>I (1)</i>
10%	2.508	3.763	-2.570	-3.860
5%	3.037	4.443	-2.860	-4.190
1%	4.257	6.040	-3.430	-4.790

Note(s): Where I (0) and I(1) denote the lower and upper band critical values at 10%, 5% and 1% significance level of the Pesaran, Shin and Smith bounds test

Source(s): Authors' computation

4.5 Dynamic ARDL model: simulating short- and long-run effects

Table 8 presents the DARDL estimates for the short- and long-run effects. The results indicate that NRE consumption significantly enhances Türkiye’s EW in the long run but is statistically insignificant in the short run. Specifically, a 1% increase in NRE raises EW by 0.009% in the long run (5% level) and by 0.004% in the short run, ceteris paribus. This suggests that NRE is central to industrial expansion, economic growth, employment and overall EW in Türkiye. Türkiye heavily relies on fossil fuels for energy security and industrial development, a reliance underscored by a recent 10-year LNG (liquefied natural gas) deal with TotalEnergies (Reuters, 2024), which supports employment, income and business profitability. However, this reliance raises environmental concerns, as Türkiye was Europe’s largest CO₂ emitter from fossil fuel-based power in 2024, releasing 154.5 million metric tons (Reuters, 2025). While NRE supports EW, mitigating its environmental impact is essential for sustainable growth. Our findings are consistent with studies in Iran and India (Noorani et al., 2022; Subhan et al., 2024), which highlighted the positive effect of NRE on EW. However, they contrast with Chaudhry et al. (2021) and Saliminezhad et al. (2024), who argued that NRE hampers economic growth. This divergence likely stems from differences in welfare measurement, as those studies relied on GDP-based growth rather than an EW index.

Table 8. Short- and long-run dynamic ARDL simulation results

Variables	Coefficient	Std. errors	t-value
ECT	-0.215**	0.096	-2.25
<i>Short run</i>			
Non-renewable	0.004	0.003	1.47
Green innovation	0.006	0.004	1.66
Institutions	-0.235***	0.079	-2.99
Inflation	-0.002**	0.001	-2.00
Foreign direct Invst	-0.027	0.019	-1.38
<i>Long run</i>			
Non-renewable	0.009**	0.004	2.24
Green innovation	0.012**	0.005	2.21
Institutions	-0.11**	0.049	-2.16
Inflation	-0.002**	0.001	-2.02
Foreign direct Invst	0.006	0.024	0.26
R ² = 0.903	Adj r ² = 847	Root MSE = 0.0498	Prob > F = 0.000

Note(s): ***p < 0.01, **p < 0.05, *p < 0.1 show significance at 1%, 5 and 10% respectively

Source(s): Authors' computation

Similarly, GI positively affects EW in both the short and long run, though the short-run impact is insignificant. The estimated coefficients suggest that a 1% increase in GI raises EW by 0.012% in the long run and 0.006% in the short run. This implies that while immediate benefits are limited, GI is critical in advancing EW over the long run. The insignificant short-run effect may reflect up-front costs and investment needs for new technologies, which may take time to yield results. However, long-term benefits materialize with sustained investment. Türkiye's initial National Energy Efficiency Action Plan (2017–2023) attracted USD 8.5 billion in investments, supporting research and development, renewable energy infrastructure and job creation (CEO Today, 2025). Expanding renewable energy could add USD 8 billion to GDP annually, generate 300,000 jobs by 2030, and cut emissions by 8% (ILO, 2022). Also, GI-support measures such as a carbon tax on the fossil fuel industry can promote household income in the medium and long term (Dogan et al., 2023). Our results align with Sun et al. (2023), however, they contradict Wang et al. (2025), who found that GI negatively impacted economic growth in China. The differences likely reflect dataset choices and country-specific factors.

Conversely, the results indicate that INS has a significant negative impact on EW in both the short and long run. Specifically, a deterioration in INS decreases EW by 0.24% and 0.11% in the short and long run, respectively. This indicates that weak institutions are detrimental to fostering EW in Türkiye. Weak institutions—marked by corruption, bureaucratic inefficiency, and inconsistent policies—undermine investor confidence and encourage capital flight. The OECD (2021) reported that Türkiye's weak institutions increase risk premiums and refinancing costs and deter foreign direct investment. Moreover, the country ranked 96th in the 2021 Transparency International Corruption Perceptions Index (T.I, 2024), reflecting governance challenges that hinder economic efficiency. Türkiye has implemented reforms like the e-government platform to enhance transparency and accessibility. However, structural challenges such as inflation and macroeconomic instability may undermine such reforms and erode public trust. For instance, Türkiye's real wages, adjusted for inflation, fell from 124.75 TL (USD 23.4) in 2019 to 75 TL (USD 5) in 2022, affecting purchasing power (Mohammed, 2024). These persistent challenges may overshadow reforms and attenuate the direct influence of INS on EW. Our results are consistent with Kafka (2024) but contradict Şentürk and Ali (2022), who found a positive relationship between INS and EW in Türkiye. The discrepancies may stem from differences in the measurement of welfare: they used GDP as a proxy, whereas our study employs a broader EW index.

Regarding the control variables, INF adversely affects EW. A 1% increase in INF reduces EW by 0.002% in both the short and long run, underscoring inflation's detrimental impact. Inflation raises business costs, reduces consumer purchasing power, prompts job cuts, erodes real incomes and leads to a decline in welfare standards. Our findings align with Akinci and Demiröz's (2024) study, which found inflation's adverse impact on EW. FDI reveals insignificant negative (short-run) and positive (long-run) effects on EW in the short and long run. This suggests that FDI does not materially contribute to Türkiye's EW. Our result is in line with Gidiglo et al. (2023), who reported statistically insignificant effects of FDI on welfare.

The ECT captures the speed of adjustment. The ECT is significant and negative, indicating that the factors investigated have a long-term association. Specifically, the coefficient implies that 22% of any equilibrium is corrected each period in the long run. According to the R-squared statistic, the regressors included in this study explain about 90% of the variation in EW. The F-statistic's estimated *p*-value shows that the model is an appropriate fit for this investigation.

4.6 Impulse response results

The DARDL simulations model visualizes fluctuations in explanatory variables and their impact on EW while holding other regressors constant. A 10% positive shock to NRE

increases EW in both the short and long run (Figure 3a), while a 10% negative shock significantly decreases it (Figure 3b). Similarly, a 10% rise in GI positively affects EW across both horizons (Figure 4a), while a 10% decline shows a similar effect (Figure 4b). For INS, a 10% increase in institutional weakness (i.e. weaker INS) causes a decline in EW (Figure 5a), whereas a 10% decrease in institutional weakness (i.e. stronger INS) predicts a boost in EW over both periods (Figure 5b).

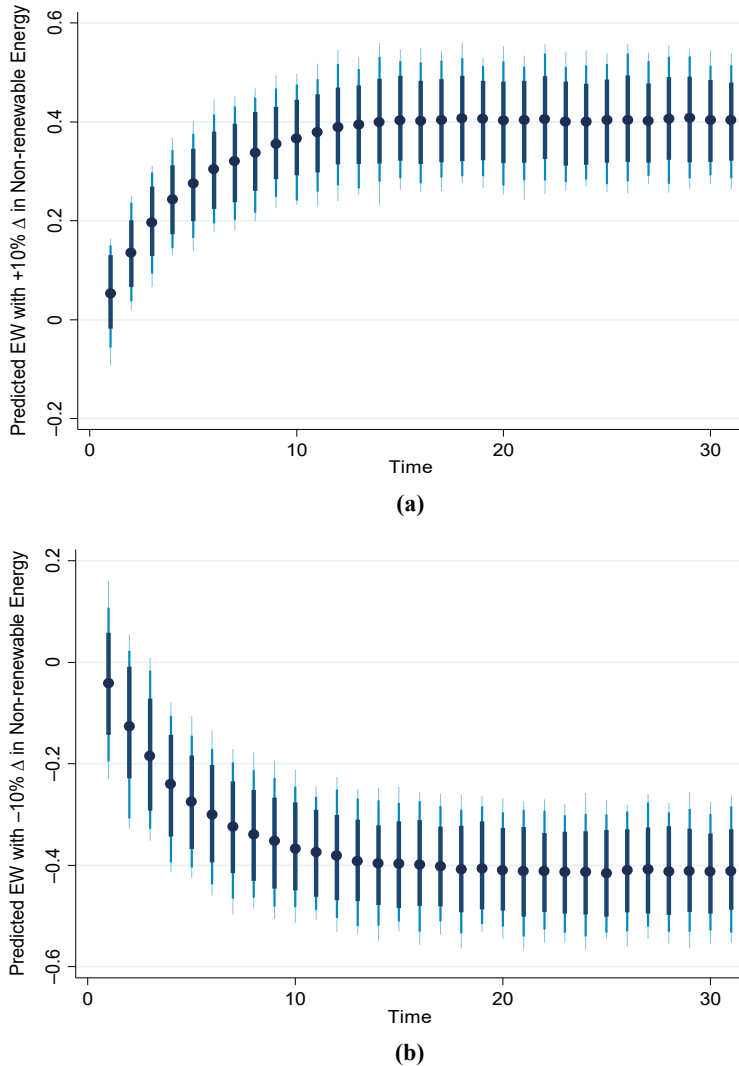


Figure 3. (a), (b) Impulse response plot for non-renewable and economic welfare. This plot illustrates the impact of a 10% increase or decrease in non-renewable energy on economic Welfare. The dots represent the average predicted values, while the dark blue to light blue lines show the 75%, 90% and 95% confidence intervals, respectively. Source(s): Authors' computation

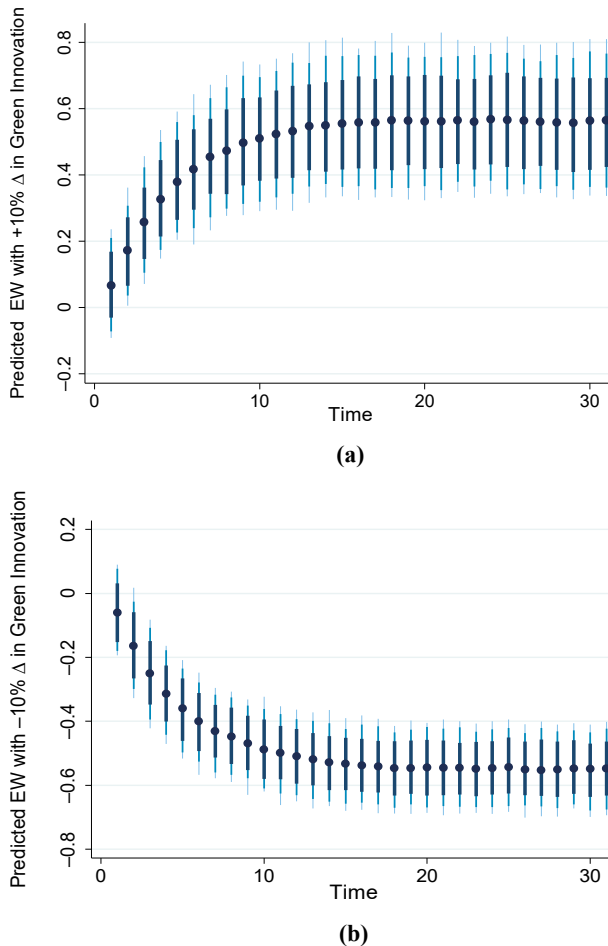


Figure 4. (a), (b) The Impulse Response Plot for Green Innovation and Economic Welfare. It depicts a 10% increase and decrease in renewable energy and its impact on economic Welfare. The dots indicate the average prediction value. Conversely, the dark blue to light blue line specifies 75, 90 and 95% confidence intervals, respectively. Source(s): Authors' computation

4.7 Frequency domain causality results

The FDC tests establish short, medium-, and long-run causality between NRE, GI, INS, INF, FDI and EW at frequencies, $\omega_i = 0.05$, $\omega_i = 1.50$ and $\omega_i = 2.50$. The results are summarized in Table 9 and reveal that NRE and GI influence EW across all time horizons, whereas INS impacts EW only in the short and long run.

The spectral causality graph (Figure 6a) shows a unidirectional relationship from NRE to EW, with no reverse causality (Figure 6b). This outcome is supported by Azami and Almasi (2020) but contradicts the work of Menegaki and Tugcu (2018). Similarly, Figure 8a indicates a unidirectional causality from INS to EW, with no reverse causality (Figure 8b), supporting Parsa and Datta (2023), who found that INS drives economic growth. On the other hand, GI and EW exhibit a bidirectional relationship. Figure 7a illustrates causality from GI to EW, while Figure 7b shows that EW Granger causes GI. This suggests that GI enhances well-being, while improved welfare fosters more significant

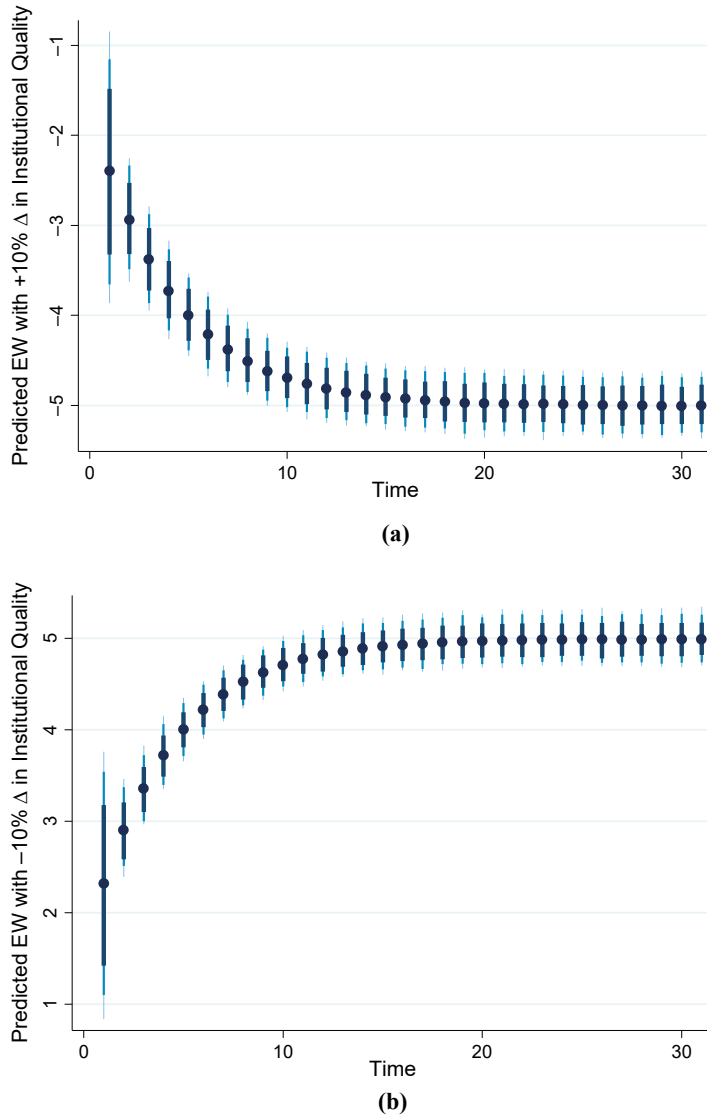


Figure 5. (a), (b) The Impulse Response Plot for Institutional Quality and Economic Welfare. It indicates a 10% increase and decrease in weak institutions and its effect on economic Welfare. The dots show the average prediction value, and the dark blue to light blue line specifies 75, 90 and 95% confidence intervals, respectively. Source(s): Authors' computation

support for GI and a sustainable lifestyle. The findings are in harmony with the work of Wang *et al.* (2025). (See Figure 8)

4.8 Diagnostic statistics tests

Table 10 presents the diagnostic analysis. The Breusch-Godfrey LM test indicates the absence of serial correlation. The ARCH and Breusch-Pagan-Godfrey tests suggest that the model is free from heteroscedasticity. The Jarque-Bera test results show that the residuals are normally

distributed. Finally, we investigate possible structural breaks using CUSUM test for parameter stability. Figure 9 shows that the estimated CUSUM statistic falls within the 95% confidence interval band, supporting coefficient stability over time. Overall, the diagnostic tests indicate a well-specified model that does not suffer from serial correlation. In essence, reliable inference can be drawn from our results.

5. Conclusion and recommendation

This study empirically examines the short- and long-run determinants of EW in Türkiye, focusing on the impact of NRE, GI and INS while controlling for INF and FDI. Our findings indicate a positive relationship between NRE and EW in both the short run and long term, though only the long run is statistically significant, underscoring the critical role of NRE as a driver of EW in Türkiye. Likewise, GI positively influences EW, suggesting that while its short-run impact may be limited, it contributes to long-term EW through economic growth, job creation and environmental sustainability. Conversely, INS exerts a negative effect on EW in both time horizons, highlighting the detrimental impact of institutional weaknesses.

Furthermore, the frequency-domain causality test results confirm that NRE and GI Granger-cause EW in the short, medium and long run, whereas INS shows Granger causality only in the short and long run. Findings also show unidirectional causality from NRE and INS to EW, while a bidirectional relationship exists between GI and EW. Our study bridges the gap between practice and theory: our empirical findings are consistent with the energy-led growth hypothesis (ELGH), the endogenous growth model and North's institutional economic theory, reinforcing our understanding of the role of energy, green innovation and institutions in shaping EW. This study contributes to the literature by offering a holistic analysis of the effect of NRE, GI and INS on the EW index in Türkiye, an approach that remains relatively rare.

Based on our empirical findings, we propose the following policy directions: Türkiye's government should continue cutting carbon emissions and expanding renewable energy use while balancing growth and sustainability. Prioritizing green patents across sectors will promote environmental sustainability, economic growth and technological progress. There is also a need to invest in AI-powered energy forecasting systems and to expand the use of smart grids and demand-response technologies to reduce waste and optimize renewables. Although the government targets an increase in wind and solar capacity to 120,000 MW by 2035 with multi-billion-dollar investments (Anadolu Agency, 2024), macroeconomic conditions and fossil fuel dependency may pose challenges. Therefore, attracting more private investment to complement government efforts is essential. This includes cutting the current 48-month permit

Table 9. Frequency-domain causality test

Direction of causality	Long-term $\omega_i = 0.05$	Medium-term $\omega_i = 1.50$	Short-term $\omega_i = 2.50$
NRE \Rightarrow EW	16.1890 (0.0003)***	11.7788 (0.002)***	9.4481 (0.009)***
GI \Leftrightarrow EW	30.9392 (0.000)***	9.333 (0.009)***	5.0937 (0.078)*
INS \Rightarrow EW	5.5169 (0.0634)*	4.4837 (0.1063)	7.036 (0.03)**

Note(s): *p*-values in parentheses; ****p* < 0.01, ***p* < 0.05, **p* < 0.1 show significance at 1%, 5 and 10% respectively

Source(s): Authors' computation

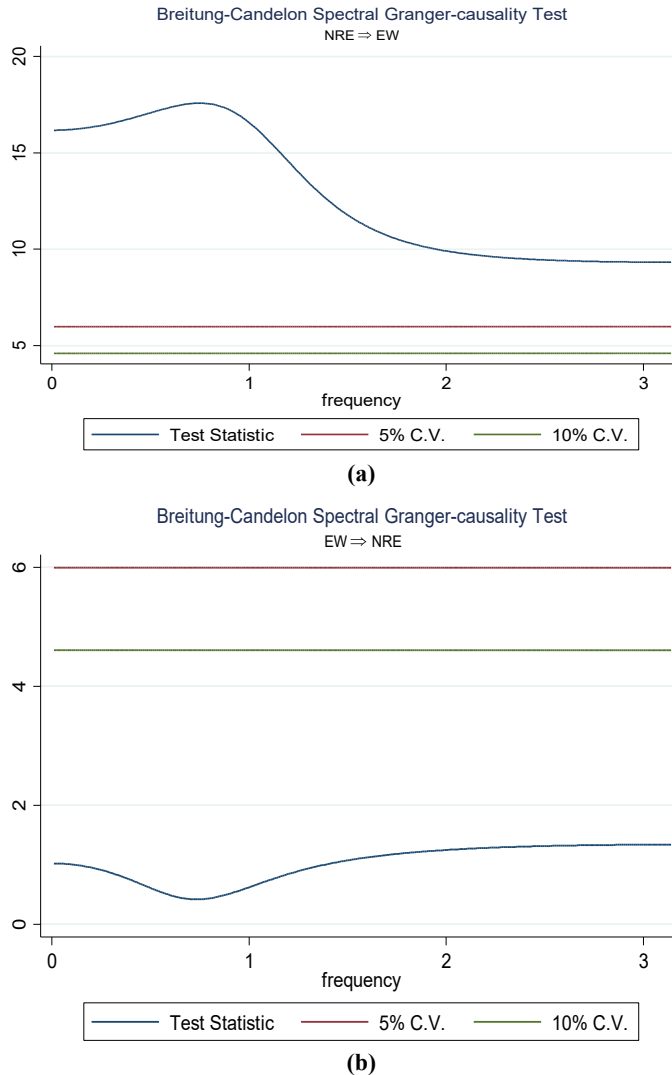
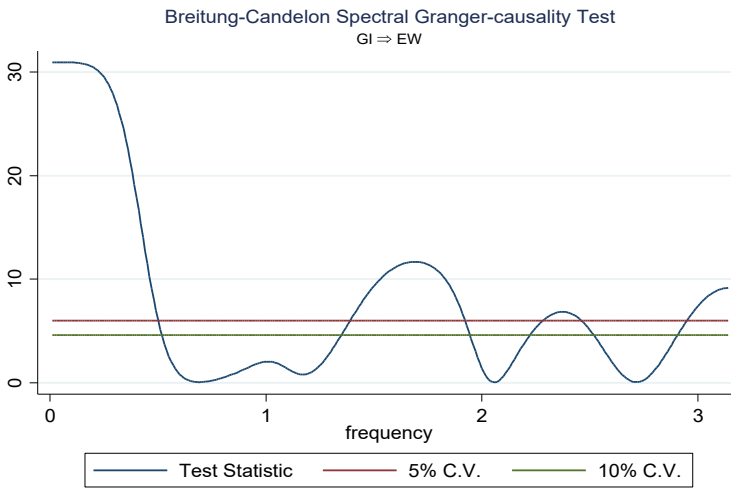


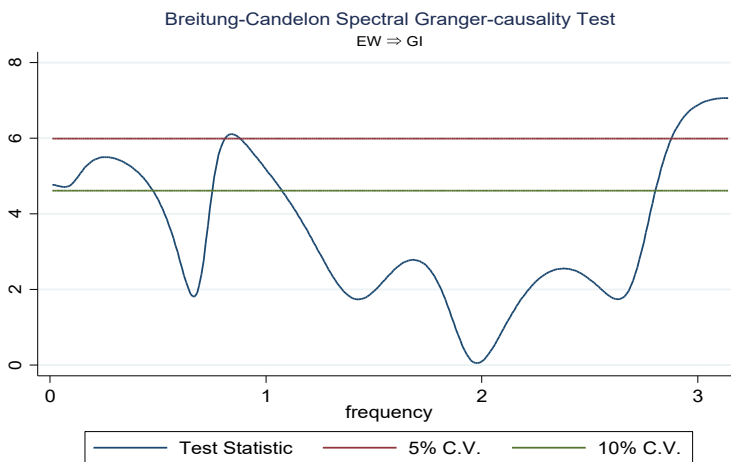
Figure 6. (a), (b) Spectral causality between NRE and EW. Source(s): Authors' computation

processing time for renewable energy projects to accelerate returns on investment and broadening access to green credit through low-interest loans and streamlined approvals. These measures will encourage firms and industries to transition more quickly to green innovation, accelerating the development of domestic renewable infrastructure.

Strengthening governance is equally vital. The government should establish robust systems to detect and punish corruption, alongside expanded legal aid programs to ensure equitable access to justice. The Turkish government's judicial reform initiatives to uphold the rule of law, foster inclusivity and promote transparency are commendable. However, reforms may still face resistance from entrenched political and economic interests. Thus, successful implementation will require broad public support and coordination among the government, civil society groups, opposition parties and the bureaucracy to ensure long-term progress.



(a)

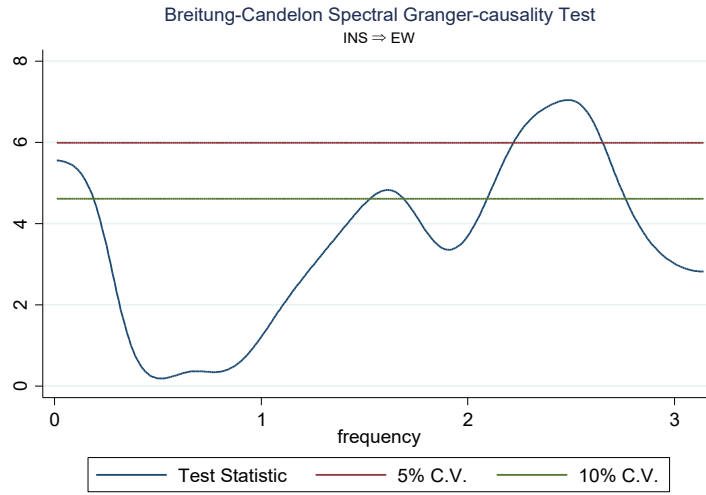


(b)

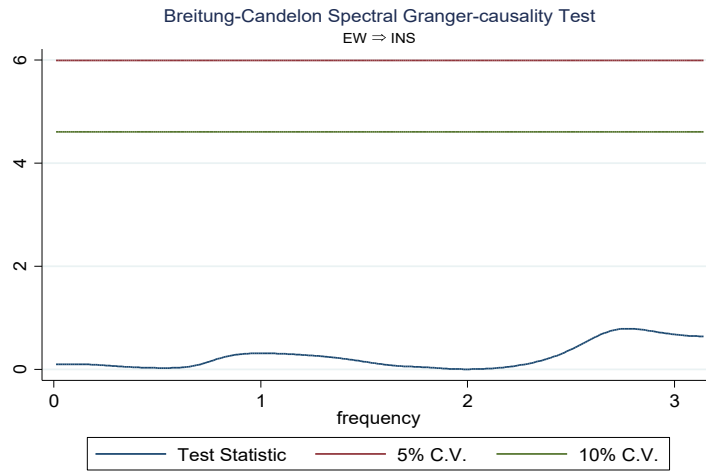
Figure 7. (a), (b) Spectral causality between GI and EW. Source(s): Authors' computation

A strong institutional and political environment is positively associated with better macroeconomic outcomes. To improve macroeconomic stability, the government should adopt strategies such as rationalizing public spending, anchoring price stability and tightening monetary policy where appropriate. The Turkish central bank's recent interest rate hikes and fiscal measures to counter inflationary pressures are commendable. Moreover, open and transparent communication between the government, the central bank and the public is crucial for setting realistic expectations and fostering trust among local and international stakeholders.

The current work has some limitations that warrant further research. The dataset does not include other essential variables influencing economic welfare, such as trade, fiscal policies and labor-market dynamics. Future studies could explore these variables, evaluate policy



(a)



(b)

Figure 8. (a), (b) Spectral causality between INS and EW. Source(s): Authors' computation

Table 10. Diagnostic tests

Diagnostic test	X^2 (p-value)	Results
Breusch-Godfrey LM	0.6011	No evidence of serial correlations
Breusch-Pagan-Godfrey	0.1107	No evidence of heteroscedasticity
Jarque Bera test	0.7324	Residuals are normally estimated
Ramsey reset test	0.4680	Proper specification of the model

Source(s): Authors' computation

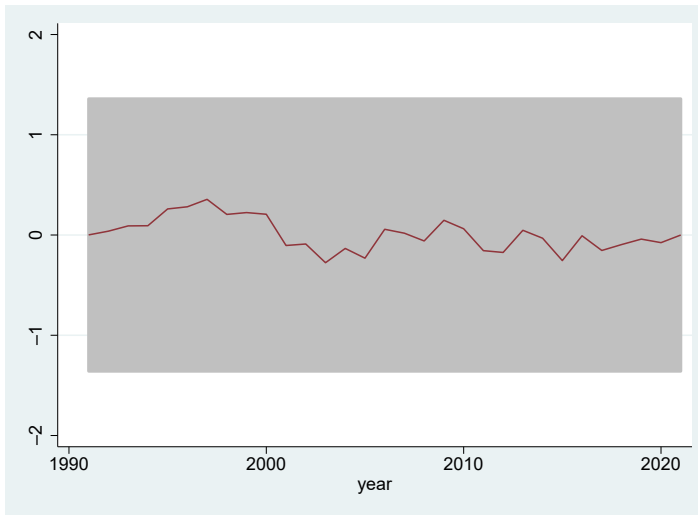


Figure 9. Cumulative sum test using OLS CUSUM plot for parameter stability. Source(s): Authors' computation

interventions and assess external shocks— such as financial crises and geopolitical risks — to better understand Türkiye's welfare trajectory. Additionally, expanding the research to include multiple countries could enable the application of different methodologies and a broader set of variables, helping to capture nonlinear and threshold effects.

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Further reading

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