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Exploring the Non-linear Relation Between Renewable Energy and Productivity in Türkiye

Türkiye'de Yenilenebilir Enerji ile Verimlilik Arasındaki Doğrusal Olmayan İlişkinin İncelenmesi

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Abstract

This study aims to investigate the asymmetric effects of renewable energy use on Türkiye's total factor productivity (TFP) by applying the Non-linear Autoregressive Distributed Lag (NARDL) model for the period 1990-2019. TFP is treated as the response variable, whereas the share of renewable energy use, trade openness, and human capital are involved in the model as explanatory variables. The empirical results reveal a lucid asymmetric association between renewable energy and TFP. Positive shocks in renewable energy share reveal a statistically significant and positive effect on TFP, while negative shocks do not appear to have a significant effect. This finding highlights the role of renewable energy capacity expansion as a driver of economic productivity, while contractions do not produce equally strong adverse effects. In addition, trade openness is found to support productivity in the long run, while human capital counterintuitively exhibits a negative effect on TFP. Also, Diagnostic tests support the stability and statistical validity of the estimated model. The findings imply that renewable energy policies should prioritize expansion strategies, given their positive and asymmetric effects on TFP.

Keywords: Renewable Energy, Total Factor Productivity, Türkiye, Asymmetric Effects.

JEL Classification: C32, O47, Q42, Q43.

Öz

Bu çalışma, 1990-2019 dönemi için Doğrusal Olmayan Otoregresif Dağıtılmış Gecikmeler (NARDL) modeli uygulanarak, yenilenebilir enerji kullanımının Türkiye'nin toplam faktör verimliliği (TFP) üzerindeki asimetrik etkilerini incelemeyi amaçlamaktadır. Çalışmada TFP bağımlı değişken olarak ele alınırken, yenilenebilir enerji kullanımının payı, dışa açıklık ve beşerî sermaye ise açıklayıcı değişkenler olarak modele dâhil edilmiştir. Ampirik sonuçlar, yenilenebilir enerji ile TFP arasında açık bir asimetrik ilişki olduğunu ortaya koymaktadır. Yenilenebilir enerji payındaki pozitif şokların TFP üzerinde istatistiksel olarak anlamlı ve pozitif bir etkisi bulunurken, negatif şokların anlamlı bir etkisi gözlemlenmemektedir. Bu bulgu, yenilenebilir enerji kapasitesinin artırılmasının ekonomik verimlilik için bir itici güç olduğunu, buna karşın daralmaların aynı ölçüde güçlü olumsuz etkiler üretmediğini göstermektedir. Ayrıca, dışa açıklığın uzun vadede verimliliği desteklediği tespit edilirken, beşerî sermayenin TFP üzerinde şaşırtıcı biçimde olumsuz bir etkisi olduğu görülmüştür. Bununla birlikte, gerçekleştirilen tanılayıcı testler, tahmin edilen modelin istikrarını ve istatistiksel geçerliliğini desteklemektedir. Elde edilen bulgular, toplam faktör verimliliği üzerindeki olumlu ve asimetrik etkileri nedeniyle yenilenebilir enerji politikalarında genişleme odaklı stratejilerin tercih edilmesi gerektiğini göstermektedir.

Anahtar Kelimeler: Yenilenebilir Enerji, Toplam Faktör Verimliliği, Türkiye, Asimetrik Etkiler.

Jel Sınıflandırması: C32, O47, Q42, Q43.

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1. Introduction

Total factor productivity (TFP) is a fundamental indicator that ensures the sustainability of economic growth, regardless of the quantitative increases in the factors of production. TFP is vital for economic growth as it captures the efficiency of converting inputs into outputs. It reflects the overall productivity of an economy and can be considered as a source of output growth (Chen, 1997). In addition, higher TFP is associated with better technological levels, higher capital per worker, and more significant returns, and it covers all the effects that enhance the productivity of physical factors (Ahmad et al., 2010).

TFP is central to explaining the long-term dynamics of economic growth, so it is critical to comprehend its influencing factors. Such an analysis will help determine strategies to accelerate TFP and economic growth. Existing studies have systematically addressed the impacts of the economic indicators (Degu & Bekele, 2019; Teeli et al., 2023), structural elements (Goldar et al., 2023; Jalles, 2024), and institutional characteristics (Balcerzak & Pietrzak, 2016; Ngo & Nguyen, 2020) on TFP. However, the increasing sensitivity to environmental sustainability at the global level, especially in the recent period, and the acceleration of energy transformation processes necessitate re-evaluating the potential effects of energy resources on productivity. In this context, it is crucial to incorporate renewable energy consumption in the analysis not only in terms of environmental performance or energy security but also in terms of its potential contributions to the efficiency and productivity level of production processes.

In this context, the structure of energy consumption has also become an important factor affecting the efficiency of the production process (Tugcu & Tiwari, 2016). Traditional fossil-based energy systems bring many problems, especially environmental negativities (Chien, 2022). Expanding the weight of renewable energy sources in the energy mixture offers important opportunities for both environmental sustainability and economic efficiency. However, factors such as the high costs of renewable energy investments, production costs, and prices of alternative fuels make the direction of the effect of this transformation on TFP unclear (Sohag et al., 2021). Moreover, the influence of both renewable and non-renewable energy on TFP may not be linear, and increase-decrease movements may produce different results (Paul et al., 2022). Therefore, answering questions such as the direction, magnitude, and symmetricity of the impact of renewable energy on TFP represents an important gap in the literature.

In countries dependent on energy, such as Türkiye, energy policies must no longer be evaluated solely within the framework of energy supply security or environmental sustainability but also in terms of economic efficiency and production effectiveness. In Türkiye, as a developing country, understanding the impact of increasing renewable resources in the energy mix on efficiency indicators such as TFP is crucial regarding resource allocation and policy direction. Indeed, empirical studies on OECD countries show that renewable energy increases TFP in the long term (Sohag et al., 2021). However, this impact may also vary depending on the region, economic activity level, societal context, environmental preservation, and technological disparities (Li et al., 2024). Moreover, as Şengül (2023) emphasizes, macroeconomic constraints arising from global tax competition and fiscal capacity erosion may limit the ability of developing countries like Türkiye to finance and implement long-term renewable energy strategies effectively.

Figure 1. TFP of Türkiye over 1990-2019

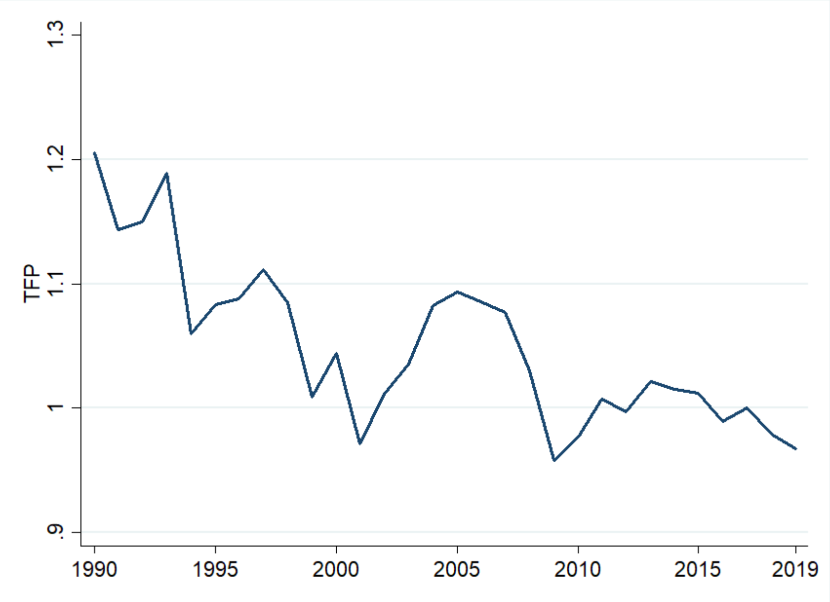
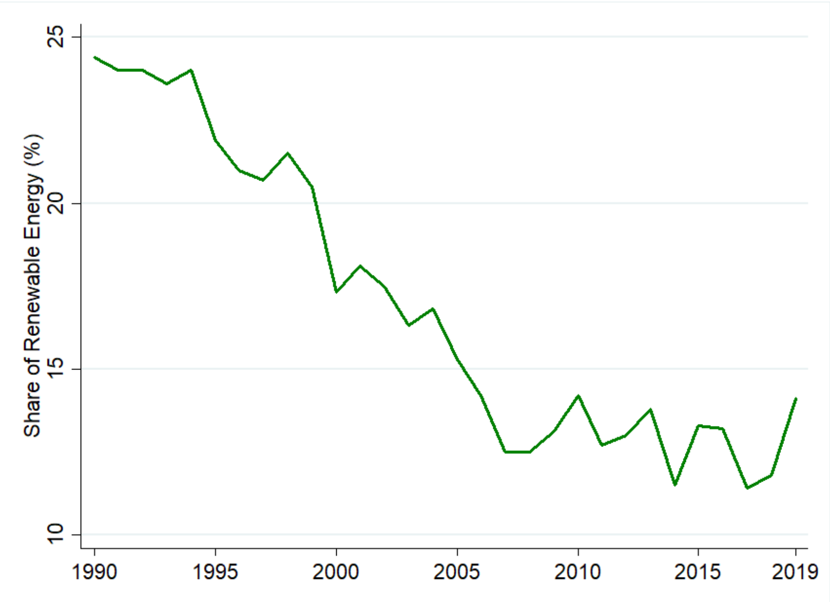


Figure 2. Share of the Renewable Energy in Aggregate Use in Türkiye over 1990-2019



Figures 1 and 2 show Türkiye's TFP and renewable energy shares. When the data for the period 1990–2019 are examined, remarkable fluctuations are observed in both TFP and the portion of renewable energy usage in overall energy in Türkiye. In the early 1990s, the portion of renewable energy was around 24%, which was also a period when TFP was relatively high. However, a significant decrease was observed in both indicators until the mid-2000s. While there was a sharp decrease in TFP, especially in the years close to the 2008 global crisis, there was a constant drop in renewable energy's share.

Although TFP has shown a relative recovery trend after 2010, the portion of renewable energy has not reached past levels. As of 2014, both indicators have fluctuated but have been observed to be horizontal. This fact indicates that the effects of the transformation process in Türkiye's energy structure on efficiency have changed over time, and it emphasizes the importance of periodic analysis in the study.

These observations reveal that TFP and renewable energy indicators have common breaking points not only in terms of level but also in terms of temporal dynamics. In such a case, it is substantial to examine the contribution of renewable energy to efficiency and production. Therefore, the primary purpose of this research is to analyze the influence of renewable energy use on total factor productivity in Türkiye. Variables such as growth and productivity are affected by many different factors. In this study, various control variables, as well as possible asymmetric impacts of renewable energy share, are examined.

This work makes a number of contributions to the literature in terms of both content and methodology. First, while many studies concentrate on the connection between renewable energy and economic growth, this research directly examines TFP and reveals how productivity is affected by energy transition. Second, the analysis provides empirical verification from a developing country's perspective, specifically Türkiye. Third, this research models the asymmetric effects of energy transitions so that the potential consequences of energy policies can be assessed more practically.

2. Literature Review

TFP is a crucial determinant of income and growth differences across countries. Thus, understanding its influencing factors can inform policymaking to enhance TFP growth. Many scholars analyze the effects of several variables like initial income, trade openness, education, institutions, financial development, human capital, technology level, investment, innovation, and R&D (see Ascari & Di Cosmo, 2004; Isaksson, 2007; Danquah et al., 2014; Kale & Rath, 2018; Adnan et al., 2020; Linh, 2021). In addition, there are also studies examining asymmetric relationships (see Arbex et al., 2018; Udeagha & Ngepah, 2021; Xie et al., 2021). Among the wide range of factors examined in the literature, some stand out due to their persistent and direct linkage with productivity performance. In this context, the present study focuses on three key variables - human capital, trade openness, and renewable energy - which are frequently cited as fundamental drivers of total factor productivity yet still leave room for deeper investigation, especially in the context of developing economies. Below, a more focused discussion of each of these determinants is provided.

Human capital significantly influences TFP. A more educated, healthy, and skilled workforce is expected to produce more output with the same amount of input. This means that TFP increases with human capital. Indeed, Miller and Upadhay (2000) argue that human capital generally affects TFP positively. Wei and Hao (2011) find that human capital exerts a significant and affirmative influence on TFP growth across Chinese provinces. Conversely, the authors also contend that the impact of human capital varies across regions depending on the level of education. Habib et al. (2019) also show that human capital positively affects TFP in their study covering 16 countries. On the other hand, Gong (2016) finds that human capital inequality negatively affects TFP, while high-quality human capital positively affects it. Okunade et al. (2022) also find that human capital hinders productivity growth below a certain threshold value. Wang (2023) observe that rural human capital negatively affects the agricultural total factor productivity.

One of the factors affecting TFP is the trade openness of countries. Foreign trade openness can increase international competition and, therefore, productivity. At the same time, foreign trade can encourage technological innovation and knowledge transfer. In general, foreign trade openness makes a positive contribution to productivity growth or economic growth with these aspects. Danquah et al. (2014), for instance, demonstrate that trade openness promotes TFP growth in a sample of 67 countries. Supporting this finding, Haider et al. (2019) report a similar positive link between trade openness and TFP in the case of India. Likewise, Oliveira de Almeida et al. (2024) provide evidence of a positive impact of trade openness on TFP in Brazil. In a more specific context, Wu and Han (2022) investigate the effects of China's Belt and Road Initiative at the city level and find that this initiative significantly enhances TFP in key provinces. Abizadeh and Pandey (2009), who take into account sectoral differences for 20 OECD countries, find that openness has a significant effect on TFP growth only in the service sector, while there is no significant association in the agriculture and industry sectors.

Renewable energy usage can also increase efficiency through various channels. The increasing portion of renewable energy may create a more sustainable and efficient production process by reducing dependency on fossil fuels and reducing costs. This may result in an overall improvement in efficiency. For instance, Sohag et al. (2021) argue that the increasing share of renewable energy in the production process in OECD countries increases TFP in the long run. However, Tugcu and Tiwari (2016) do not find a significant causal connection between renewable energy usage and TFP growth in BRICS countries. In their study covering Chinese provinces, Li et al. (2024) show that renewable energy development significantly increases green TFP. Xie et al. (2021) observe a non-linear link between renewable energy transition and Green TFP. Wang and Yan (2023) also show in their study examining Chinese cities that renewable energy is generally beneficial in improving total factor energy efficiency but exhibits significant heterogeneity and nonlinearity in certain provinces.

When the existing literature is examined, it is seen that there are many different variables at institutional, technical, demographic, and economic levels among the factors affecting TFP. While it is realized that variables such as openness to trade, renewable energy use, and technological progress generally have positive effects, different aspects of these effects are also observed in some studies. It is thought that the different results obtained may be due to the characteristics of the region examined, the periods covered, the analysis methods used, and the existence of asymmetric relationships. In this context, it can be said that advanced methods that can consider asymmetric and non-linear relationships should be used in the analysis of these variables whose effects on TFP are examined.

3. Data and Empirical Framework

This research employs a set of variables compiled from different sources to analyze how renewable energy influences TFP in Türkiye. TFP and human capital index variables are compiled from the Penn World Tables (PWT) developed by Feenstra et al. (2015). The share of renewable energy in final use and trade openness variables are compiled from the World Bank (2025a) and World Bank (2025b), respectively. Table 1 displays the definitions and summary statistics of the variables.

Variable	Definition	Mean	Std. Dev.	Minimum	Maximum	Source
TFP	TFP at constant national prices (2017=1).	1.049	0.066	0.958	1.205	PWT
renew	The share of renewable energy consumption in total final energy use.	16.940	4.463	11.400	24.400	World Bank
hc	The human capital index, based on years of schooling and returns to education.	2.107	0.219	1.802	2.514	PWT
trade	The share of total exports and imports of goods and services in gross domestic product.	47.001	8.300	30.476	63.193	World Bank

According to the summary statistics in Table 1, TFP is at the level of 1.049 on average and has a relatively stable distribution with a low standard deviation (0.066). The variable of renewable energy use varies between 11.4 and 24.4 with a mean of 16.94, indicating a relatively wider distribution in the data set. The human capital index is distributed in a very narrow range (1.802 - 2.514) with a mean of 2.107 and exhibits low variance. Trade openness is the variable with the highest mean with an average of 47.00, and shows a wide distribution between 30.476 and 63.193.

This study primarily aims to investigate the impact of renewable energy on total factor productivity in Türkiye. One of the methods frequently used in time series analyses is the Autoregressive Distributed Lag (ARDL) model. The purpose of using this model developed by Pesaran et al. (2001) is that short-term and long-term impacts may be estimated with the ARDL model, the degrees of stationarity of the variables used can be different, and it can be applied to a small number of samples. While this method can make many inferences, potential asymmetries cannot be captured. Therefore, in this study, the non-linear ARDL model proposed by Shin et al. (2014), which can capture asymmetric effects as well as the flexible properties of ARDL, will be used.

In this respect, we start our analysis by regarding the non-linear ARDL model in equation (1).

$$TFP_t = \beta_0 + \sum_{i=1}^{a} \beta_{1i} TFP_{t-i} + \sum_{i=0}^{b} \beta_{2i} ren_{t-i}^{+} + \sum_{i=0}^{c} \beta_{3i} ren_{t-i}^{-} + \sum_{i=0}^{d} \beta_{4i} trade_{t-i} + \sum_{i=0}^{e} \beta_{5i} hc_{t-i} + u_t \qquad (1)$$

where a, b, c, d, and e are the optimum lag values to be determined by the information criteria. TFP shows total factor productivity, $trade$ represents trade openness, hc is the human capital, and ε_t denotes the error term. The ren^{+} and ren^{-} variables show the partial sums of the positive and negative adjustments in the ren that can be defined as $ren_t = ren_0 + ren_t^{+} + ren_t^{-}$.

We may define equation (1) 's relationship in the error correction form with the trend as follows.

$$\begin{aligned}\Delta TFP_t = {} & \alpha_0 + \alpha_1 t + \sum_{i=1}^{a} \beta_{1i} \Delta TFP_{t-i} + \sum_{i=0}^{b} \beta_{2i} \Delta ren_{t-i}^{+} + \sum_{i=0}^{c} \beta_{3i} \Delta ren_{t-i}^{-} + \sum_{i=0}^{d} \beta_{4i} \Delta trade_{t-i} \\ & + \sum_{i=0}^{e} \beta_{5i} \Delta hc_{t-i} + \beta_6 TFP_{t-1} + \beta_7 ren_{t-i}^{+} + \beta_8 ren_{t-i}^{-} + \beta_9 trade_{t-1} + \beta_{10} hc_{t-1} + e_t \end{aligned} \qquad (2)$$

The conventional ARDL model captures both the short-run and the long-run linear relationship among variables. On the other hand, the non-linear ARDL (NARDL) method proposed by Shin et al. (2014) can augment the model by including the asymmetric relationship between variables. The NARDL approach can describe positive and negative partial sums of the ren variable as follows:

$$ren_t^{+} = \sum_{j=1}^{t} \Delta ren_t^{+} = \sum_{j=1}^{t} \max(\Delta ren_j, 0) \text{ and}$$

$$ren_t^{-} = \sum_{j=1}^{t} \Delta ren_t^{-} = \sum_{j=1}^{t} \min(\Delta ren_j, 0)$$

In equation (2), the bound test can analyze the existence of a long-term cointegration among the variables. In this regard, the following hypotheses are tested.

$$\begin{gathered} H_0: \beta_6 = \beta_7 = \beta_8 = \beta_9 = \beta_{10} = 0 \\ H_1: At\ least\ one\ of\ the\ parameters\ is\ different\ from\ zero. \end{gathered} \qquad (3)$$

In other words, the null hypothesis indicates the absence of cointegration, while the alternative hypothesis suggests that a cointegrated relationship exists among the variables. Furthermore, asymmetric impacts of the variables can also be tested by the parameters in equation (2). The long-run asymmetric impacts may be tested by the hypothesis of $\theta^{+} = \theta^{-}$, where θ^{+} and θ^{-} are the lon-term coefficients of the ren^{+} and ren^{-} variables[1]. Similarly, short-term asymmetric influences are examined by testing the hypothesis of $\sum_{i=0}^{b} \beta_{2i} = \sum_{i=0}^{c} \beta_{3i}$.

Then, we can construct a conditional error correction model to analyze the short-run dynamics.

$$\begin{aligned}\Delta TFP_t = {} & \alpha_0 + \alpha_1 t + \sum_{i=1}^{a} \alpha_{1i} \Delta TFP_{t-i} + \sum_{i=0}^{b} \alpha_{2i} \Delta ren_{t-i}^{+} + \sum_{i=0}^{c} \alpha_{3i} \Delta ren_{t-i}^{-} + \sum_{i=0}^{d} \alpha_{4i} \Delta trade_{t-i} \\ & + \sum_{i=0}^{e} \alpha_{5i} \Delta hc_{t-i} + \gamma ect_{t-1} + e_t \end{aligned} \qquad (4)$$

[1] Long-run coefficients are calculated by the parameters in equation (2) as follows. $\theta^{+} = \beta_7/\beta_6$ and $\theta^{-} = \beta_8/\beta_6$.

In equation (4), the γ coefficient represents the speed of adjustment and shows how rapidly short-term deviations reach equilibrium in the long term.

4. Empirical Results

This part of the study reports the findings based on our investigation. Before the NARDL analysis, we tested the stationarity of the variables that we used. Table 2 represents the unit root test results based on Augmented Dickey-Fuller (ADF) and Zivot and Andrews (2002) (ZA) tests.

Table 2. Unit Root Tests

	ADF test statistics		ZA test statistics	
Variable	Intercept	Trend and Intercept	Intercept	Trend and Intercept
TFP	-2.57	-4.43***	-4.07	-4.37
ΔTFP	-6.66***	-6.53***	-6.91***	-6.70***
renew	-1.60	-1.36	-1.56	-5.46**
$\Delta renew$	-5.20***	-5.77***	-7.09***	-7.01***
hc	3.23	2.96	-2.72	-4.55
Δhc	0.14	-4.30**	-7.71***	-17.59***
trade	-0.37	-3.88**	-4.15	-6.38***
$\Delta trade$	-4.86***	-3.73**	-6.55***	-6.51***

Notes: ** and *** show the significance levels at 5% and 1%, respectively. Null hypotheses of both approaches assume that the corresponding series includes unit root.

Estimation results in Table 2 present varied results for some variables. For example, our dependent variable *TFP* is stationary around a trend at the level according to the ADF test, while its first difference is stationary according to the ZA test. If we consider only the intercept model, it can be said that *TFP* is stationary at the first difference. A similar situation applies to the *renew* variable. Although it seems trend-stationary at the level according to the ZA test, when all tests are taken into account, we can say that the *renew* variable is I(1). The ADF test with intercept for the *hc* variable indicates that there is a unit root even at the first difference. However, when the pattern of this series is examined, a non-decreasing trend is seen. Therefore, *hc* can also be accepted as I(1). The *trade* variable is trend-stationary at the level according to both the ADF and ZA tests. Therefore, this situation may indicate that this series is I(0). Although there are unclear results, it is obvious that the stationarity degrees of all variables are not 2, which is a desired situation for the ARDL model.

Since all variables meet the requirements of the NARDL approach, we can conduct an NARDL model to examine asymmetric relationships. Based on the Schwarz Information Criteria, optimal lag lengths for the corresponding variables are determined as NARDL (1, 3, 0, 3, 0). Before investigating the short-run and long-run dynamics, we conduct the bound test to determine the existence of cointegration. Table 3 reports the bound test results for the NARDL (1, 3, 0, 3, 0) model.

Table 3. Bounds Test Results

Model	F-stat	Significance Level	Critical Values for Lower Bounds	Critical Values for Upper Bounds
NARDL (1, 3, 0, 3, 0)	12.04	10%	3.43	4.62
		5%	4.15	5.54
		1%	5.86	7.56

Note: Critical values are provided for the finite sample case when the number of observations is 30.

The calculated F-statistics is pretty higher than the critical value for the upper bound at 1% significance level, implying the rejection of the no relationship hypothesis. In other words, bounds test results suggest that there is a long-term cointegration relationship among the variables. After the confirmation of the cointegration, we can investigate the short and long-run dynamics suggested by the NARDL model.

Table 4. Estimation Results of the NARDL (1, 3, 0, 3, 0) Model

Short-Run Coefficients		
Variables	Coefficient	P-Value
Δren_t^+	0.028	0.010
Δren_{t-1}^+	-0.078	0.000
Δren_{t-2}^+	-0.030	0.033
$\Delta trade_t$	0.001	0.128
$\Delta trade_{t-1}$	-0.006	0.000
$\Delta trade_{t-2}$	-0.005	0.000
ECM_{t-1}	-0.715	0.000
Trend	0.062	0.000
Constant	8.867	0.000
Long-Run Coefficients		
ren^+	0.208	0.002
ren^-	-0.020	0.130
$trade$	0.014	0.011
hc	-6.652	0.002
Long-Run Asymmetric Test		
	Test-Statistic	P-Value
W_{LR}	15.044	0.002
Diagnostic Tests		
Heteroscedasticity test	10.404	0.580
Breusch-Godfrey Serial Correlation LM test	3.087	0.214
Jarque-Bera test on normality	0.395	0.821
Ramsey reset test	0.242	0.632
CUSUM	Stable	
CUSUMQ	Stable	

According to the results from the diagnostic tests, the stability is ensured for the estimated model. Short-term results of the NARDL model reveal that the current value of the ren^+ variable has a positive and significant effect on TFP, while its lagged values are negative. This situation shows that positive shocks in renewable energy can create fluctuating or temporary negative effects in the short term. While the current value of foreign trade openness is insignificant in the short term, its lagged values are negative and significant. This situation shows that foreign trade shocks can suppress TFP in the short term. One of the most important results is that the coefficient of the error correction term is -0.715 and significant at 1% significance level. Accordingly, it shows that the model returns from short-term deviations to long-term balance at a rate of 71.5%.

According to the long-term estimation results, the increase in ren^+ has a significant and positive effect on TFP in the long term. Consistent with some prior literature, our results indicate that increased renewable energy use enhances long-term production efficiency - highlighting Türkiye's successful energy transition trajectory. The ren^- variable, which shows the effect of negative changes in renewable energy, is not found to be significant at conventional significance levels. The Wald test result also confirms this asymmetric relationship. Among the control variables, trade openness is also estimated as positive and significant. This indicates that open economies can increase TFP. However, the human capital index is also negative and statistically significant. This unexpected result shows that although human capital increases quantitatively, its effect on productivity may be negative.

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Conclusion

This research explores the asymmetric effects of renewable energy use on TFP in Türkiye for the period 1990-2019. According to the results obtained through the NARDL model, the short-run impacts of the ren^{+} variable on TFP fluctuate. This situation can be rationalized by the fact that renewable energy investments play a supporting role in production processes in the short term, as well as the maturity period of investment processes or the time it takes for infrastructural transformation. The negative and significant foreign trade openness indicates that short-term fluctuations in foreign trade can put pressure on TFP. This situation can be explained by sudden exchange rate fluctuations, variability in foreign trade policies or sensitivity to external shocks.

When the long-term coefficients are examined, positive shocks in the portion of renewable energy use have a significant and positive effect on TFP. This finding reveals that energy policies based on environmental sustainability can provide benefits not only in terms of environmental but also economic efficiency. On the other hand, the fact that negative energy shocks do not have a significant effect in the long term suggests that renewable energy systems may be relatively resilient to adverse conditions. These types of non-linear and heterogenous relationships are also confirmed by some scholars (Xie et al., 2021; Wang & Yan, 2023).

Trade openness has a positive and significant effect on TFP in the long term. This result shows that open economies can increase their productivity by benefiting from knowledge and technology transfer. There are many studies finding similar effects of trade openness on TFP (Danquah et al., 2014; Haider et al., 2019; Wu & Han, 2022; Oliveira de Almeida et al., 2024). However, considering the negative effects in the short term, it is understood that foreign trade policies should be carried out in a stable and guiding manner. In contrast, the long-term coefficient of the human capital variable is negative and significant. This unexpected result shows that the quantitative increase in human capital does not directly coincide with the increase in productivity. Factors such as structural problems in the education system and skill mismatches with the labor market may explain this result. While majority of the studies support positive effect of human capital (Miller & Upadhay, 2000; Wei & Hao, 2011; Habib et al., 2019), some studies suggest that different levels of human capital may have varying impacts on TFP. For example, Okunade et al. (2022) realize the requirement of a certain threshold value to observe positive impacts while Wang (2023) find that rural human capital negatively affects the agricultural total factor productivity.

Increasing renewable energy share has positive effects on economic productivity in both the short and long term. Therefore, it is recommended that the relevant incentive mechanisms be increased and the technological infrastructure strengthened. Foreign trade policies support productivity in the long term. However, considering the vulnerability to short-term fluctuations, an economic structure resistant to external shocks should be developed. Human capital policies should be strengthened qualitatively. It is recommended that the quality of the education system be increased, vocational skills be aligned with market demands, and strategies be developed to prevent brain drain.

These findings underscore the resilience of renewable energy contributions to productivity: while expansion stimulates TFP, contraction does not proportionally hinder it - a crucial insight for policy prioritization. This asymmetric dynamic reveals that renewable energy expansion is a more effective driver of productivity than its contraction is a source of harm, emphasizing the strategic importance of sustained investment in green energy.

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Extended Abstract

Background

Total Factor Productivity (TFP) is widely regarded as a critical determinant of long-term economic growth, reflecting the efficiency with which inputs are transformed into outputs. In recent years, the global transition toward sustainable development has placed increasing emphasis on the role of renewable energy in supporting not only environmental goals but also economic efficiency. While many studies have explored the link between renewable energy and economic growth, fewer have investigated its specific effects on productivity, particularly in the context of developing economies such as Türkiye. Moreover, the possibility that the effects of renewable energy may be nonlinear and asymmetric has gained attention, yet remains underexplored in empirical research.

Research Purpose

This study aims to examine the asymmetric effects of the share renewable energy use on total factor productivity (TFP) in Türkiye over the period 1990–2019. The analysis further considers the roles of trade openness and human capital as control variables. By investigating both positive and negative shocks in renewable energy use, the study seeks to determine whether increases and decreases in renewable energy have symmetric or differing impacts on productivity.

Methodology

The analysis employs the Nonlinear Autoregressive Distributed Lag (NARDL) model developed by Shin et al. (2014), which enables the estimation of both short-run and long-run dynamics, while capturing potential asymmetries in the relationship between the variables. Stationarity was tested using ADF and Zivot-Andrews unit root tests, and the bounds testing procedure was applied to assess cointegration.

Findings

Empirical results reveal a statistically significant and asymmetric relationship between renewable energy and TFP. Positive shocks in renewable energy use increase TFP in both the short and long term, while negative shocks do not yield significant adverse effects. Trade openness positively contributes to TFP in the long run, though its short-term effects appear negative. In contrast, human capital demonstrates a counterintuitive negative effect on TFP in the long term, suggesting potential mismatches in the education system or inefficiencies in labor market alignment. The error correction term is significant and negative, confirming the existence of a long-term equilibrium relationship among the variables.

Conclusion

The findings underscore the strategic importance of expanding renewable energy capacity as a means to improve productivity and economic efficiency. The asymmetric nature of the results implies that increases in renewable energy use are more influential than decreases are harmful, highlighting the resilience of the energy system. Policymakers should prioritize incentives and infrastructure investments to support the renewable energy transition. Additionally, long-term productivity gains require not only openness to global markets but also substantial improvements in the quality and relevance of human capital through education reform and skill development.