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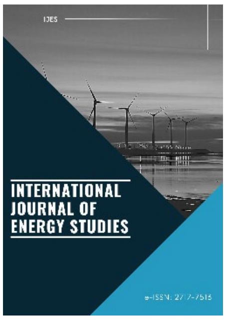

Research Article

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Determinants of renewable energy investment in Turkey: A wavelet-based quantile regression and causality approach

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Highlights

- GDP exerts a positive effect on renewable energy investments across all quantiles and frequency components in Türkiye.
- Oil prices largely stimulate renewable energy investments, but exhibit a suppressive effect at middle quantiles over the medium term.
- Carbon intensity negatively affects renewable energy investments, indicating that fossil fuel dependence constrains the energy transition.
- Causal relationships between renewable energy investments and GDP, oil prices, and carbon intensity, are predominantly pronounced in the long run and at upper quantiles.
- Wavelet Quantile Regression and Causality methods reveal nonlinear, heterogeneous dynamics that conventional linear approaches would fail to capture.

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ABSTRACT

This study examines the relationship between Renewable Energy Investments (REINV) and Economic Growth (GDP), Oil Prices (OP), and Carbon Intensity (CI) in Türkiye for the period 2001–2024. Annual data were converted to quarterly frequency using the quadratic-match method to enable the application of wavelet-based methods. Given the assumption that relationships among variables may exhibit a nonlinear and heterogeneous structure, Wavelet Quantile Regression (WQR) and Wavelet Quantile Granger Causality (WQGC) methods were employed. Energy market uncertainties, dependence on non-renewable sources, and environmental pressures have made it imperative for energy-dependent countries such as Türkiye to channel investments toward renewable energy. In the empirical analysis process, the nonlinear structure of the variables was first examined via the BDS test, after which stationarity properties were established using the WQADF and WQPP unit root tests. The effects of GDP, OP, and CI on REINV were analyzed through WQR, while causal relationships were examined using WQGC. The findings demonstrate that relationships among variables differ across quantile and frequency dimensions. GDP exerts a positive and supportive effect on REINV across all frequencies and quantiles. The effect of OP is largely positive; however, a suppressive effect is observed at middle quantiles and over the medium term. Contrary to expectations, the relationship between CI and REINV was found to be negative, with fossil fuel dependence constraining renewable energy investments particularly in the short run. WQGC results indicate that causal relationships become more pronounced predominantly in the long run and at upper quantiles, with causality running from GDP, OP, and CI to REINV being especially evident over longer horizons. These results underscore that, in order to increase REINV in Türkiye, financing opportunities, green innovation, technological advancement, and sustainable environmental and energy policies must be addressed in conjunction with GDP growth.

Keywords: Renewable energy investments, Oil prices, Carbon intensity, Wavelet quantile regression and causality, Türkiye

1. INTRODUCTION

The fight against global climate change has become one of the most critical macroeconomic and environmental challenges of the twenty-first century. The most defining transformation in response to the impacts of global climate change has been the shift away from fossil fuel dependence toward renewable energy sources. The intensive use of fossil fuels in energy systems along with rising greenhouse gas emissions, volatility in energy prices, decarbonization commitments, and import dependency has prompted international organizations and the private sector to increase renewable energy investments. In this context, renewable energy sources are regarded not merely as an environmentally beneficial alternative contributing to the reduction of carbon emissions, but also as a strategic investment domain in terms of sustainable growth, energy supply security, technological transformation, and green finance. Investments in renewable sources such as solar, wind, geothermal, biomass, and hydroelectric power enable countries to diversify their energy portfolios in alignment with low-carbon development targets and to establish more stable energy economies resilient to global fluctuations in fossil fuel prices. According to the International Renewable Energy Agency [19], global renewable energy capacity rose from 1,136 GW to 2,350 GW between 2009 and 2018. Nevertheless, the determinants of renewable energy investments exhibit significant variation across countries and over time, thereby complicating the implementation of a uniform policy approach. The tensions between the United States and Iran, as well as the declining confidence in fossil fuels and reduced demand as highlighted by the International Energy Agency suggest that governments will revise their energy strategies and that the transition toward a more electrified future will accelerate [15]. According to the United Nations, the recent fossil fuel cost crisis has intensified emphasis on the economic contribution of renewables, with many governments stressing the urgent need to accelerate renewable energy planning, given that renewables can provide safer, cheaper, and cleaner energy that is not held hostage by narrow shipping corridors or global conflicts. Furthermore, it has been underscored that renewables play an indispensable role in restoring national security, economic stability, competitiveness, policy autonomy, and fundamental sovereignty [5].

Türkiye stands out as a significant actor in this global transformation, owing to its strategic geographic location and rich natural resource potential. As a developing economy that is heavily dependent on energy imports, Türkiye has strategically oriented itself toward clean energy sources such as wind, solar, and geothermal, driven by the cost pressure of energy expenditures on its current account deficit and its net-zero emissions target set for 2053. While only 41% of Türkiye's total installed capacity derived from renewable sources in 2000, this share rose to 57% by 2023; and as of November 2024, the installed renewable energy capacity surpassed the 115 GW threshold, positioning Türkiye fifth in Europe and eleventh in the world in terms of renewable energy generation. The fact that 99.5% of the installed capacity added to the system in 2023 came from renewable sources is a clear indicator that this transformation has indeed gained momentum [12,37]. However, this favorable picture does not fully conceal the structural vulnerabilities of Türkiye's energy system: Türkiye imports 93% of its oil and 99% of its natural gas; energy imports account for more than 20% of the total import bill, exerting persistent pressure on the current account deficit; and in 2022, the energy import bill reached USD 97 billion, becoming the most critical determinant of the trade deficit [18]. This structural contradiction between rapid growth in renewable energy capacity on one hand and chronic fossil fuel dependence on the other necessitates a more nuanced analytical framework for examining investment dynamics. Türkiye ratified the Paris Agreement in 2021 and formally adopted the net-zero emissions target for 2053; to achieve this goal, solar energy capacity must be increased from 18.5 GW to 76.9 GW and wind energy capacity from 12.3 GW to 43.1 GW by 2035, requiring an investment of USD 59 billion in renewable energy alone and an additional USD 28 billion for grid modernization [13,10]. The YEKDEM and YEKA tender systems stand out as the principal policy instruments of this process; however, the question of which macroeconomic factors actually drive investment decisions remains empirically unanswered.

A review of the literature on the determinants of renewable energy investments reveals that financial, technological, institutional, and spatial factors are prominent. Koengkan et al. [21] demonstrated that financial openness and public investment positively influence renewable energy capacity; Zheng et al. [48] found that artificial intelligence contributes to this process in a nonlinear manner; Weng et al. [42] showed that clean energy investments generate spatial spillover effects; and Chang et al. [8] established that the Jevons paradox operates in low-capacity countries. In Türkiye-focused studies, Seydioğulları [35] and Bekar [6] emphasized that the transition to renewable energy has become an environmental and geopolitical necessity, while Ürün and Soyu [39] drew attention to Türkiye's untapped resource potential. Yılmaz [46] demonstrated that economic growth and foreign direct investment drive renewable energy consumption; Saraç et al. [34] showed that renewable energy consumption contributes positively to employment; and Akın et al. [3] found that technological innovation and renewable energy consumption jointly reduce carbon emissions. The existing empirical literature on the determinants of renewable energy investments appears insufficient in terms of the distributional location and temporal dimensions of these relationships. Conventional panel data and time series methods assume that relationships among variables are symmetric and linear around the conditional mean, thereby ignoring the asymmetries between dynamics during periods of low investment and those during periods of high investment. Moreover, a framework distinguishing the effects of short-term cyclical factors such as oil price shocks and growth fluctuations from long-term structural determinants has not yet been investigated specifically for Türkiye. Accordingly, this study aims to examine the effect of economic growth, crude oil prices, and carbon intensity on renewable energy investments in Türkiye from both distributional and time-frequency perspectives.

This study makes several key contributions to the renewable energy literature. The Türkiye dataset is analyzed using Wavelet Quantile Regression and Quantile-Based Causality methods, thereby examining distributional heterogeneity and time-frequency dynamics within a single integrated framework. Additionally, the asymmetric behavioral patterns of oil prices and carbon intensity on renewable energy investments across different investment regimes are systematically identified. Finally, period- and distribution-sensitive policy recommendations are developed in line with Türkiye's 2035 and 2053 energy targets.

A four-stage econometric strategy based on annual data covering the 2001–2024 period for Türkiye is implemented in this study. Renewable energy investments (REINV) serve as the dependent variable, while economic growth (GDP), oil price (OP), and carbon intensity (CI) are employed as independent variables. First, the nonlinear dependence structure among variables is investigated through the BDS Linearity Test; subsequently, the stationarity properties of the series are tested using the Wavelet Quantile Augmented Dickey-Fuller (WQADF) and Wavelet Quantile Phillips-Perron (WQPP) tests. Wavelet Quantile Regression (WQR) and the Wavelet Quantile Granger Causality Test (WQGC) serve as the primary analytical tools. This integrated approach enables the simultaneous examination of the effects of variables on renewable energy investments across different quantiles of the distribution ($\tau = 0.10$ to 0.90) as well as across short-, medium-, and long-run time scales.

The remainder of this study is organized as follows. Section 2 introduces the dataset and variables employed in the study. Section 3 describes the methodological framework for the WQR and WQGC methods. Section 4 presents the empirical findings, while Section 5 discusses the findings within the context of the literature. Section 6 contains the conclusions and policy recommendations.

2. DATA

In this study, the relationship among REINV, GDP, OP, and CI for Türkiye was investigated. For this purpose, the annual change in renewable energy installed capacity (MW) was used to represent REINV, the dependent variable. To this end, the capacity figure of the previous year was subtracted from that of the current year to calculate the amount of new investment realized in the relevant year. In the literature, REINV has commonly been proxied using installed capacity data [8,21]. However, these studies have taken into account the cumulative nature of investment while neglecting the investment flow, that is, new investments realized within a specific period. In the present study, the measurement approach in the literature is extended by calculating the annual change, with the aim of more accurately capturing the variation in energy investments over time. More specifically, although REINV can be measured in monetary terms, it is not always possible to obtain complete, consistent, and long-term data of this kind. For this reason, installed renewable energy capacity, which reflects the cumulative stock structure of investment, is commonly used in the literature as a proxy for REINV. Building on this approach, the present study calculates the annual change in installed renewable energy capacity to capture the amount of new renewable energy investment corresponding to a specific period. Accordingly, the increase in installed renewable energy capacity each year constitutes the REINV variable used in this study. Data for the dependent variable were compiled from the International Renewable Energy Agency [19,20] database. Data for the independent variables were obtained from the following sources: GDP per capita data from the World Bank [43], OP data representing European Brent Spot prices from the U.S. Energy Information Administration [18], and CI data representing the carbon intensity of GDP from the World Bank [43]. The starting year of the study period was set as 2000, corresponding to the first year for which REINV data were available, and the ending year as 2024, the latest year for which GDP and CI data were accessible. This approach eliminated discrepancies in the start and end years of the data and allowed for the analysis of the longest possible period. A total of 25 years of annual data covering the 2000–2024 period were compiled prior to the analyses. Because preparing the REINV variable series required first-differencing the series, the the starting year was shifted forward by one. Therefore, the analyses cover the 2001–2024 period using annual data. Accordingly, given that the available dataset was limited for the application of wavelet-based methods requiring high-frequency data, annual data were converted to quarterly frequency. The conversion was performed using the quadratic-match approach applied in Olasehinde-Williams et al. [28], Olasehinde-Williams et al. [29], and Coban et al. [11]. This method constructs a local second-degree polynomial function for each observation in the low-frequency series, from which high-frequency observations for the relevant period are derived. This approach preserves the low-frequency data structure while yielding the higher number of observations required for empirical analysis [27,30]. To apply wavelet-based methods, the annual data were converted into quarterly frequency. However, the quarterly observations generated through this transformation should not be considered equivalent to directly observed quarterly data. Since the annual series were converted into quarterly data while preserving their general trend, this procedure naturally involves certain limitations. Although the transformed data help capture the overall movement of the series, they may not fully reflect short-term fluctuations that could be observed in actual quarterly data. Therefore, the empirical findings should be interpreted by considering the limitations associated with this frequency conversion. A logarithmic transformation was applied to the variables used in order to mitigate the potential effects of heteroscedasticity and scale differences.

Descriptive statistics for the variables used are presented in Table 1. According to the results in Table 1, GDP has the highest and CI has the lowest mean value. Similarly, GDP exhibits a higher maximum value compared to the other variables. The large difference between the maximum and minimum values of REINV may reflect the divergence in economic transformation and the extent to which policymakers have channeled efforts toward renewable energy investments over the period under examination. All variables have negative skewness values. Kurtosis values are positive and platykurtic, falling below 3 for all series. According to the Jarque-Bera test statistics and probability values, all series except GDP are not normally distributed, while GDP exhibits a normal distribution.

Table 1. Descriptive Statistics

Statistics	REINV	GDP	OP	CI
Mean	5.885	7.803	4.133	-0.797
Median	6.364	7.817	4.206	-0.782
Maximum	7.546	8.264	4.756	-0.631
Minimum	2.473	7.277	3.184	-1.057
Std. Deviation	1.224	0.278	0.453	0.124
Skewness	-0.838	-0.122	-0.630	-0.574
Kurtosis	2.827	1.975	2.475	2.409
Jarque-Bera	11.348***	4.440	7.446**	6.675**
Probability	0.003	0.109	0.024	0.036
Observations	96	96	96	96

Note: ***, **, and * denote statistical significance at the 1%, 5%, and 10% levels, respectively

3. METHODOLOGY

In this study, the relationship between REINV and GDP, OP, and CI in Türkiye was examined using a wavelet-quantile approach. This choice is grounded in the assumption that the relationship among the variables will exhibit nonlinear and heterogeneous behavior. Accordingly, the dynamics of the relationships among the variables are captured across both different time frequencies and different quantiles. To this end, the linearity of the variables was first examined using the Broock et al. [7] BDS test. The null and alternative hypotheses of this test are as follows:

H_0= The series is independently and identically distributed.
H_1= The series is not independently and identically distributed.

Subsequently, the stationarity properties of the variables were examined using the Wavelet Quantile Augmented Dickey-Fuller (WQADF) and Wavelet Quantile Phillips-Perron (WQPP) tests. While conventional linear methods assume that parameters remain constant across all quantiles, WQADF and WQPP are capable of revealing relationships that vary across different quantiles. These methods are therefore more appropriate for series with dynamic and heterogeneous structures, such as economic and financial variables, and they account for the possibility that relationships among variables may differ under varying economic conditions [16]. The WQADF and WQPP tests, which are extended forms of the QPP and QADF tests augmented with wavelet transformation, examine the stationarity properties of variables at both frequency and quantile levels unlike conventional tests that focus on average behavior. In this way, the variation in the stationarity structure of series across different time scales at low, medium, and high quantiles can be monitored, in contrast to the conventional ADF and PP tests that assess stationarity based on average behavior [2,4]. The null and alternative hypotheses of these tests are as follows:

H_0 = The series contains a unit root at the relevant quantile.
H_1= The series is stationary at the relevant quantile.

The Wavelet Quantile Regression (WQR) method was used to investigate the relationship among the variables whose stationarity structures were examined. Developed by Adebayo and Özkan [1], this method is an extended form that integrates conventional quantile regression with wavelet application. This approach makes it possible to examine how the relationship between variables changes across time and quantiles. In the WQR method, time series are first decomposed into short-, medium-, and long-run components using the Maximal Overlap Discrete Wavelet Transform (MODWT) developed by Percival and Walden [32]. This procedure allows for the separate examination of both low-frequency long-run trends and high-frequency short-run fluctuations in the series [26]. Quantile regression is then estimated using the detail coefficients obtained at each wavelet level, thereby revealing the effects of the independent variables on the quantiles of the dependent variable across different periods [17]. In this context, the WQR model can be expressed as follows:

$$Q_\tau\big(d_j(Y)\big|\, d_j\,(X)\big) = \beta_0(\tau) + \beta_1(\tau) d_j(X) \tag{1}$$

In Equation 1, $d_j(Y)$ and $d_j\,(X)$ denote the wavelet components of the dependent and independent variables, respectively, at decomposition level j. The term $Q_\tau\big(d_j(Y)\big|\, d_j\,(X)\big)$ represents the τ-th conditional quantile of $d_j(Y)$ given $d_j\,(X)$. $\beta_0(\tau)$ represents the intercept term and $\beta_1(\tau)$ denotes the slope coefficient at the corresponding quantile. This method enables a more detailed identification of nonlinear and asymmetric relationships among the variables.

The causal relationship among the variables was examined using the Wavelet Quantile Granger Causality (WQGC) method developed by Özkan et al. [31]. This method combines Granger causality [14] and quantile estimation methods [14,22] to reveal how the causal relationship between two variables varies across different quantiles and time horizons. In this respect, it provides more comprehensive results than methods that focus solely on either the temporal or quantile dimension. In the WQGC method, the dependent variable Y and the potential causal variable X are first decomposed at level z using MODWT. Subsequently, quantile series for each decomposition level of Y are constructed over the range 0.05–0.95. Finally, a VAR model is estimated between each quantile series of Y and the decomposed series of variable X, and the Granger causality test is applied. The WQGC method is estimated using the following model:

$$dz[Y]_{\tau t} = \partial_{z,\tau} + \sum \vartheta_{z,\tau,\mu} dz[Y]_{\tau t-\mu} + \sum \beta_{z,\tau,\mu} dz[X]_{t-\mu} + \varepsilon_{t,z,\tau} \tag{2}$$

where $\partial_{z,\tau}$ denotes the intercept at the τ −th conditional quantile and $dz[Y]_t$ decomposition level; $dz[Y]_t$ represents the τ-th conditional quantile series of the dependent variable at the z-th decomposition level; $dz[X]$ denotes the z-th decomposition level of the independent variable X; μ

is the lag length; and $\varepsilon_{t,z,\tau}$ is the error term at the τ-th conditional quantile, z-th decomposition level, and time t. If $\beta_{z,\tau,\mu} \neq 0$ and is statistically significant, variable X is considered to Granger-cause the τ-th conditional quantile series of Y at the z-th decomposition level. This method enables the examination of whether and at which quantile(s) and time horizon(s) a causal relationship exists. Furthermore, this method is regarded as a robustness test for the Wavelet Quantile Correlation (WQC) findings [25].

4. RESULTS

The wavelet unit root test, wavelet quantile regression, and wavelet quantile Granger causality test results obtained for the variables used in this study are interpreted below. Prior to the analyses, the linearity of the variables was tested.

Table 2. BDS Test Results

Dimensions	REINV	GDP	OP	CI
2	27.909 (0.000***)	45.400 (0.000***)	27.887 (0.000***)	29.439 (0.000***)
3	29.077 (0.000***)	48.022 (0.000***)	29.081 (0.000***)	30.458 (0.000***)
4	30.644 (0.000***)	51.582 (0.000***)	30.473 (0.000***)	31.983 (0.000***)
5	33.073 (0.000***)	57.069 (0.000***)	32.565 (0.000***)	34.583 (0.000***)
6	36.723 (0.000***)	64.710 (0.000***)	35.559 (0.000***)	38.385 (0.000***)

Note: The values in the table represent the z-statistics estimated for each dimension. Values in parentheses denote the probability values associated with the respective z-statistics. *** denotes statistical significance at the 1% level.

Table 2 presents the BDS test results conducted to examine the linearity of the variables. The results indicate that all variables are significant across all embedding dimensions, with the null hypothesis rejected at the 1% significance level. Accordingly, it is evident that the variables do not possess a linear structure and that the relationships among them cannot be explained through a linear process. For this reason, the use of methods that examine the relationships between REINV and GDP, OP, and CI separately at low, medium, and high quantiles, while accounting for heterogeneous relationships rather than methods that address these relationships solely at the mean level, will yield more reliable results.

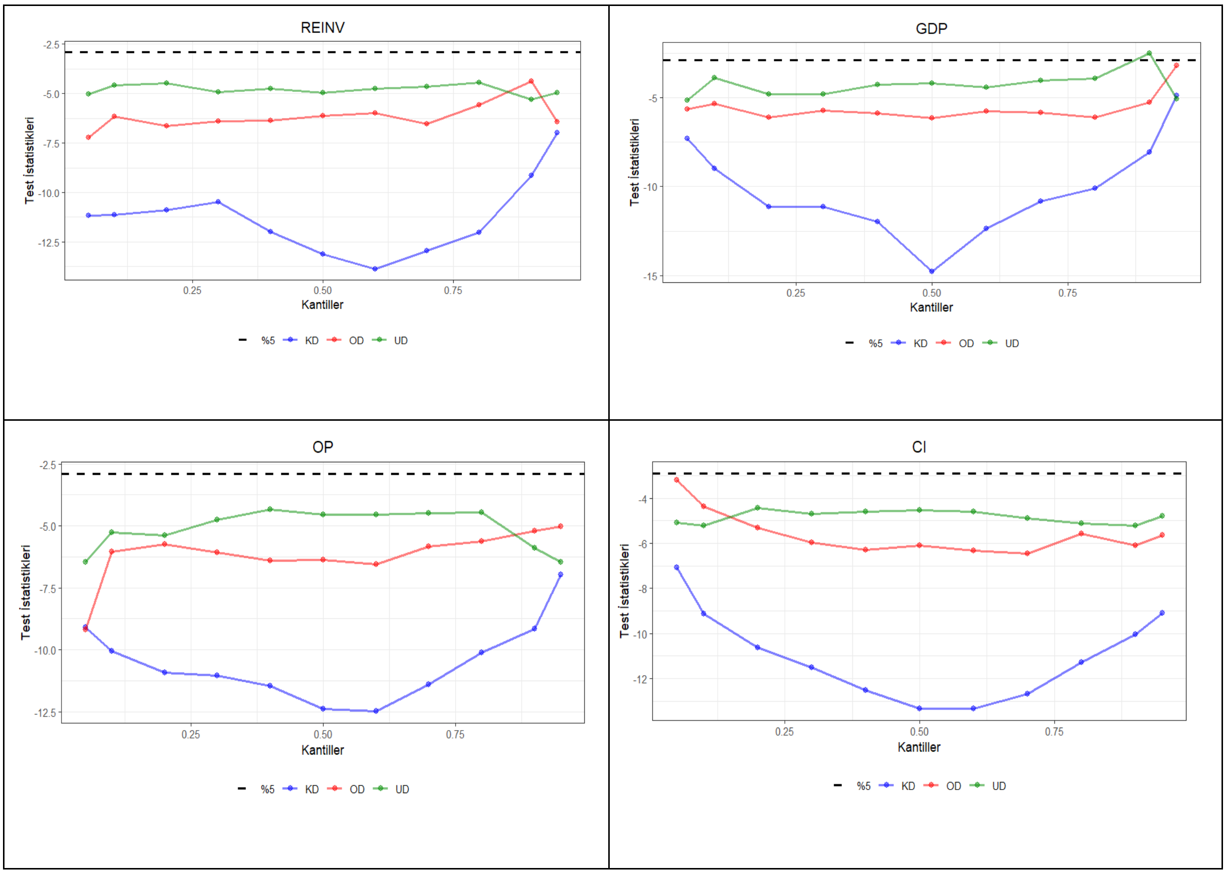

Figure 1. Wavelet Quantile Phillips-Perron (WQPP) Results

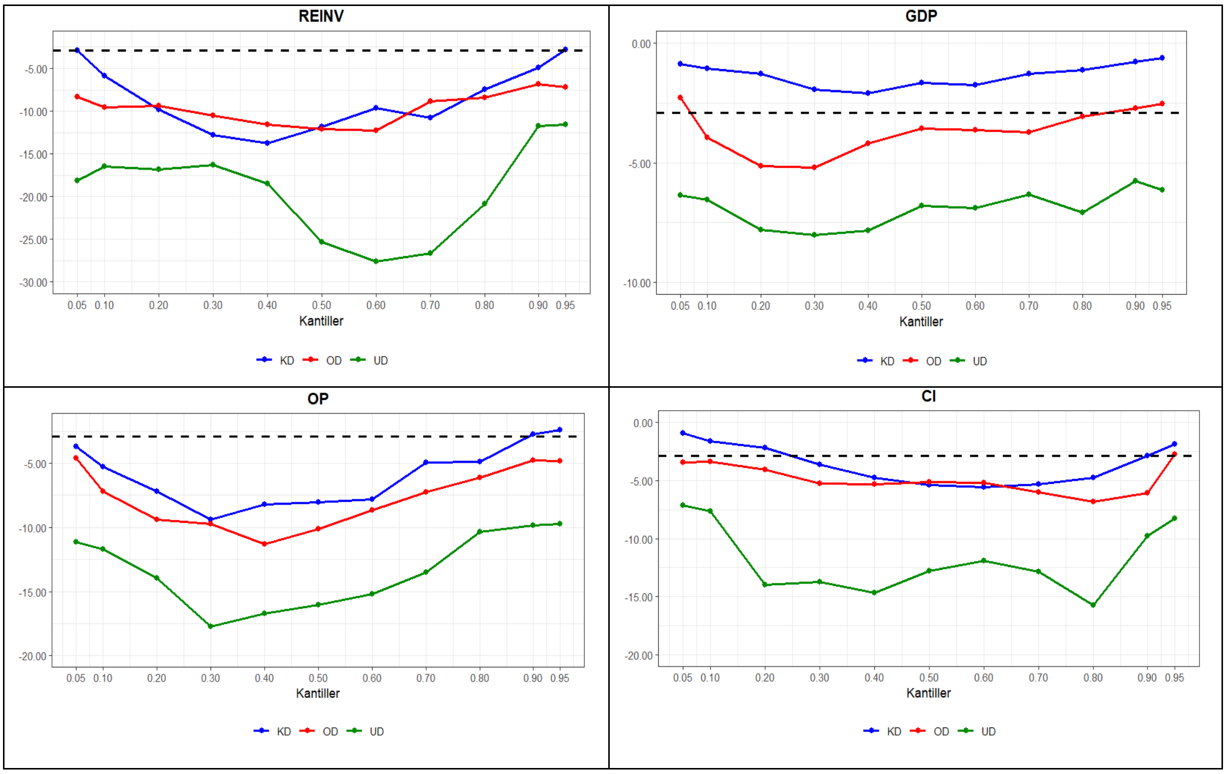

Figure 2. Wavelet Quantile Augmented Dickey-Fuller (WQADF) Results

The wavelet approach reveals the behavior of variables across different frequencies and quantiles. The WQADF and WQPP unit root test results presented in Figures 1 and 2 indicate that the stationarity properties of the variables do not exhibit uniform behavior throughout the entire distribution, but rather vary across quantiles. According to the results of these tests, which offer a more comprehensive evaluation than classical unit root tests, the impact of shocks on the variables is not uniform but varies across the analysis period and all quantiles. This finding confirms the methodological appropriateness of the WQR and WQGC tests in examining the relationships among the variables. In Figures 1 and 2, the dashed line indicates significance at the 5% level.

According to the WQR results presented in Figure 3, the effects of GDP, OP, and CI on REINV are observed to vary across frequency and quantile levels. At this point, REINV is seen to be affected by energy market fluctuations and environmental pressures in addition to economic magnitude to varying degrees.

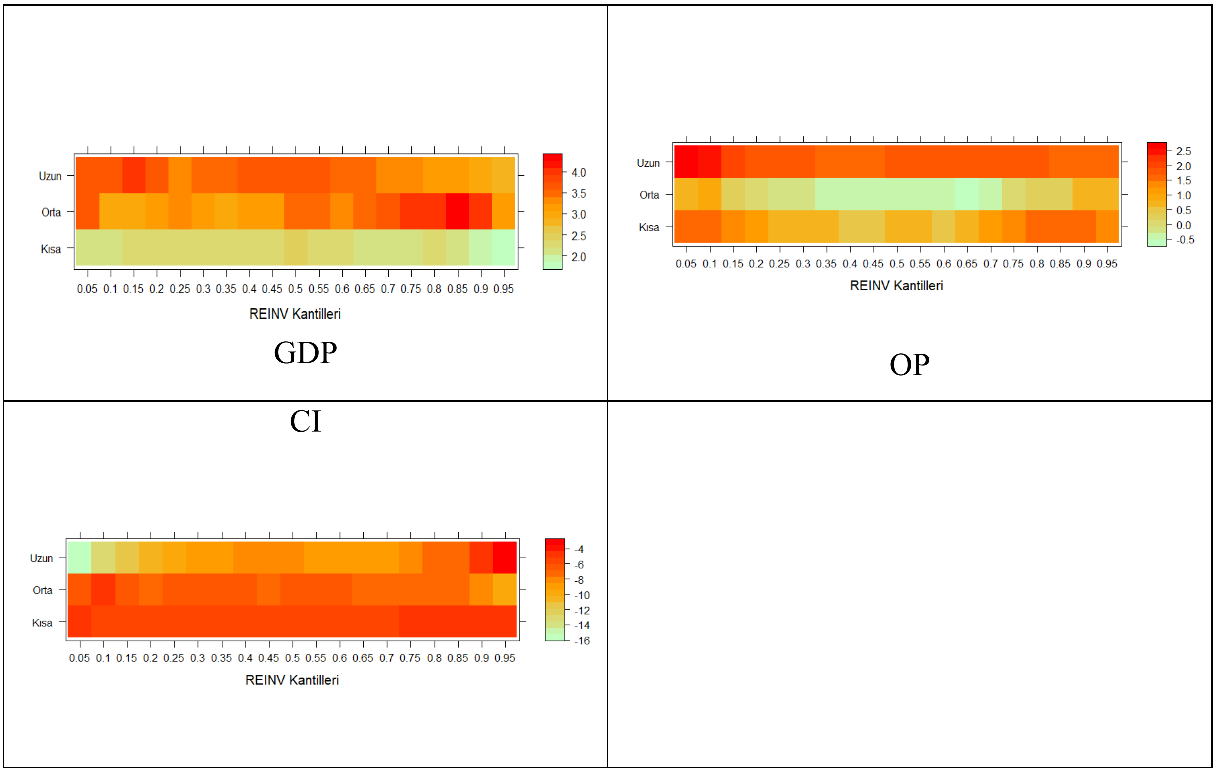

Figure 3. Wavelet Quantile Regression (WQR) Results

The effect of GDP on REINV is positive across all frequencies and quantiles. Accordingly, increases in GDP create a supportive environment for the expansion of REINV. In other words, since GDP enables both public and private sector investments to increase, it may also stimulate

REINV. The relationship between OP and REINV is largely positive. However, a negative relationship was observed exclusively at middle quantiles (0.35–0.70) and over the medium term. When the findings related to the OP variable are evaluated together, it can be stated that OP exerts a supportive effect, as renewable energy sources become relatively more attractive during periods when the costs of non-renewable namely fossil fuel energy increase. Furthermore, it was found that OP has a suppressive effect under conditions of heightened uncertainty in energy markets and low REINV. For this reason, the relationship between OP and REINV is nonlinear and may vary across different time periods and quantiles. As CI increases, environmental pressures are expected to intensify, thereby accelerating the shift toward REINV. However, contrary to expectations, the results regarding the relationship between CI and REINV were found to be negative. There is, in particular, a strong inhibitory effect on REINV across all quantiles in the short run. This finding can be explained by the fact that developing countries such as Türkiye are highly dependent on energy imports the vast majority of which consist of non-renewable fuels and that production and energy investments are based on non-renewable fossil energy. As a result, dependence on the non-renewable energy structure increases, which constitutes a significant obstacle to the transition toward REINV.

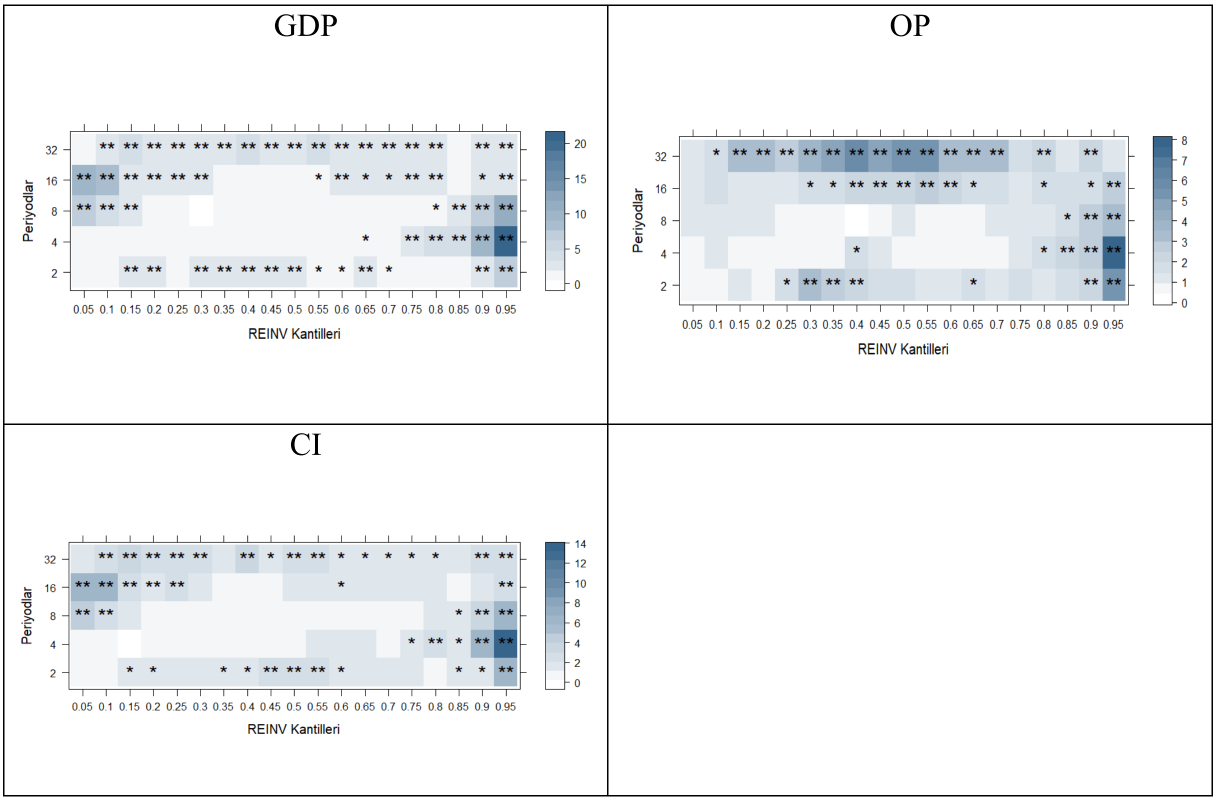

Figure 4. Wavelet Quantile Granger Causality (WQGC) Results

Note: ** and * indicate the rejection of the null hypothesis of no Granger causality at the 5% and 10% significance levels, respectively

The WQGC results vary across quantiles and frequencies in a manner similar to the WQR results. According to the results presented in Figure 4, causal relationships running from GDP, OP, and CI to REINV are predominantly observed in the long run across nearly all quantiles, and in the medium run primarily at high quantiles (0.75–0.95). Furthermore, the causality results obtained for the variables support the WQR findings. In other words, increases in GDP will further raise energy demand, and given Türkiye's dependence on non-renewable energy, risks such as uncertainties in energy supply security will increase the need for alternative energy investments. Regarding OP, the upward trend in prices driven by the dependence of developing economies' such as Türkiye on non-renewable energy, creates cost pressure, thereby complicating the transition to REINV. Nevertheless, throughout most of the period examined across time and quantile dimensions, this relationship is supportive of REINV, contingent on conditions in energy markets. In this respect, one may speak of the existence of a bidirectional mechanism in the causal relationship running from OP to REINV. Examining the results related to CI, a causal relationship toward REINV is identified; however, this relationship is found to operate in a manner that inhibits REINV. This result indicates that CI alone is insufficient to increase REINV, and that the provision of increased incentives to finance investment-related costs, as well as political support from policymakers in this area, are necessary.

5. DISCUSSION

The findings obtained for Türkiye demonstrate that the relationships between REINV and GDP, OP, and CI exhibit a nonlinear and heterogeneous structure, implying that the existing relationship may vary across time and quantile dimensions. In this context, while BDS test results confirm a nonlinear relationship among the variables, the WQADF and WQPP unit root tests show that these relationship possess different dynamics across time scales and quantile levels. The WQGC results further reveal that the causal relationships running from GDP, OP, and CI to REINV vary across the quantile and frequency dimensions. This indicates that REINV is sensitive to different determinants across its short-, medium-, and long-run frequency components. In particular, the strong causal relationships from GDP to REINV underscore that GDP is one of the primary determinants of the energy transition, while the causality from OP to REINV highlights that fluctuations in energy markets exert an influence on energy investment decisions. Similarly, the

CI–REINV relationship reveals that environmental pressures constitute a significant determinant of the energy transition, albeit one that varies periodically. In light of these results, it is evident that explaining REINV solely through average effects would be insufficient, as this may fail to fully reflect the heterogeneous structure of energy markets. These results are consistent with the findings of Chen [9] and Tambari et al. [38], who indicate that the relationship between REINV and environmental and economic dynamics is asymmetric and time-dependent.

The results pertaining to the relationship between GDP and REINV demonstrate that increases in GDP support REINV across numerous quantiles and frequency components. However, the relationship was found to be more pronounced particularly in the medium- and long-run frequency components, while remaining relatively weak in the short-run frequency component. Periods in which the magnitude of the coefficient increases can be explained by GDP's enhancement of investment capacity toward REINV, facilitation of financing for the energy transition, and the consequent rise in energy demand. Conversely, periods in which the effect weakens indicate that GDP does not always translate directly into REINV and that this may change depending on financing costs and energy policies. The findings for GDP are consistent with those of Chen [9], who argues that an increase in GDP will boost REINV and, in doing so, exert a dampening effect on carbon emissions. In the literature, studies pointing to a mutual and complementary link between REINV and GDP include Muneer et al. [24], who note that REINV contributes to GDP, employment, and long-run emission reductions in Saudi Arabia and that this effect may reciprocally stimulate GDP and employment. Xu et al. [45] demonstrate that sustainable finance and REINV increase economic activity while supporting a sustainable environment, and that economic activity increased through sustainable finance plays an incentivizing role in REINV. Additionally, Wang and Debel [40], building on renewable energy consumption, state that increases in REINV are associated with higher GDP and industrial value added. While these studies do not directly support our finding with the same direction of causality, they broadly align with the findings of the present study in demonstrating a mutual link between GDP and REINV. Therefore, the positive effect running from GDP to REINV identified in this study can be said to reflect the mutual interaction between economic expansion and the energy transition.

The relationship between OP and REINV is similarly observed to vary across the quantile and frequency dimensions. In particular, the relationship was found to be relatively weak and negative at the medium-term frequency component and at middle quantile levels. Nonetheless, a positive and strong interaction of OP on REINV exists across numerous quantiles and frequency components. This demonstrates that OP stimulates REINV in certain periods while acting as a constraining factor in others. This pattern, which reveals the presence of both cost and substitution effects of OP on REINV, is similar to the finding of Tambari et al. [38] that the relationship between OP and REINV may be either symmetric or asymmetric, with positive shocks in OP suppressing REINV in certain countries. Furthermore, the finding that OP supports REINV in this study is corroborated by the works of Zhao et al. [47], who demonstrate that oil price volatility is effective on REINV, and Shahi MD and Somosi [36], who emphasize that increases in fossil fuel prices direct countries toward REINV.

The relationship between CI and REINV, unlike the other variables, is found to be negative across all quantile and frequency components. Accordingly, it can be stated that CI has a suppressive effect on REINV. This can be explained by the fact that the production structure in developing countries such as Türkiye is built around fossil fuels, and that the energy component largely consists of non-renewable energy structures due to the high costs that a transition to REINV would entail. The findings of this study differ from those of Ren et al. [33], who argue that CI positively influences REINV. Moreover, the findings indirectly align with studies in the literature suggesting that the relationship between CI and REINV is shaped through financial structures. These studies indicate how support from financial credits for green innovation, industrial structure transformation, and energy transformation in production structures can reduce CI; that businesses are directed toward REINV through green finance policies; and that this relationship is nonlinear [23,41,44,49]. In this framework, the findings obtained for Türkiye demonstrate that increases in CI alone are insufficient to increase REINV, and that financing costs, technological innovation, and the composition of the energy mix play decisive roles. The fact that investments do not increase to the desired level particularly during periods of high CI suggests that the energy transition process still contains structural limitations and that the use of non-renewable energy remains intensive. Although an increase in CI is expected to create pressure for a transition away from non-renewable energy, the extent to which this pressure translates positively into REINV depends on the availability of appropriate financing conditions, policy incentives, and sector-specific technological capacity. In Türkiye, which is classified as a developing country and remains highly dependent on imported energy, factors such as high initial investment costs and insufficient financing may prevent CI from effectively stimulating REINV. Therefore, the negative relationship between CI and REINV suggests that the environmental pressure associated with carbon intensity may be weakened by financial, structural, and institutional constraints before it can be transformed into renewable energy investment.

When the findings are evaluated together, they demonstrate that REINV in Türkiye is strongly influenced by economic and environmental factors such as GDP, OP, and CI. However, these effects are neither constant nor linear, as they vary across low, medium, and high quantiles. Therefore, decisions and policies regarding the energy transition must be formulated not solely on the basis of average market conditions, but by taking into account different economic and environmental dynamics. In particular, to increase REINV in a sustainable manner, it is essential not only to focus on GDP growth, but also to reduce financing costs, promote green finance practices, enhance innovation capacity in energy technologies, and formulate and consistently implement long-term energy policies that reduce dependence on non-renewable energy. Policy measures aimed at increasing REINV should primarily be designed to reduce the financial burden associated with investment. The development of green financing channels, such as low-interest loans and green bonds, together with various incentives and guarantee mechanisms, may create a supportive effect on REINV and generate positive momentum in renewable energy investments. In addition, instruments such as emissions trading systems or carbon pricing mechanisms may increase the cost of non-renewable energy use and make REINV relatively more attractive. Furthermore, initiatives such as strengthening the technological infrastructure in the renewable energy sector, promoting innovation, and expanding energy storage capacity may contribute to the long-term sustainability of REINV in Türkiye.

6. CONCLUSION

Uncertainties in global energy markets, fluctuations in energy prices, and risks related to energy supply are directing countries toward renewable energy sources. This is particularly significant for developing economies such as Türkiye, which exhibit high levels of energy import dependence. In this context, identifying the determinants of REINV is of great importance for the design of policies aimed at energy transition. This study aimed to investigate the relationship between REINV and GDP, OP, and CI for Türkiye. To this end, quarterly data spanning the period 2001–2024 were analyzed using a wavelet-quantile approach. Within this framework, the BDS test was applied to examine the linearity structure of the variables; WQADF and WQPP tests were employed for unit root testing; and the WQR and WQGC methods were used to determine the magnitude of effects and the direction of causality among the variables, respectively. According to the findings, the relationships among the variables vary across frequency and quantile dimensions and are neither linear nor homogeneous. The BDS test confirmed that the variables contain nonlinear dynamics, while the WQADF and WQPP tests established that their stationarity structures can vary by quantile and frequency component. These preliminary test results therefore support the use of wavelet-quantile-based approaches.

According to the results obtained from the WQR analysis, REINV is affected to varying degrees by all the variables examined, depending on the frequency component and quantile level. In this regard, the effect of GDP representing economic growth on REINV is positive across the short-, medium-, and long-run frequency components. This result supports the view that the growth environment created by increases in GDP in Türkiye may lead to capacity expansion and that, in order to meet the energy demand resulting from increased capacity, a shift toward REINV may occur. However, the variation of this positive effect across frequency and quantile dimensions indicates that GDP does not always exert an impact of the same magnitude on REINV. Accordingly, a sustained continuous effect can be achieved through financing opportunities, public incentives, and sustainable energy policies. The findings regarding OP similarly indicate that the relationship is largely positive. Nevertheless, the relationship was found to be negative and relatively weaker, particularly in the medium-frequency component and at middle quantile levels. This finding indicates that the effect of OP on REINV operates in two directions: supportive and suppressive. This implies that as OP rises in Türkiye, REINV may increase as an alternative to non-renewable energy, while uncertainty in energy markets, rising costs, and insufficient financing opportunities may lead to a decline in REINV. The effect of CI on REINV, on the other hand, is negative across all frequency and quantile components. This result for Türkiye supports the view that REINV is not solely influenced by CI but that uncertainties in economic and energy markets play a significant role. Therefore, the positive effect of increases in CI on REINV may be realized through increased incentives for installation costs related to REINV, facilitation of financing opportunities, technological innovations, and enhanced levels of environmental awareness regarding energy use at both the individual and institutional levels.

The WQGC results also support the WQR findings. The causal relationships running from GDP, OP, and CI to REINV are observed to hold particularly in the long run across many quantiles, and are also evident across numerous frequency and quantile levels. This accordingly underscores that REINV is influenced by economic, energy, and environmental indicators, especially in the long-run frequency components. Moreover, the causal relationship among the variables is found to be more pronounced, particularly at higher quantile levels of REINV. This finding may indicate that REINV becomes more sensitive to economic and environmental determinants beyond a certain threshold. In general terms, increases in REINV in Türkiye depend not only on the continuity of GDP, but also on uncertainties in OP and increases in CI. For this reason, policymakers should pursue a sustainable, multidimensional energy transition strategy aimed at increasing REINV. In this context, it is of great importance that economic measures be taken to facilitate financing and reduce costs, that innovation toward renewable energy be supported, and that policies prioritizing energy supply security be developed and resolutely implemented. In this context, improving green financing opportunities may help ease the financing conditions for REINV. Instruments such as increasing green bond issuances, reducing the cost of green credit, providing tax incentives, offering investment guarantees, and implementing carbon pricing mechanisms can support renewable energy investments. In this way, greater private sector participation in REINV can be encouraged, thereby contributing to an increase in renewable energy investment. In addition, improvements in grid infrastructure and energy storage capacity, together with the development of innovation and technological capabilities, may help REINV follow a more stable and sustainable path over the long term.

This study contributes to the literature by examining the determinants of REINV in Türkiye across frequency and quantile dimensions. However, considering the data period and variable set of the study, future research could extend the work by employing different variables that may influence REINV. In addition, different variables for Türkiye and/or different countries over a broader temporal horizon could be examined to comprehensively compare the determinants of REINV. This would enable identification of the variables that most strongly trigger REINV in each country.

DECLARATION OF ETHICAL STANDARDS

The The authors of the paper submitted declare that nothing which is necessary for achieving the paper requires ethical committee and/or legal-special permissions.

CONTRIBUTION OF THE AUTHORS

Mustafa UYSAL: Conceptualization, Supervision, Writing, Review, Editing

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CONFLICT OF INTEREST

There is no conflict of interest in this study.

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