

RESEARCH ARTICLE

Estimation of output and substitution possibilities between energy and non-energy inputs in Türkiye: Evidence from ridge regression

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ABSTRACT

The increase in CO₂ emissions resulting from fossil fuel consumption contributes to climate change and raises concerns about the attainment of environmental sustainability. This empirical study examines the potential for inter-factor and inter-fuel substitution in Türkiye from 1988 to 2023, focusing on the country's transition from fossil fuels to clean energy within the framework of environmental sustainability. Using ridge regression based on the translog production model, the findings reveal that the average output elasticities for non-energy inputs (labor and capital) and energy-specific inputs (petroleum, natural gas, coal, hydropower, and biomass) are positive. In addition, the average elasticities of substitution between factors in Türkiye range from 0.8463 to 1.5925, while those between fuel types range from 0.0058 to 0.1586. The results suggest that Türkiye has the potential to substitute fossil fuels with hydropower and biomass to meet the 2030 and 2050 targets outlined in the Paris Climate Agreement.

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INTRODUCTION

Economic paradigms emphasize different aspects of the interpretation of economic variables. Neoclassical Economics (NE), also known as mainstream economics, assesses the economy from the supply perspective. Because NE focuses on the supply side of the economy, it views labor productivity and capital accumulation as the most important factors in increasing productivity [1, 2]. As a result, NE estimates growth models with traditional input factors (labor and capital). However, following the 1973 oil crisis, when the Organization of Petroleum Exporting Countries (OPEC) reduced oil supply, energy was accepted as a factor of production along with labor and capital [3]. The rapid industrialization, primarily driven by the use of fossil fuels (FF) such as oil, coal, and natural gas, sparked concerns in the late 1980s about the feasibility of achieving environmental sustainability [4, 5, 6]. However, NE did not take into account the finite nature of natural resources and instead regarded the environment as an unlimited resource [7, 8, 9].

In the late 1990s, a new movement called Ecological Economics (EE) began to explore ways to build a sustainable economy that is good for the environment [10]. Developed by economists such as Boulding, Daly, Georgescu-Roegen, Holling, and Odum, EE emphasizes resource limitation and

environmental sustainability to promote a just world order and environmental protection [11, 12]. Specifically, Boulding highlighted the finite nature of the Earth's resources and asserted that economic activities should be mindful of ecological constraints [13]. In contrast to NE, which treats the environment as an infinite resource, Boulding emphasized the importance of balancing economic growth with ecological sustainability [14, 15]. Moreover, Boulding adopted a nature-conscious perspective, advocating that human activities should not exceed the Earth's capacity to renew resources. Similar to Boulding, Daly, a significant contributor to the development of EE, criticized the goal of infinite growth inherent in NE, which relegates the environment to a secondary role. He argued that prioritizing the environment and acknowledging the depletion of natural resources are crucial for building a foundation for environmental sustainability [14]. One of Daly's key arguments regarding natural resources is that they and capital are not substitutable but rather complementary factors [16].

One of the key concepts introduced by EE is the law of entropy, also known as the second law of thermodynamics, a term originally derived from Physics [17, 18, 19]. In exploring the relationship between natural resources and economic growth, [20] argues that the economic system's conversion of high-density, valuable resources into commodities and waste

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increases entropy. The increase in entropy impedes the efficient utilization of natural resources, leading to energy inefficiency and limiting economic progress. Consequently, environmental sustainability is compromised, pollution increases, and resources depleted [21, 22, 23]. One of the key contributions of the entropy law to economics is its role as a constraints on natural resources in the execution of economic activities [24]. This law establishes a limit on the substitutability between human capital and natural capital [25]. Consequently, it challenges the traditional view of NE through the use of advanced technology, and replaces it with the understanding that natural resources are at risk of depletion unless corrective actions are taken.

Another insight provided by the law of entropy is that energy becomes progressively less useful with each use [22]. Given the essential role of energy in production, the substitution of energy with other inputs is limited due to the constant need for additional energy. This contradicts the assumption of a continuous substitution relationship between production factors, as proposed by NE. According to the law of entropy, FF cause a significant increase in entropy, which reduces energy efficiency [26]. However, fossil fuels continue to dominate the global energy mix, resulting in significant carbon dioxide (CO₂) emissions and contributing to climate change. Specifically, in 2023, global energy consumption reached 619.63 Exajoule (EJ), of which (196.43) EJ derived from petroleum, (164.03) EJ from coal, (144.37) EJ from natural gas, (24.57 EJ) from nuclear energy, (39.65 EJ) from hydroelectricity, and (50.58) EJ from renewable energy sources [27].

Under the authority of the United Nations Framework Convention on Climate Change (UNFCCC), the UN instituted the Kyoto Protocol (COP³) in 1997 and the Paris Climate Agreement (COP²¹) in 2015 with state parties to address climate change [28]. Greenhouse gas (GHG) emissions are a major contributor to climate change. COP³ raised the issue of GHG emissions, and COP²¹ accepted quantitative emission reduction targets [29]. COP²¹ aims to reduce GHG emissions gradually by 2030 and limit global warming to 1.5°C by 2050. The NDCs established at COP²¹ propose strategies to increase the share of clean and renewable energy sources (C-RES), such as nuclear, solar, wind, hydropower, geothermal and biofuels, in total national energy consumption by 2030, while aiming to achieve net-zero CO₂ emissions by 2050 [30].

The extent to substitute FF and increase the share of C-RES in the energy mix depends on the fuel substitution potential. The first study on inter-fuel substitution potential was carried out by Berndt and Wood [31]. Following this benchmarking study, our research presents three key research questions: First, to what extent can non-energy inputs (labor and capital) substitute for energy-specific inputs (coal, oil, natural gas, hydropower, and biomass) in Türkiye's production process? Second, what are the substitution elasticities between different fuel types, and how do they impact Türkiye's energy transition? Finally, how feasible is Türkiye's transition from fossil fuels to clean energy sources like hydropower and biomass to achieve environmental sustainability targets for 2030 and 2050? To answers these questions, this empirical study employs the Ridge Regression (RR) approach to estimate Translog Production Function (TPF) developed by Christensen et al. [32] to examine the substitution potential among fossil fuels, hydropower, and biomass.

This study uses time series energy data for Türkiye from 1988 to 2023. Türkiye is the case study of choice for a number of reasons. Firstly, in 2023, Türkiye contributed 411.102 million tonnes (Mt) of CO₂ emissions to the global total of 35,129.792 Mt from coal, oil, and natural gas [27]. Türkiye ranks 2nd in Europe for CO₂ emissions, with 411.102 Mt, following Germany, which emitted 571.859 Mt, out of a European total

of 3,546.767 Mt. Secondly, Türkiye's hydroelectric capacity in 2023 was at 31,779 megawatts (MW), representing 2.26% of the global hydroelectric capacity of 1,407,754 MW [33]. Thirdly, Türkiye generated 63,854 terawatt-hours (TWh) of electricity from hydropower in 2023, accounting for approximately 10% of Europe's total hydropower generation of 638,699 TWh [34]. Lastly, Türkiye consumed 0.20 Exajoules (EJ) of biomass in 2023, contributing to the global biomass consumption of 8.74 EJ, and ranking 4th in Europe after Germany (0.57) EJ, the United Kingdom (0.39) EJ, and Italy (0.22) EJ [27]. Considering these factors, we decided to focus on the economy of Türkiye.

This empirical study attempts to improve the existing literature on the Türkiye economy in multiple dimensions. First, it examines the potential for substituting non-energy inputs (labor and capital) with energy-specific inputs (coal, oil, natural gas, hydropower, and biomass) in the context of stimulating economic growth, maintaining the energy supply chain, and prioritizing environmental sustainability. Second, it employed the TPF to examine output and substitution elasticities between pairs of non-energy and energy-specific variables. The estimation of output elasticities explains the production factors that drive economic growth, while the estimation of substitution elasticities identifies the most efficient factors for production substitution, thereby ensuring energy security and environmental sustainability. Finally, it examines the potential for transitioning from FF to C-RES within the economy of Türkiye to assist in the development of sustainable energy policies concerning climate change. To the best of the authors' knowledge, this is the first empirical study that analyzes inter-factor and inter-fuel substitution potential in Türkiye by estimating output and substitution elasticities for FF, and C-RES.

The structure of this article is as follows: Initially, the relevant empirical literature is reviewed, followed by an evaluation of Türkiye's energy profile. Subsequently, the data, model, and methodology are outlined. The empirical results are then presented and discussed, and the paper concludes with policy recommendations.

LITERATURE REVIEW

It was not until the 1973 crisis that energy was recognized as a factor of production. Starting in 1973, the OPEC reduced oil supply in response to the Arab-Israeli conflict. This reduction resulted in the price of a barrel of oil to quadrupled to \$12 per barrel [35, 36]. The increase in the oil price per barrel, attributed to supply issues and increased demand, led to a reduction in global production volume [37]. This brought about the belief that energy is as significant a factor as labor and capital variables. Thus, the disruption of the oil supply chain and the escalating oil prices led to the gradual inclusion of energy in the production function [38]. Prior to the 1973 oil crisis, production functions were estimated primarily with labor and capital factors [39]. As it became clear that energy is equally crucial as capital and labor, it began to be integrated into production functions. The integration of energy into production functions also led to the research on the substitutability of energy between labor and capital factors. Understanding the substitution relationship among factors of production is necessary for the optimal allocation of resources [40]. Research on the potential for energy substitution with non-energy inputs could have major implications for policy due to the rising prices and shortage of energy resources. This literature review consists of studies examining inter-factor substitution relationships, followed by those exploring inter-fuel substitution relationships, and

finally studies focusing on both inter-factor and inter-fuel substitution relationships.

The first study of inter-factor substitution relationships was conducted by Christensen et al. [32] for the US manufacturing industry spanning 1929–1969. The study concluded that the two-input model is inappropriate for the production process when employing the Least Squares (LS) estimator with consumption, investment, capital, and labor variables. On the other hand, Berndt and Wood [31] conducted another study on the US manufacturing sector, which similarly examined the substitution relationships among factors. The variables of labor, capital, energy, and materials spanning 1947–1971 were analyzed employing Iterative Three-Stage Least Squares (I3SLS) and a Translog Cost Function (TCF). The empirical study's findings indicated that labor and energy are substitutable, whereas capital and energy are complementary. Similarly, Griffin and Gregory [41] analyzed the US manufacturing sector from 1947 to 1971, utilizing capital, labor, and energy variables through the Zellner estimator, and concluded that capital and energy are substitutable factors, contrary to the findings of Berndt and Wood [31]. Consequently, the results of the pioneering research on the inter-factor substitution and complementarity relationship are inconsistent.

The interactions of inter-factor substitution have been increasingly studied at the national level and across various sectors. Specifically, Smyth et al. [42] examined the Chinese steel sector from 1978 to 2007, while Lin and Fei [43] analyzed the Chinese agricultural sector from 1980 to 2012, using TPF. Their findings indicate that the substitution potential between energy and capital exceeds that between energy and labor. On the other hand, Liu et al. [44] analyzed the substitution relationships among capital, labor, and energy in China's heavy industry spanning 1994–2014 using TCF, finding that the highest substitution exists between labor and energy. Ouyang et al. [45] reported the substitution relationship among labor, capital, and energy in the Shanghai transportation sector from 2000 to 2014 using the Bootstrap method. The study's findings align with those of Liu et al. [44], that there is a highly significant substitution relationship between labor and energy. Additionally, Javid [46] analyzed the factors of labor, capital, electricity, oil, and natural gas in Saudi Arabia's industrial sector spanning 1990–2020 employing TPF model and concluded that all inputs are substitutable. Finally, Raza et al. [47] examined inter-factor substitution possibility in India's industrial sector from 1990 to 2020 using TPF and discovered that labor–energy and capital–energy substitution progressed more rapidly than capital–labor substitution, consistent with previous studies.

The need to replace FF, which dominate the energy mix, with clean and renewable energy has gained momentum, particularly since the Paris Climate Agreement was signed in 2015. This dynamism has resulted in an expanded examination of inter-fuel substitution possibilities. Notably, Xie and Hawkes [48] used TPF to examine the substitution relationships in China's transportation sector spanning 1980–2010, using oil, coal, natural gas, and electricity as variables. The study's findings reveal that a highly significant substitution relationship in China's transportation sector is between oil and natural gas. Suh [49] applied the Differential Fuel Allocation Model (DFAM) to analyze substitution and complementarity patterns within the US industrial sector from 1970 to 2010, adding biomass fuel alongside the variables employed by Xie and Hawkes [48]. The results of the study indicate that biomass serves as a substitute for coal and natural gas, as well as a complementary factor for electricity. Moreover, Lin and Atsagli [50] examined the substitution

relationship among coal, electricity, and oil inputs in the South African economy between 1980–2012 with TPF. The results of this empirical study validated that input factors are substitutable, in accordance with previous studies. Particularly, Opeyemi [51] analyzed the substitution relationship of FF with renewable energy sources (RES) in the Nigerian economy from 1987 to 2016. This study, consistent with most previous empirical research, was conducted using TPF, and all factors were reported as substitutes. In contrast to earlier empirical studies, Bello and Solarin [52] analyzed the substitution potential within the US electricity sector from 1985 to 2018, examining FF and C-RES (such as hydropower, nuclear power, wind power, biofuels, biomass, geothermal, and solar energy). Their findings indicated that all input factors are substitutes.

In order to overcome environmental destruction, studies on inter-factor and inter-fuel substitution relationships are increasing in the interest of shifting to C-RES. Particularly, Pindyck [53] conducted one of the first studies to examine substitution relationships between traditional factors and fuels. The TCF was used to analyze labor, capital, and energy (oil, gas, coal, and electricity) in Canada, France, Italy, Japan, the Netherlands, Norway, Sweden, the United Kingdom, the United States, and West Germany from 1963 to 1973. The study's findings indicate that energy and capital substitution, as well as electricity demand, are less elastic than for other fuels. Ma et al. [54] employed the Two Stage Translog Cost Function (L2TCF) to analyze labor, capital, coal, electricity, diesel, and gasoline fuels in the Chinese economy from 1995 to 2004. The results of the study show that capital, labor, electricity, coal, gasoline, and diesel are substitutable, while coal and diesel are complementary. Notably, Wesseh et al. [55] used both TPF and TCF methodologies to examine substitution options in Liberia's industrial sector spanning 1980–2010. The results of the study demonstrated that labor, capital, oil, and electricity are all substitutable input factors. All inputs are substitutable, according to Wesseh and Lin [56], who used TPF model to analyze the labor, capital, coal, electricity, and oil inputs in the African economy between 1980 and 2011.

Furthermore, Lin and Tian [57] found that all inputs are substitutable through the Seemingly Unrelated Regression (SUR) estimator, utilizing data on labor, capital, coal, oil, and hydropower for China's light industry from 1980 to 2013. Likewise, Wang and Lin [58] reported a comparatively low substitution relationship among coal, oil, and electricity using TCF in China's iron and steel industry from 1985 to 2011. Khalid and Jalil [59] analyzed the factors of labor, capital, hydropower, oil, and natural gas in the Pakistani economy from 1980 to 2013 using TPF model, and concluded that substituting natural gas for coal could mitigate environmental degradation. Furthermore, Khalid et al. [60] conducted a study on Pakistan's energy sector, analyzing labor, capital, coal, hydropower, and oil variables from 1980 to 2017 using TPF, and concluded that all input factors are substitutable. Ultimately, Raza and Cucculelli [61] employed TPF to analyze the substitution probabilities of factors in Pakistan's energy sector from 1986 to 2019, integrating nuclear energy into the variables used by Khalid et al. [60]. The study found that FF and C-RES can substitute one another.

The empirical literature on inter-factor and inter-fuel substitution possibilities is relatively scarce, particularly in relation to the Türkiye economy. In a study on Türkiye, Songur [62] analyzed the relationships of inter-factor and inter-fuel substitution for the period 1982–2014, using data on the consumption of natural gas, oil, and coal, alongside labor and capital. Similarly, the empirical study by Başeğmez [63] conducted the potential for inter-factor substitution

using the TPF methodology, analyzing data on labor, capital, and total energy consumption from 1980 to 2016 across 22 developing economies, including Türkiye.

The review of the existing empirical literature highlights that global studies provide mixed outcomes concerning the substitution potential between energy-specific and non-energy inputs. However, empirical literature on Türkiye remains limited, as existing studies do not fully disaggregate C-RES into different components. Therefore, this empirical study aims to address this notable research gap by examining a comprehensive analysis of output and substitution possibilities between fossil fuels and C-RES in Türkiye.

Insights from Türkiye's Energy Profile

In 2023, approximately 85% of global energy demand was met by FF [27]. Similar to the global trend, Türkiye's energy mix remains heavily reliant on FF. During that year, Türkiye consumed a total of 7 EJ of energy, with (2.30) EJ from petroleum, (1.74) EJ from natural gas, and (1.65) EJ from coal, highlighting the dominance of FF in its energy consumption. In addition, Türkiye was responsible for generating 411,102 Mt of the global total of 35.129,792 Mt of CO₂ emissions in 2023, accounting for approximately 1.17% of worldwide emissions (refer to Figure 1) [27].

Following its acceptance of COP²¹ in 2015, Türkiye became a party to the agreement in 2016. Following its participation in COP²¹, Türkiye is attempting to enhance the share of C-RES by reducing FF consumption in the energy mix, as promised (refer to Figure 2) [65].

Under the Sustainable Development Goals (SDGs), Goal 7 (affordable and clean energy) identifies C-RES as energy sources that are carbon neutral and can reduce the vulnerability of energy supply chains [69]. Conversely, a gradual reduction in FF consumption and an increase in C-RES consumption is crucial for both environmental sustainability and energy supply security [51, 66, 67]. However, the proportion of C-RES in electricity generation was 42.3% in 2023. Convenient climatic conditions in Türkiye and the efficacy of its hydropower plants resulted in a 20% contribution to electricity generation (refer to Figure 3) [65].

Finally, given current C-RES potential, Türkiye intends to increase installed capacity to 35.1 gigawatts (GW) in hydropower plants and 5.1 GW in geothermal and biomass power plants by 2035 [68]. Therefore, Türkiye's energy transition efforts are aligned with the 2030 and 2050 climate goals, which aim to support environmental sustainability and guarantee energy supply security [69].

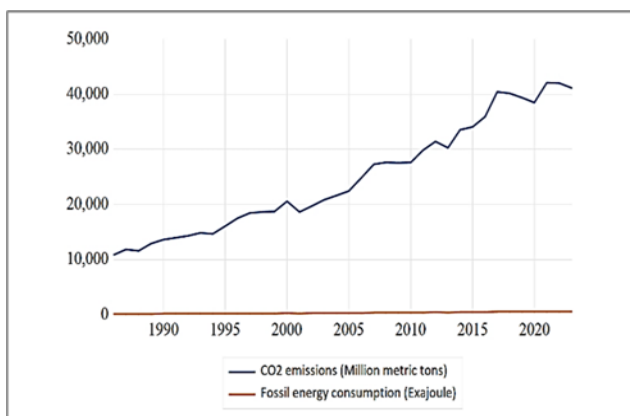


Figure 1. Türkiye's fossil energy consumption and energy-related CO₂ emissions spanning 1986–2023 [27]

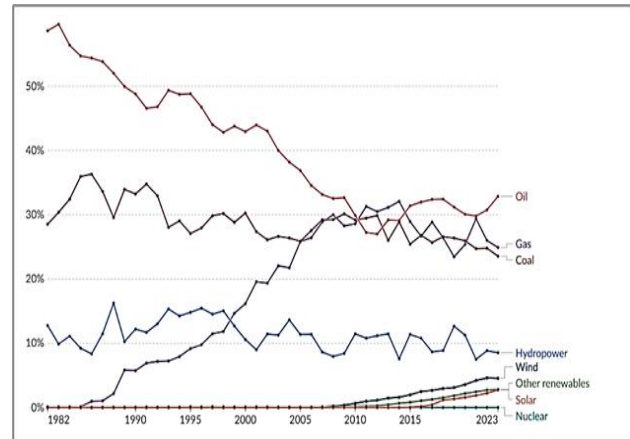


Figure 2. Share of energy consumption by source in Türkiye spanning 1982–2023 [65]

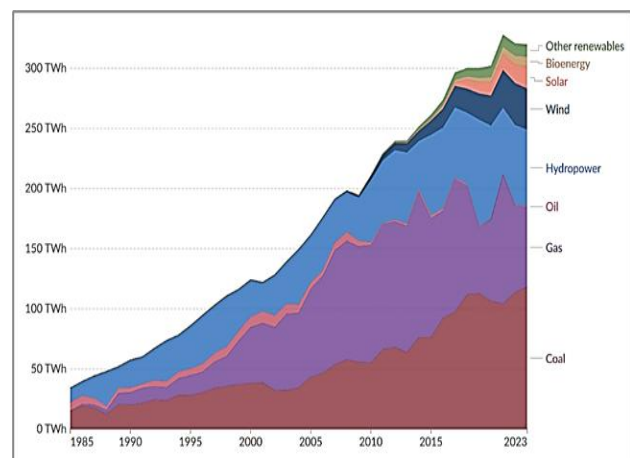


Figure 3. Electricity generation by source in Türkiye spanning 1985–2023 [65]

DATA, EMPIRICAL MODEL AND METHODOLOGY

Data Description

This empirical study attempts to analyze the degree of inter-factor and inter-fuel substitution possibilities employing annual time series data on total output, labor force, gross capital formation, coal, petroleum, natural gas, hydroelectricity and biomass energy in the Türkiye economy spanning (1988–2023). The energy variables selected for the empirical analysis take into account the energy dynamics of Türkiye and the availability of data. To prevent misleading regression findings in the empirical analysis, the data is transformed into natural logarithmic (\ln) forms. The \ln transformation provides the interpretation of estimated parameters as elasticities.

For this empirical analysis, total output is measured in real GDP (Y_t) in 2015 US\$, and real GDP data is collected from the World Development Indicators (WDI) database [70]. Labor force (L_t) data, measured in thousands of individuals, is sourced from the International Financial Statistics (IFS) database [71]. Moreover, data on the consumption of coal (C_t), petroleum (P_t), natural gas (NG_t), hydroelectricity (HE_t), and biomass (B_t) were compiled from the Statistical Review of World Energy (2024) [27]. Additionally, all energy data employed in this empirical analysis are aggregated in Exajoule (EJ). Since the gross capital stock formation data is not readily available, we have constructed this series using the Perpetual Inventory Method (PIM), as show in Eq. (1):

$$K_t = K_{t-1}(1 - \delta) + I_t \tag{1}$$

In Eq. (1), K_t denotes the gross capital stock for period t , K_{t-1} indicates the gross capital stock for period $t-1$, δ denotes fixed capital consumption (assumed to be 5%), I_t denotes the gross domestic capital investment during the period, and the initial denotes the time index (1988-2023). Data on gross domestic investment (I_t), in the form of current US\$, is gathered from the WDI database. Following the previous empirical studies by Bello and Ch'ng [66], Khalid et al. [60], as well as Raza and Cucculelli [61], we construct the first observation of the gross capital stock (K_0) series, as indicated in Eq. (2):

$$\text{Capital Stock } (K_0) = \frac{\text{Gross Investment } (I_t)}{\text{Average GDP growth } (g) + \text{Depreciation rate } (\delta)} \tag{2}$$

In Eq. (2), K_0 denotes the first gross capital stock value for the base year (1988), I_t represents the gross domestic investment for year t , g denotes the average GDP growth rate over the sample period, and δ signifies the depreciation rate applied to the gross domestic investment. Table 1 summarizes the variables under consideration.

Empirical Model

Translog production function

Initially, the Cobb-Douglas (C-D) production function, the Constant Elasticity of Substitution (CES) function, and the Variable Elasticity of Substitution (VES) function, have been employed to estimate the substitution possibilities between different input factors. However, these production functions have been criticized by researchers due to certain limitations. For instance, the C-D production function, developed by Cobb and Douglas [3], assumes homogeneity of labor and capital, with a constant elasticity of substitution between the input factors. This assumption overlooks the potential for differential substitution possibilities between labor types, such as skilled versus unskilled labor, or between forms of capital, such as physical versus human capital [72]. Similarly, the CES production function also assumes constant substitution between inputs [73]. In contrast, the VES production function does not assume a constant elasticity of substitution, allowing for more flexibility in modeling input relationships [74]. However, the estimation of the VES function requires knowledge of factor prices. The constraints inherent in the C-D, CES, and VES production functions limit their ability to flexibly estimate production levels.

To overcome these limitations, researched have employed the Translog Production Function (TPF), developed by Christensen et al. [32], for estimating substitution elasticities between different pairs of inputs. Notably, this production

framework provides greater flexibility in estimation, particularly when the number of inputs exceeds two, and addresses the limitations inherent in other production functions. This production framework allows both returns to scale and elasticities of substitution to vary, without imposing restrictions on the substitutability between input factors. Furthermore, the TPF is a second-order Taylor approximation of a general production function, with its primary advantage being its flexibility, especially when compared to the C-D and CES production functions. One of the key advantages of the TPF is its ability to incorporate quadratic and exponential terms into the proposed econometric model. The inclusion of a quadratic term enables us to capture of nonlinear relationships between inputs and output. The TPF is particularly useful for modeling situations with more than two inputs, allowing for the representation of linear relationships along with quadratic terms [75]. Unlike other production functions, the TPF does not assume a constant elasticity of substitution [76]. Consequently, in this study, we have applied this flexible production method to estimate the inter-factor and inter-fuel substitution possibilities between different pairs of energy-specific and non-energy inputs. The general representation of the TPF is outlined in Eq. (3):

$$\ln(Y_t) = \beta_0 + \sum_{i=1}^n \beta_i \ln(X_{it}) + \sum_{i=1}^n \beta_{ii} \ln(X_{it})^2 + \frac{1}{2} \sum_{i=1}^n \sum_{j=1}^n \beta_{ij} \ln(X_{it}) \ln(X_{jt}) \tag{3}$$

In Eq. (3), Y_t represents Türkiye's real GDP in period t (dependent variable), β_0 signifies the intercept term, X_{it} indicates various input factors (set of explanatory variables), β_i denotes parameter estimates, and the subscript t refers to the time index (1988–2023). Eq. (4) shows the suggested TPF model for the Türkiye economy in \ln form:

$$\begin{aligned} \ln Y_t = & \beta_0 + \beta_L \ln L_t + \beta_K \ln K_t + \beta_P \ln P_t + \beta_{NG} \ln NG_t + \beta_C \ln C_t + \\ & \beta_{HE} \ln HE_t + \beta_B \ln B_t + \beta_{LK} \ln L_t \ln K_t + \beta_{LP} \ln L_t \ln P_t + \\ & \beta_{LNG} \ln L_t \ln NG_t + \beta_{LC} \ln L_t \ln C_t + \beta_{LHE} \ln L_t \ln HE_t + \beta_{LB} \ln L_t \ln B_t + \\ & \beta_{KP} \ln K_t \ln P_t + \beta_{KNG} \ln K_t \ln NG_t + \beta_{KC} \ln K_t \ln C_t + \beta_{KHE} \ln K_t \ln HE_t + \\ & \beta_{KB} \ln K_t \ln B_t + \beta_{PNG} \ln P_t \ln NG_t + \beta_{PC} \ln P_t \ln C_t + \beta_{PHE} \ln P_t \ln HE_t + \\ & \beta_{PB} \ln P_t \ln B_t + \beta_{NGC} \ln NG_t \ln C_t + \beta_{NGHE} \ln NG_t \ln HE_t + \\ & \beta_{NGB} \ln NG_t \ln B_t + \beta_{CHE} \ln C_t \ln HE_t + \beta_{CB} \ln C_t \ln B_t + \beta_{HEB} \ln HE_t \ln B_t + \\ & \beta_{LL} (\ln L_t)^2 + \beta_{KK} (\ln K_t)^2 + \beta_{PP} (\ln P_t)^2 + \beta_{NGNG} (\ln NG_t)^2 + \\ & \beta_{CC} (\ln C_t)^2 + \beta_{HEHE} (\ln HE_t)^2 + \beta_{BB} (\ln B_t)^2 + \varepsilon_t \end{aligned} \tag{4}$$

In Eq. (4), Y_t , L_t , K_t , P_t , NG_t , C_t , HE_t , and B_t indicate total output, labor employment, gross capital stock, and the consumption of petroleum, natural gas, coal, hydroelectricity, and biomass. Moreover, the symbol ε_t refers to the unpredictable disturbed component of the model.

Table 1. Variable definitions and data sources

Variable	Symbol	Measurement Unit	Source
Real Gross Domestic Product (GDP)	Y_t	Constant 2015 US\$	WDI
Labor Force	L_t	Thousand (age: 15+)	IFS
Gross Capital Stock	K_t	Gross capital formation (constant 2015 US\$)	WDI
Petroleum Consumption	P_t	Exajoule	Energy Institute
Natural Gas Consumption	NG_t	Exajoule	Energy Institute
Coal Consumption	C_t	Exajoule	Energy Institute
Hydroelectricity Consumption	HE_t	Exajoule	Energy Institute
Biomass Consumption	B_t	Exajoule	Energy Institute

Methodology

This section outlines the methodology in three distinct sub-categories: the ridge regression estimator, followed by estimation of output and substitution elasticities between different input pairs.

Ridge regression estimator

Since we have included a large number of explanatory variables in the proposed TPF, therefore, we suspect the presence of significant Multicollinearity (MCL). In the presence of severe MCL, the OLS estimator produces biased results, inflate Standard Errors (SE), reduce the values of partial *t*-statistics, yield insignificant *p*-values, and diminish the model's predictive power.

To avoid these issues, Ridge Regression (RR) estimator, proposed by Hoerl and Kennard [77], provides an effective solution to address the multicollinearity (MCL). The RR estimator constrains the magnitude of the regression coefficients by introducing bias into the regression model. This adjustment helps prevent the inflation of SE, mitigates the reduction in *t*-statistics, and modifies the *p*-values accordingly. This method incorporates a ridge parameter (λ) value into the model, which facilitates bias correction, reduces SE, and enhances the reliability of the estimated parameters.

The RR estimator integrates a λ value into the estimation model, which enables bias adjustment, decrease the SE, and increasing the reliability of the parameters. The RR technique notably reduces the basic issue associated with the OLS estimator, $\hat{\beta}_{OLS} = (X'X)^{-1}X'Y$, by incorporating a small constant, λ , into the diagonal components of the cross-product matrix $X'X$ prior to its being inverted [77]. The RR estimator, obtained through integrating the λ value into the OLS estimator, is shown in Eq. (5):

$$\hat{\beta}_{Ridge} = (X'X + \lambda I_p)^{-1}X'Y \tag{5}$$

Determining the optimal λ value presents a critical challenge in RR methodology. The standardization of parameters and the enhancement of predictive accuracy depend on the careful selection of the λ value, which lies within the range of 0 to 1 ($0 < \lambda < 1$). Hoerl and Kennard [77] created the ridge trace plot to identify the optimal lambda value. The optimal λ value is determined at the point where the RR coefficients ($\hat{\beta}_{Ridge}$) stabilize and the signs of the coefficients are properly aligned. The ridge plot indicates selecting the minimal value of λ at which the standardized coefficients stabilize.

Output elasticities

Output elasticity is defined as the ratio of the marginal physical product (MPP) to the average physical product (APP). When the output elasticity exceeds 1, it indicates increasing returns to scale (MPP > APP). If the output elasticity is less than 1, it signifies decreasing returns to scale (MPP < APP). When the output elasticity equals 1, it represents the point at which diminishing returns begin (MPP = APP) [78]. The point at which output elasticity equals 1 signifies the onset of diminishing returns and indicates the minimum amount of the relevant factor of production required to maintain production efficiency.

The output elasticity for an input *i* is calculated according to Eq. (6), as presented in the studies by Lin and Ahmad [79], Lin and Liu [80]:

$$\phi_{it} = \frac{\partial \ln Y_{it}}{\partial \ln X_{it}} = \left(\frac{\partial Y_{it}}{\partial X_{it}} \right) \left(\frac{X_{it}}{Y_{it}} \right) = \beta_i + 2\beta_{ii} \ln X_{it} + \sum_{j=1}^n \beta_{ij} \ln X_{jt} \tag{6}$$

We used Eq. (6) to calculate the output elasticities of non-energy factors (labor and capital) and energy-specific factors (oil, natural gas, coal, hydropower and biomass).

Substitution elasticities

The elasticity of substitution referred to the responsiveness of one input factor to the substitution of another input. A higher elasticity of substitution indicates a stronger effect of change. The sign of the elasticity (positive or negative) is used to differentiate between substitution and complementarity [81]. In this study, the elasticities of substitution between various pairs of energy inputs are derived from the output elasticities, which are computed using Eq. (6). The substitution elasticity refers to the relative change in the ratio of the marginal technical rate of substitution of these inputs, as expressed in Eq. (7), referring Lin and Liu [80]; Lin and Ahmad [82]:

$$\vartheta_{ij} = \frac{d \ln \left(\frac{x_i}{x_j} \right)}{d \ln \left(\frac{m_j}{m_i} \right)} \tag{7}$$

The $d \ln \left(\frac{m_j}{m_i} \right)$ in Eq. (7) represents the marginal technical rate of substitution (MRTS) between input factors *i* and *j*. Bello and Ch'ng [66] detail the MRTS as shown in Eq. (8):

$$\left[d \ln \left(\frac{m_j}{m_i} \right) \right]^{-1} = d \ln \left(\frac{m_i}{m_j} \right) = d \ln MRTS_{ij} = \frac{d MRTS_{ij}}{MRTS_{ij}}; i \neq j \tag{8}$$

Based on Eq. (8), the elasticities of substitution between factors *i* and *j*, demonstrated to be symmetric by Lin and Liu [80], are computed as presented in Eq. (9):

$$\vartheta_{ij} = \left[1 + \left[(-\beta_{ij}) + \left\{ \frac{\phi_i}{\phi_j} \right\} * (\beta_{jj}) \right] (-\phi_i + \phi_j)^{-1} \right]^{-1} \tag{9}$$

We used Eq. (9) to calculate the elasticities of substitution between pairs of non-energy factors (labor and capital) and energy-specific factors (oil, natural gas, coal, hydropower, and biomass).

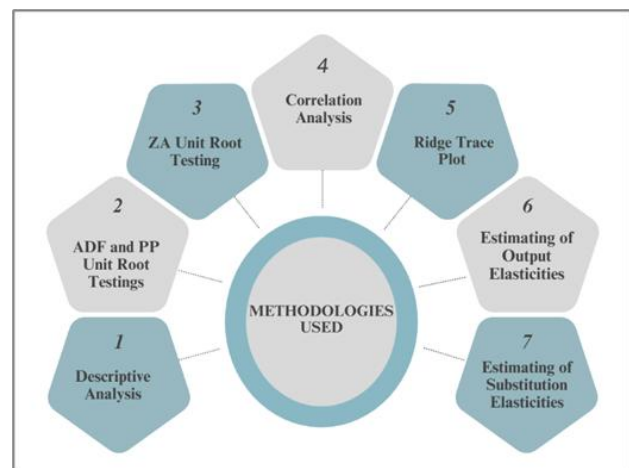


Figure 4. Methodological framework

EMPIRICAL FINDINGS

In our empirical analysis, we first evaluate the descriptive statistics of the variables. These statistics presented in Table 2 reveal that the mean and median values suggest that output (*lnY*) and capital (*lnC*) are relatively high, with capital exhibiting the greatest variability (Std. Dev = 3.4476), while labor (*lnL*) demonstrates the least variability (Std. Dev = 0.1692). The value ranges indicate notable fluctuations, particularly in natural gas (*lnNG*), which varies between 0.7242 and -3.1971, as well as biomass (*lnB*), which ranges from -2.7710 to 2.9699. Skewness values indicate that most variables are nearly symmetric, with the exceptions of capital (*lnK*) and natural gas (*lnNG*), both of which are negatively skewed (-0.7671 and -0.8290, respectively), and labor (*lnL*) and biomass, which are slightly right-skewed (0.5329 and 0.5971, respectively).

Evaluating the stationarity of the variables in the proposed empirical model is crucial for selecting the appropriate methodology. To assess stationarity, we utilize the Augmented Dickey-Fuller (ADF) test, as developed by Dickey and Fuller [83], and the Phillips and Perron (PP) unit root test, introduced by Phillips and Perron [84]. The results of the ADF

unit root test, presented in Table 3, indicate that the variable (*HE*) is statistically significant at the 1% level under the trend and intercept (*T & I*) model, while the (*B*) variable is statistically significant at the 1% level under both the intercept (*I*) and trend and intercept (*T & I*) models. The PP test results also show that the (*HE*) and (*B*) variables are significant at the 1% level under the trend and intercept (*T & I*) model.

Conversely, the variables (*Y*), (*L*), (*K*), (*P*), (*NG*), and (*C*) are non-stationary at level [*I(0)*], according to both the ADF and PP test results, but become stationary after taking their first differences [*I(1)*]. Specifically, the variables (*Y*), (*L*), and (*K*) are statistically significant at the 5% level in their first differences [*I(1)*] under both the intercept (*I*) and trend and intercept (*T & I*) models, according to the ADF test results. These variables are also significant at the 1% level according to the PP test results. In contrast, the variables (*P*), (*NG*), and (*C*) are statistically significant at the 1% level in both the ADF and PP tests across both the intercept (*I*) and trend and intercept (*T & I*) models. Therefore, based on the ADF and PP unit root tests, we conclude that the variables (*HE*) and (*B*) are stationary at level [*I(0)*], while the variables (*Y*), (*L*), (*K*), (*P*), (*NG*), and (*C*) are stationary at first difference [*I(1)*].

Table 2. Descriptive statistics

	<i>lnY</i>	<i>lnL</i>	<i>lnK</i>	<i>lnP</i>	<i>lnNG</i>	<i>lnC</i>	<i>lnHE</i>	<i>lnB</i>
Mean	27.0191	10.1296	27.2396	0.3468	-0.4255	0.0647	-0.8619	-0.3559
Median	27.0212	10.0676	28.5876	0.2901	-0.0135	0.0149	-0.8777	-1.1826
Maximum	27.8528	10.4597	32.2189	0.8333	0.7242	0.5649	-0.1709	2.9699
Minimum	26.2973	9.8871	19.8396	-0.0718	-3.1971	-0.5777	-1.6556	-2.7710
Std.Dev.	0.4766	0.1692	3.4476	0.2499	1.0486	0.3661	0.3400	1.8702
Skewness	0.1727	0.5329	-0.7671	0.4044	-0.8290	-0.0469	-0.1617	0.5971
Kurtosis	1.7644	2.0068	2.4325	2.3424	2.6183	1.5501	2.5699	1.8900
Jarque-Bera	2.4691	3.1833	3.0138	1.6300	2.3422	3.1665	0.4344	2.9873
Probability	0.2910	0.2036	0.1344	0.4426	0.1141	0.2053	0.8048	0.1362
Observations	36	36	36	36	36	36	36	36

Source: Author's calculates

Table 3. ADF and PP unit root tests results

Variable	ADF Test				PP Test				Order of Integration
	Level		First Difference		Level		First Difference		
	<i>I</i>	<i>T & I</i>	<i>I</i>	<i>T & I</i>	<i>I</i>	<i>T & I</i>	<i>I</i>	<i>T & I</i>	
<i>Y</i>	3.45 (1.00)	-0.16 (0.99)	-4.26 (0.00)**	-5.53 (0.00)**	10.39 (1.00)	0.95 (0.99)	-4.26 (0.00)***	-6.89 (0.00)***	<i>I(1)</i>
<i>L</i>	0.96 (0.99)	-0.96 (0.93)	-5.54 (0.00)**	-7.52 (0.00)**	0.96 (0.99)	-0.97 (0.94)	-5.55 (0.00)***	-5.85 (0.00)***	<i>I(1)</i>
<i>K</i>	0.37 (0.98)	-0.38 (0.97)	-6.63 (0.00)**	-6.66 (0.00)**	10.39 (1.00)	11.91 (1.00)	-5.38 (0.00)***	-6.74 (0.00)***	<i>I(1)</i>
<i>P</i>	0.83 (0.99)	-1.06 (0.92)	-5.34 (0.00)***	-5.44 (0.00)***	0.83 (0.99)	-1.31 (0.87)	-5.34 (0.00)***	-5.44 (0.00)***	<i>I(1)</i>
<i>NG</i>	-0.24 (0.92)	-2.34 (0.40)	-6.82 (0.00)***	-6.65 (0.00)***	-0.76 (0.82)	-2.28 (0.44)	-6.26 (0.00)***	-6.17 (0.00)***	<i>I(1)</i>
<i>C</i>	-0.43 (0.89)	-2.58 (0.29)	-7.81 (0.00)***	-7.67 (0.00)***	-0.80 (0.81)	-2.55 (0.30)	-7.81 (0.00)***	-7.67 (0.00)***	<i>I(1)</i>
<i>HE</i>	-2.07 (0.26)	-4.37 (0.41)***	-	-	-2.07 (0.26)	-4.41 (0.00)***	-	-	<i>I(0)</i>
<i>B</i>	-4.45 (0.00)***	-4.53 (0.41)***	-	-	3.84 (1.00)	5.41 (0.00)***	-	-	<i>I(0)</i>

Source: Author's calculates. Notes: (**) and (***) indicate 5% and 1% statistical significance level, respectively. The notation *I(0)* and *I(1)* denote the stationarity of the series at level and first difference, while '*I*' and '*T & I*' refer to tests with intercept and both trend and intercept tests.

While standard unit root tests, such as the ADF and PP tests, are commonly employed to evaluate the stationarity of variables, they do not take into account structural breaks that occur in countries. Perron [85] argued that there is a close relationship between structural change and unit roots, and that conventional unit root tests may produce biased results when a structural break is present. Specifically, in such cases, standard unit root tests may fail to reject the null hypothesis (H_0) ($H_0 = \text{Time series contains unit root (non-stationary)}$; $H_1 = \text{Time series does not contain unit root (stationary)}$). Given that stationarity tests which disregard structural breaks may yield misleading results, we employed the Zivot-Andrews (ZA) stationarity test, introduced by Zivot and Andrews [86], to evaluate the stationarity of our variables while accounting for structural breaks.

The results of the ZA test, as shown in Table 4, indicate that all variables are non-stationary at level, except for the (HE) variable, which is statistically significant at the 5% level and thus stationary at level $I(0)$. In contrast, the (Y), (L), and (P) variables are stationary at the 1% significance level, while the (K), (NG), (C), (HE), and (B) variables are stationary in their first differences at the 5% significance level $I(1)$. Therefore, while the results of the ADF and PP unit root tests suggest that variable (B) is stationary at level $I(0)$, following Perron's [85] assertion that standard unit root tests may yield misleading results in the presence of a structural break, we

assessed all variables in their first differences $I(1)$, with the exception of variable (B), in our empirical analysis.

The proposed TPF model of this empirical study contains cross, quadratic, and exponential terms of the independent variables. We cannot use the OLS estimator to estimate the TPF model in order to prevent inaccurate findings [79]. Through the Pearson correlation coefficient, we examined the extent of linear relationships between independent pairs [87]. The Pearson correlation coefficient indicates that a significant MCL issue occurs when the correlation between independent variables surpasses 0.8 [88, 89]. The correlation analysis results in Table 5 indicate that numerous pairwise correlations surpass the widely recognized threshold of 0.8 (0.81, 0.82, 0.83, 0.84, 0.87, 0.90, 0.91, 0.93, 0.95, 0.96, and 0.98). In order to solve the MCL problem, we employ the RR methodology, which adds a penalty term (λ) into the model, resulting in biased results.

Prior to employing the RR estimator for the MCL issue among the independent variables, we utilized the ridge trace plot to determine the optimal λ value for our estimator. Figure 5 demonstrates the ridge trace plot of the λ value within the range of $0 \leq \lambda \leq 1$. Figure 6 shows the optimal λ value for our TPF model, which was 0.27. When the λ value that is determined by the Akaike Information Criterion (AIC) reaches 0.27, all coefficients in the TPF model stabilize.

Table 4. ZA unit root test results

Variable	ZA Test						
	Level			First Difference			Order of Integration
	Lag	Break year	t-statistic	Lag	Break year	t-statistic	
Y	0	1998	-1.43	0	2011	-5.79***	$I(1)$
L	0	2000	-2.66	0	2008	-6.66***	$I(1)$
K	2	2018	1.93	2	2018	-6.42**	$I(1)$
P	2	2015	-4.49	0	2012	-6.51***	$I(1)$
NG	0	2007	-3.87	0	2003	-8.77**	$I(1)$
C	2	2005	-3.34	1	2015	-8.39**	$I(1)$
HE	0	2000	-5.13**	-	-	-	$I(0)$
B	2	2018	-4.37	0	2013	-5.87**	$I(1)$

Source: Author's calculates. Note: (**) and (***) indicate 5% and 1% statistical significance level, respectively.

Table 5. Correlation analysis

Variables	L	K	P	NG	C	HE	B
L	1.0000	0.8404	0.9508	0.8161	0.9141	0.8196	0.9844
K	0.8404	1.0000	0.8751	0.9805	0.9139	0.7914	0.7939
P	0.9508	0.8751	1.0000	0.8312	0.8924	0.8475	0.9392
NG	0.8161	0.9805	0.8313	1.0000	0.9307	0.7578	0.7762
C	0.9141	0.9139	0.8924	0.9307	1.0000	0.8215	0.9077
HE	0.8196	0.7914	0.8475	0.7578	0.8215	1.0000	0.8274
B	0.9844	0.7939	0.9392	0.7762	0.9077	0.8275	1.0000

Source: Author's calculates.

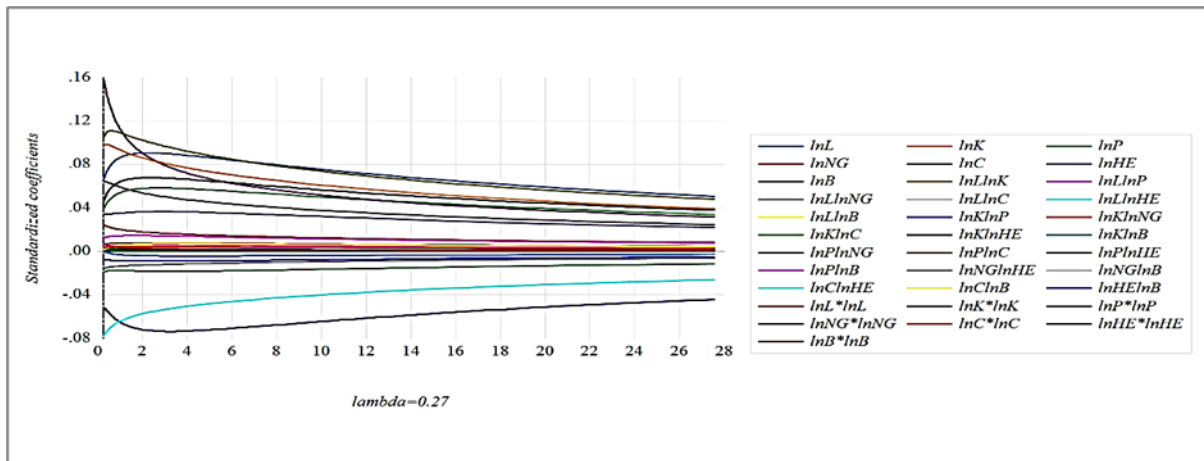


Figure 5. Ridge trace plot for ridge regression

The findings from the TPF model presented in Table 6 indicate that the cross terms (petroleum–hydropower, natural gas–hydropower, natural gas–biomass, coal–hydropower, and hydropower–biomass) and quadratic terms (natural gas–natural gas and biomass–biomass) exhibit negative values, signifying increasing returns to scale, whereas all other variables display positive values, denoting decreasing returns to scale. The results presented in Table 6 show that all the statistical test indicators, the coefficient of determination (R^2), the standard error (SE), and the significance level (F -statistic) of the regression indicate that the chosen model is correctly specified and ensures a good fit for the data. Specifically, the results show that all statistical tests for the parameter estimates are favorable, as reflected in the minimal SE (i.e., $SE < 0.1$ in most cases).

Firstly, the output elasticities for labor, capital, petroleum, natural gas, coal, hydropower, and biomass, calculated using Eq. (6) and with λ (0.27) derived from the ridge trace graph, are presented in Table 7. The empirical findings indicate that the average output elasticities for labor, capital, petroleum, natural gas, coal, hydroelectricity, and biomass in the Türkiye economy spanning (1988–2023) are 1.5925, 1.0323, 0.8563, 0.8963, 0.9106, 0.8468, and 0.8463, respectively. As the findings indicate that labor, followed by capital, has the greatest impact on output in the Türkiye economy, the marginal physical productivity of labor surpasses that of capital. Conversely, coal demonstrates a higher output elasticity than other energy inputs. Despite its contribution to CO_2 emissions and climate change, coal remains a dominant fuel in the Türkiye economy throughout the sample period, surpassing other energy sources. These findings suggest that the Türkiye economy is reliant on labor-intensive production, with coal use making the largest contribution to quantitative income, notwithstanding its adverse impact on climate change. The empirical findings of our study are in agreement with those of Bello and Ch'ng [66], Raza and Lin [90], Raza and Cucculelli [61], and Raza et al. [47], Khalid et al. [60], Zhang and Lin [91].

Secondly, using the output elasticities calculated based on Eq. (6), the inter-factor elasticities of substitution, derived from Eq. (9), are presented in Table 8. The results of the inter-factor elasticities of substitution indicate that all input pairs exhibit positive values across the sample period. According to the economic growth literature, inputs are considered substitutable when the elasticity of substitution between input pairs is greater than zero, neutral when the elasticity is

equal to zero, and complementary when the elasticity is less than zero. Therefore, the inter-factor elasticities of substitution in the Türkiye economy suggest that the inputs can be substituted for one another during the relevant period.

The extent of the relationship between capital and energy is determined by changes in energy prices, according to Apostolakis [92]. An increase in energy prices may stimulate capital accumulation if energy and capital are substitutable. However, if labor and capital are complementary, higher energy prices are expected to reduce the rate of capital growth. Consequently, the literature remains divided on whether energy and capital are complementary or substitutable. We calculated the average elasticity of substitution between labor and capital to be 0.5662. Since the elasticity of substitution between labor and capital is greater than zero, this indicates that, according to economic theory, these factors are able to substitute for each other. The average elasticity of substitution between labor and capital is 0.5662, supporting previous studies by Bello and Ch'ng [66], Alvarez-Cuadrado et al. [33], Raza et al. [47], and Khalid et al. [60]. Conversely, our empirical findings differ from those of Bardazzi et al. [93], who identify a complementary connection between labor and capital.

Table 8 illustrates the findings of the elasticities of substitution between labor and FF (petroleum, natural gas, and coal) and C-RES (hydropower and biomass). The average elasticities of substitution between labor and fossil fuels, as well as clean and renewable energy sources, have been calculated as (0.6167, 0.5881, 0.6506, 0.6673, and 0.6509) respectively. Hydroelectricity exhibited the highest labor substitution potential in the Türkiye economy compared to other fuels during the sample period. As a result, when labor costs rise in a labor-intensive country like Türkiye, the use of hydropower offsets labor costs while also promoting environmental sustainability as a clean energy source. The findings we obtained align with those of Bello & Ch'ng [66], Raza and Cucculelli [61] as well as Lin and Raza [94].

The average capital substitution potentials for FF and C-RES, as presented in Table 8, are calculated as 0.8370, 0.1104, 0.1701, 0.1828, and 0.1787, respectively. Empirical findings indicate that capital demonstrates highest substitution potential with petroleum compared to other fuels. Conversely, natural gas displays the lowest substitution potential regarding capital on average. Compared to fossil fuels such as coal and petroleum, natural gas has a lesser impact on environmental degradation. Considering that the

Türkiye economy depends on natural gas imports, stabilizing the demand for natural gas and achieving output growth can be realized through capital enhancement. During this period, the average substitution potential of capital with coal, hydroelectricity, and biomass in Türkiye shows similar results. Reducing coal consumption, a major factor in environmental degradation, can be facilitated by increased

capital investment. Furthermore, the development of new hydropower plants and advancements in biomass extraction and processing technologies can accelerate Türkiye's shift towards C-RES. Our results align with those of Bello and Ch'ng [66], Raza et al. [47], Bello and Solarin [44], and Khalid et al. [60].

Table 6. Results of the ridge regression

<i>Dependent variable = $\ln Y_t$</i>			
<i>Lambda value (λ) = 0.27</i>			
<i>R² = 0.96</i>			
<i>SE: 0.06</i>			
<i>F-statistic: 14.67</i>			
<i>Probability value: 0.02</i>			
Parameter	Coefficient	Standard Error	t-statistic
β_0	25.5642	0.9311	27.456
β_L	0.0668	0.0737	0.9064
β_K	0.0067	0.0064	1.0469
β_P	0.0397	0.0446	0.8901
β_{NG}	0.0244	0.0639	0.8318
β_C	0.0641	0.0233	2.7510
β_{HE}	0.0344	0.0344	1.0000
β_B	0.0065	0.0068	0.9558
β_{LK}	0.0005	0.0006	0.8333
β_{LP}	0.0039	0.0043	0.9069
β_{LNG}	0.0025	0.0024	1.0417
β_{LC}	0.0063	0.0063	1.0000
β_{LHE}	0.0035	0.0035	1.0000
β_{LB}	0.0007	0.0007	1.0000
β_{KP}	0.0017	0.0018	0.9444
β_{KNG}	0.0013	0.0012	1.0833
β_{KC}	0.0026	0.0025	1.0400
β_{KHE}	0.0010	0.0010	1.0000
β_{KB}	0.0003	0.0003	1.0000
β_{PNG}	0.1575	0.1441	1.0929
β_{PC}	0.1054	0.1093	0.9643
β_{PHE}	-0.0517	-0.0543	0.9521
β_{PB}	0.0126	0.0131	0.9618
β_{NGC}	0.0130	0.0064	2.0313
β_{NGHE}	-0.0159	-0.0151	1.0529
β_{NGB}	-0.0019	-0.0023	0.8261
β_{CHE}	-0.0773	-0.0738	1.0474
β_{CB}	0.0008	0.0026	0.7376
β_{HEB}	-0.0081	-0.0080	1.0125
β_{LL}	0.0034	0.0037	0.9189
β_{KK}	0.0001	0.0001	1.0000
β_{PP}	0.0471	0.0530	0.8887
β_{NGNG}	-0.0001	-0.0010	1.0000
β_{CC}	0.0874	0.0938	0.9317
β_{HEHE}	-0.0187	-0.0181	1.0331
β_{BB}	0.0069	0.0059	1.1695

Source: Author's calculates.

Table 7. Estimates of output elasticity

Years	ϕ_L	ϕ_K	ϕ_P	ϕ_{NG}	ϕ_C	ϕ_{HE}	ϕ_B
1988	1.3598	0.7661	0.5717	0.6656	0.6530	0.6197	0.6148
1989	1.3787	0.7867	0.6130	0.6804	0.6779	0.6205	0.6315
1990	1.4010	0.8130	0.6369	0.7050	0.7040	0.6515	0.6554
1991	1.4194	0.8313	0.6575	0.7196	0.7239	0.6664	0.6736
1992	1.4344	0.8494	0.6740	0.7360	0.7379	0.6861	0.6876
1993	1.4452	0.8681	0.6901	0.7554	0.7468	0.7084	0.7024
1994	1.4543	0.8752	0.6956	0.7576	0.7510	0.7089	0.7063
1995	1.4872	0.9127	0.7336	0.7939	0.7854	0.7457	0.7436
1996	1.5101	0.9385	0.7590	0.8174	0.8147	0.7719	0.7641
1997	1.5286	0.9615	0.7824	0.8351	0.8402	0.7896	0.7849
1998	1.5428	0.9797	0.7962	0.8473	0.8549	0.8040	0.7963
1999	1.5377	0.9752	0.7943	0.8407	0.8437	0.7907	0.7871
2000	1.5465	0.9903	0.8096	0.8538	0.8623	0.7980	0.7992
2001	1.5287	0.9717	0.7927	0.8317	0.8305	0.7700	0.7808
2002	1.5522	0.9979	0.8173	0.8570	0.8558	0.8039	0.8023
2003	1.5615	1.0099	0.8317	0.8662	0.8706	0.8152	0.8100
2004	1.5691	1.0245	0.8454	0.8795	0.8868	0.8365	0.8224
2005	1.5705	1.0261	0.8503	0.8791	0.8871	0.8311	0.8207
2006	1.5917	1.0491	0.8749	0.9021	0.9192	0.8562	0.8430
2007	1.6027	1.0596	0.8884	0.9127	0.9367	0.8586	0.8564
2008	1.6067	1.0623	0.8913	0.9139	0.9389	0.8577	0.8595
2009	1.6201	1.0718	0.9012	0.9256	0.9527	0.8712	0.8758
2010	1.6432	1.0944	0.9232	0.9446	0.9743	0.9040	0.8988
2011	1.6593	1.1097	0.9401	0.9565	0.9922	0.9172	0.9121
2012	1.6758	1.1248	0.9559	0.9736	1.0120	0.9355	0.9295
2013	1.6790	1.1270	0.9572	0.9774	1.0036	0.9371	0.9330
2014	1.6842	1.1310	0.9620	0.9818	1.0156	0.9271	0.9391
2015	1.7118	1.1573	0.9871	1.0139	1.0386	0.9697	0.9666
2016	1.7268	1.1711	0.9994	1.0298	1.0582	0.9827	0.9818
2017	1.7384	1.1820	1.0122	1.0422	1.0690	0.9867	0.9926
2018	1.7442	1.1875	1.0146	1.0467	1.0758	0.9920	0.9984
2019	1.7593	1.2018	1.0270	1.0611	1.0920	1.0199	1.0143
2020	1.7487	1.1973	1.0215	1.0519	1.0828	1.0083	1.0082
2021	1.7577	1.2049	1.0318	1.0594	1.0893	1.0017	1.0144
2022	1.7762	1.2258	1.0444	1.0763	1.1054	1.0230	1.0304
2023	1.7759	1.2270	1.0416	1.0771	1.0999	1.0200	1.0291
Av.	1.5925	1.0323	0.8563	0.8963	0.9106	0.8468	0.8463

Source: Author's calculates.

Table 8. Estimates of inter-factor elasticity of substitution

Years	ϑ_{LK}	ϑ_{LP}	ϑ_{LNG}	ϑ_{LC}	ϑ_{LHE}	ϑ_{LB}	ϑ_{KP}	ϑ_{KNG}	ϑ_{KC}	ϑ_{KHE}	ϑ_{KB}
1988	0.5027	0.4983	0.4846	0.4961	0.5164	0.5057	0.8795	0.0987	0.1698	0.1368	0.1373
1989	0.5102	0.5088	0.4949	0.5168	0.5255	0.5180	0.8721	0.0956	0.1566	0.1536	0.1414
1990	0.5181	0.5211	0.5065	0.5329	0.5432	0.5331	0.8704	0.0962	0.1600	0.1513	0.1446
1991	0.5256	0.5313	0.5158	0.5461	0.5554	0.5452	0.8658	0.0952	0.1593	0.1550	0.1455
1992	0.5302	0.5394	0.5235	0.5567	0.5664	0.5549	0.8639	0.0990	0.1617	0.1547	0.1497
1993	0.5307	0.5441	0.5292	0.5647	0.5746	0.5622	0.8652	0.1076	0.1649	0.1526	0.1538
1994	0.5351	0.5497	0.5343	0.5703	0.5800	0.5677	0.8587	0.1101	0.1666	0.1585	0.1568
1995	0.5447	0.5662	0.5505	0.5925	0.6019	0.5888	0.8578	0.1135	0.1683	0.1609	0.1588
1996	0.5511	0.5777	0.5603	0.6073	0.6167	0.6032	0.8552	0.1110	0.1699	0.1618	0.1644
1997	0.5547	0.5871	0.5671	0.6189	0.6285	0.6145	0.8485	0.1093	0.1706	0.1674	0.1674
1998	0.5568	0.5946	0.5733	0.6278	0.6374	0.6234	0.8408	0.1126	0.1753	0.1716	0.1740
1999	0.5548	0.5925	0.5728	0.6243	0.6349	0.6206	0.8377	0.1183	0.1728	0.1791	0.1778
2000	0.5533	0.5956	0.5738	0.6290	0.6406	0.6257	0.8353	0.1156	0.1734	0.1867	0.1812
2001	0.5483	0.5880	0.5697	0.6181	0.6294	0.6148	0.8299	0.1266	0.1710	0.1938	0.1800
2002	0.5538	0.5991	0.5801	0.6322	0.6443	0.6295	0.8294	0.1279	0.1737	0.1886	0.1854
2003	0.5548	0.6037	0.5827	0.6369	0.6500	0.6354	0.8258	0.1257	0.1720	0.1899	0.1897
2004	0.5520	0.6055	0.5831	0.6401	0.6529	0.6394	0.8244	0.1246	0.1734	0.1847	0.1923
2005	0.5523	0.6068	0.5841	0.6402	0.6548	0.6407	0.8216	0.1258	0.1705	0.1910	0.1952
2006	0.5569	0.6162	0.5888	0.6512	0.6672	0.6534	0.8221	0.1183	0.1701	0.1904	0.1972
2007	0.5605	0.6214	0.5904	0.6566	0.6756	0.6595	0.8226	0.1121	0.1676	0.1982	0.1951
2008	0.5625	0.6243	0.5928	0.6591	0.6789	0.6620	0.8205	0.1127	0.1676	0.2016	0.1950
2009	0.5694	0.6312	0.5979	0.6675	0.6873	0.6693	0.8239	0.1090	0.1675	0.1985	0.1894
2010	0.5763	0.6437	0.6077	0.6805	0.6991	0.6828	0.8194	0.1101	0.1689	0.1901	0.1901
2011	0.5813	0.6529	0.6129	0.6888	0.7095	0.6928	0.8151	0.1080	0.1679	0.1928	0.1926
2012	0.5870	0.6603	0.6173	0.6979	0.7187	0.7020	0.8182	0.1039	0.1676	0.1905	0.1912
2013	0.5888	0.6615	0.6250	0.7004	0.7212	0.7037	0.8204	0.1137	0.1686	0.1911	0.1901
2014	0.5913	0.6643	0.6233	0.7034	0.7291	0.7064	0.8211	0.1064	0.1680	0.2045	0.1882
2015	0.5999	0.6744	0.6363	0.7191	0.7405	0.7219	0.8297	0.1096	0.1698	0.1900	0.1881
2016	0.6051	0.6806	0.6390	0.7284	0.7501	0.7302	0.8327	0.1044	0.1717	0.1914	0.1873
2017	0.6087	0.6851	0.6437	0.7339	0.7600	0.7369	0.8348	0.1047	0.1702	0.1986	0.1879
2018	0.6106	0.6884	0.6452	0.7387	0.7637	0.7401	0.8337	0.1035	0.1734	0.1990	0.1877
2019	0.6153	0.6953	0.6499	0.7480	0.7666	0.7480	0.8340	0.1019	0.1757	0.1861	0.1867
2020	0.6066	0.6899	0.6451	0.7398	0.7610	0.7401	0.8276	0.1062	0.1766	0.1930	0.1881
2021	0.6105	0.6947	0.6501	0.7439	0.7733	0.7463	0.8278	0.1073	0.1740	0.2071	0.1896
2022	0.6127	0.7035	0.6582	0.7567	0.7829	0.7575	0.8229	0.1119	0.1829	0.2077	0.1952
2023	0.6112	0.7028	0.6617	0.7579	0.7841	0.7579	0.8222	0.1182	0.1868	0.2119	0.1976
Av.	0.5662	0.6167	0.5881	0.6506	0.6673	0.6509	0.8370	0.1104	0.1701	0.1828	0.1787

Source: Author's calculates.

Table 9. Estimates of inter-fuel elasticity of substitution

Years	ϑ_{PNG}	ϑ_{PC}	ϑ_{PHE}	ϑ_{PB}	ϑ_{NGC}	ϑ_{NGHE}	ϑ_{NGB}	ϑ_{CHE}	ϑ_{CB}	ϑ_{HEB}
1988	0.0878	0.1703	0.0455	0.0489	0.0768	0.0505	0.0441	0.0333	0.0370	0.0048
1989	0.0647	0.0303	0.0590	0.0473	0.0625	0.0077	0.0186	0.0566	0.0449	0.0110
1990	0.0656	0.0115	0.0530	0.0481	0.0648	0.0150	0.0185	0.0522	0.0471	0.0038
1991	0.0602	0.0487	0.0528	0.0447	0.0643	0.0091	0.0161	0.0570	0.0488	0.0072
1992	0.0603	0.0215	0.0498	0.0470	0.0621	0.0124	0.0137	0.0517	0.0488	0.0016
1993	0.0635	0.1118	0.0470	0.0515	0.0554	0.0188	0.0123	0.0386	0.0432	0.0059
1994	0.0605	0.0841	0.0488	0.0500	0.0542	0.0136	0.0107	0.0423	0.0436	0.0026
1995	0.0591	0.1098	0.0484	0.0492	0.0510	0.0124	0.0099	0.0400	0.0410	0.0021
1996	0.0574	0.0324	0.0458	0.0520	0.0548	0.0131	0.0051	0.0432	0.0495	0.0077
1997	0.0519	0.0568	0.0458	0.0492	0.0569	0.0073	0.0024	0.0509	0.0541	0.0047
1998	0.0506	0.0824	0.0438	0.0500	0.0580	0.0080	0.0002	0.0513	0.0573	0.0076
1999	0.0459	0.0343	0.0503	0.0525	0.0489	0.0036	0.0071	0.0533	0.0554	0.0036
2000	0.0438	0.0921	0.0561	0.0535	0.0522	0.0117	0.0103	0.0646	0.0618	0.0011
2001	0.0386	0.0146	0.0619	0.0499	0.0374	0.0231	0.0118	0.0607	0.0487	0.0108
2002	0.0394	0.0144	0.0535	0.0536	0.0383	0.0136	0.0148	0.0523	0.0525	0.0016
2003	0.0343	0.0494	0.0515	0.0552	0.0387	0.0168	0.0215	0.0559	0.0594	0.0052
2004	0.0339	0.0800	0.0435	0.0560	0.0411	0.0091	0.0227	0.0509	0.0631	0.0139
2005	0.0287	0.0869	0.0485	0.0573	0.0366	0.0195	0.0292	0.0565	0.0650	0.0103
2006	0.0271	0.1710	0.0465	0.0580	0.0442	0.0190	0.0314	0.0637	0.0746	0.0130
2007	0.0242	0.2256	0.0547	0.0553	0.0481	0.0303	0.0315	0.0788	0.0787	0.0021
2008	0.0226	0.2326	0.0568	0.0536	0.0474	0.0341	0.0314	0.0818	0.0779	0.0018
2009	0.0244	0.2472	0.0552	0.0491	0.0513	0.0305	0.0251	0.0823	0.0756	0.0046
2010	0.0214	0.2658	0.0412	0.0453	0.0510	0.0195	0.0242	0.0713	0.0744	0.0052
2011	0.0164	0.3041	0.0399	0.0439	0.0521	0.0232	0.0277	0.0761	0.0790	0.0051
2012	0.0177	0.3201	0.0388	0.0437	0.0560	0.0208	0.0262	0.0777	0.0815	0.0060
2013	0.0202	0.2405	0.0410	0.0440	0.0463	0.0205	0.0240	0.0676	0.0697	0.0040
2014	0.0198	0.2918	0.0556	0.0423	0.0536	0.0354	0.0227	0.0897	0.0756	0.0119
2015	0.0268	0.2295	0.0450	0.0469	0.0515	0.0177	0.0204	0.0702	0.0713	0.0031
2016	0.0304	0.2564	0.0480	0.0476	0.0589	0.0171	0.0175	0.0771	0.0758	0.0008
2017	0.0300	0.2452	0.0566	0.0492	0.0569	0.0261	0.0195	0.0840	0.0759	0.0059
2018	0.0322	0.2605	0.0559	0.0480	0.0614	0.0230	0.0161	0.0855	0.0769	0.0064
2019	0.0341	0.2728	0.0420	0.0465	0.0652	0.0072	0.0126	0.0737	0.0772	0.0056
2020	0.0305	0.2731	0.0445	0.0434	0.0616	0.0135	0.0132	0.0762	0.0742	0.0001
2021	0.0276	0.2658	0.0589	0.0447	0.0576	0.0307	0.0173	0.0894	0.0744	0.0126
2022	0.0321	0.2601	0.0545	0.0457	0.0613	0.0218	0.0139	0.0843	0.0747	0.0074
2023	0.0356	0.2150	0.0584	0.0477	0.0585	0.0221	0.0124	0.0817	0.0704	0.0091
Av.	0.0394	0.1586	0.0500	0.0492	0.0538	0.0188	0.0182	0.0645	0.0633	0.0058

Source: Author's calculates.

Finally, using the output elasticities derived from Eq. (6), the inter-fuel elasticities of substitution, as calculated according to Eq. (9), are presented in Table 9. The average substitution elasticities of various competing fuels (petroleum-natural gas, petroleum-coal, petroleum-hydroelectricity, petroleum-biomass, natural gas-coal, natural gas-hydroelectricity, natural gas-biomass, coal-hydroelectricity, coal-biomass, and hydroelectricity-biomass) are calculated

as (0.0394, 0.1586, 0.0500, 0.0492, 0.0538, 0.0188, 0.0182, 0.0645, 0.0633, and 0.0058), respectively. The findings from the inter-fuel elasticities of substitution indicate that, since the average elasticities of substitution for all fuels competing in the Türkiye economy are positive, these fuels can substitute for one another during the relevant period. During the specified period, the greatest substitution potential (0.1586) among fuel pairs in Türkiye was observed between

petroleum and coal. The ability of coal to substitute for oil suggests that, despite its polluting nature, coal can serve as a reliable fuel for the Türkiye economy in the event of disruptions to oil supply.

The potential of hydroelectricity and biomass to substitute coal is comparatively high relative to other fuels. Türkiye's total energy consumption of (7 EJ) in 2023 has been met by (2.30 EJ) of coal, (1.74 EJ) of natural gas, (1.65 EJ) of oil, (0.60 EJ) of hydroelectricity, and (0.71 EJ) of renewable energy [13]. Given that coal dominates the energy mix in Türkiye, substituting hydropower and biomass for coal is an important milestone. Furthermore, CO₂ emissions from energy in Türkiye in 2023 totaled 411.1 Mt [27]. Reducing CO₂ emissions from FF is critical for environmental sustainability of Türkiye, as committed in COP²¹, which Türkiye signed in 2016 and approved in 2021. However, the transition from coal to hydropower and biomass requires addressing key institutional, financial, and technical challenges. Institutionally, clear regulatory frameworks, long-term energy policies, and government incentives are necessary to facilitate this transition. Financially, significant investments in renewable energy infrastructure, grid modernization, and subsidies for clean energy projects are crucial. Technically, advancements in energy storage, grid integration, and efficiency improvements in hydropower and biomass energy generation must be ensured to improve their viability as substitutes for coal. As a result, our empirical findings are consistent with the notion that if coal can be replaced with clean energy sources, the net-zero emission target can be achieved by 2050. Eventually, our empirical findings align with the results obtained by Xie and Hawkes [48], Lin and Atsagli [50] as well as, Raza and Lin [88]. In contrast, our study diverges from the findings of Yıldırım et al. [95], who concluded that biomass consumption contributes to environmental degradation.

CONCLUSION AND DISCUSSION

The release of CO₂ from the use of fossil fuels is one of the most major contributors to climate change, which has been accelerated by human activities. The significance of energy as an essential component in the production process has raised concerns regarding the potential of attaining environmental sustainability. The Paris Climate Agreement seeks to lower fossil fuel consumption and raise the share of clean and renewable energy in the energy mix of participating countries by 2030, with the goal of achieving net-zero carbon emissions by 2050. Türkiye became a party to the Paris Climate Agreement in 2016 and formally endorsed the agreement in 2021. This empirical study analyzes the substitution potential between non-energy inputs (labor and capital) and energy-specific inputs (oil, natural gas, coal, hydropower, and biomass) to evaluate Türkiye's transition from fossil fuels to clean and renewable energy sources. The effectiveness of Türkiye's energy transition is assessed using Ridge Regression (RR) over the period 1988–2023, employing the Translog Production Function (TPF) model.

The empirical findings have substantial implications regarding the Türkiye economy. Firstly, the output elasticities for labor, capital, oil, natural gas, coal, hydropower, and biomass are positive throughout the sample period. Moreover, labor, followed by capital, exerts the greatest impact on output during the relevant period. Given Türkiye's status as a labor-intensive and developing country, this finding is not unexpected. In Türkiye, the improvement in labor productivity during this period strengthened the positive contribution of labor, while factors such as foreign

direct investment, technological advancements, and export growth facilitated the positive contribution of capital to output by driving the increase in capital stock. In terms of energy inputs, coal is the largest contributor to output compared to other energy sources and remains the dominant fuel. This underscores the ongoing reliance of the Türkiye economy on coal for quantitative growth, despite commitments to reduce CO₂ emissions for climate change mitigation.

Secondly, traditional factors of production (labor and capital) and energy sources (oil, natural gas, coal, hydropower, and biofuels) are found to be substitutable. Compared to other fuels, labor exhibits the lowest substitution potential with natural gas and with hydropower, while capital shows the highest substitution potential with oil and the lowest with natural gas. Furthermore, among the fuel pairs in Türkiye, the greatest substitution potential is observed between oil and coal, highlighting the country's considerable dependence on fossil fuels. Given Türkiye's reliance on natural gas imports, stabilizing natural gas demand and increasing domestic production can be achieved through advanced capital investments.

Lastly, hydroelectricity demonstrated the highest potential for labor substitution relative to other energy sources in the Türkiye economy. In a labor-intensive country like Türkiye, an increase in labor costs can be offset by the use of hydropower, which not only helps reduce labor expenses but also supports environmental sustainability as a clean energy source. Furthermore, the substitution potential of hydropower and biomass for coal in the Türkiye economy is notably higher compared to other fuels. Given that Türkiye's energy mix is heavily reliant on fossil fuels, particularly coal, the capacity of hydropower and biomass to replace coal represents a significant development. Consequently, by increasing the use of hydropower and biomass, Türkiye can progressively decrease fossil fuel consumption and, as a result, reduce CO₂ emissions, thereby achieving its climate change targets and promoting environmental sustainability.

POLICY RECOMMENDATIONS

The empirical results provide several recommendations for the Türkiye economy. Firstly, Türkiye has the ability to shift from fossil fuels (oil, natural gas, and coal) to clean and renewable energy sources (hydropower and biomass). Secondly, despite Türkiye's commitment to reducing CO₂ emissions, the output elasticities of fossil fuels are estimated to be positive. Conversely, despite being polluting fuels, the positive output elasticities of fossil fuels demonstrate their productivity-enhancing effects within the Türkiye economy. Thirdly, similar to other fossil fuels in Türkiye, the potential to substitute coal, one of the most polluting fuels, with hydroelectricity and biomass substantiates the commitment to substituting the energy mix with clean energy sources. Fourthly, to achieve the climate objectives of 2030 and 2050, Türkiye must incorporate hydropower plants utilizing cost-effective, high-yield technology. Nevertheless, while hydropower is a carbon-neutral energy source, it contains the capacity to induce climate change. Technologies that reduce seasonal disruptions in the establishment of hydropower plants should be developed.

Finally, the capacity of biomass to substitute for fossil fuels is dependent on the development of technological innovations for biomass energy production in Türkiye. The capability to substitute fossil fuels with biomass, which can be transformed into various forms using suitable obtaining

technologies, indicates that Türkiye may reduce fossil fuel consumption if appropriate steps are taken in the transition to clean energy.

RESEARCH LIMITATIONS

This empirical study examines the potential for inter-factor and inter-fuel substitution to address the existing literature gap regarding the Türkiye economy. Nonetheless, this empirical study accepts substantial constraints. The study focuses on fossil fuels and clean and renewable energy sources based on the available data; however, it is unable to analyze, such as wind and solar energy, due to insufficient data in that sub-category. Future studies can enhance the empirical literature on the Türkiye economy by obtaining data on sub-categories of renewable energy. Furthermore, this study focuses primarily on the quantitative aspects of energy substitution and does not address employment data associated with the energy market or grid technologies. As such, future research could expand upon this work by incorporating these additional variables.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this manuscript.

USE OF AI FOR WRITING ASSISTANCE

Not declared.

ETHICS

There are no ethical issues with the publication of this manuscript.

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