Environmental Science and Pollution Research (2024) 31:6610–6627
https://doi.org/10.1007/s11356-023-31766-0

TREND EDITORIAL

Sustainable energy changeover in Pakistan: prospects, progress, and policies

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Received: 12 September 2023 / Accepted: 25 December 2023 / Published online: 10 January 2024

Abstract

Fossil fuels will still dominate energy in twenty years despite green power rising. The aim of the study is to analyze the factor substitution, emission mitigation, and technological progress among energy and non-energy inputs in Pakistan. The trans-log production method is employed to analyze the viability of energy substitution and then measure the CO_2 emission reduction possibility that comes from such adoption. The results suggest the following: (1) the influence of renewable energy and nonrenewable energy on economic growth is optimistic and is increasing return to scale. However, it has the potential to contribute a 7% growth-share if capital investment is doubled beyond the present levels. (2) Output elasticity between renewable and nonrenewable energy factors is elastic and, on average, is estimated by 0.096 and 1.007. (3) Energy substitution is possible with an average of 0.852, which presents that Pakistan has the capability of moving from nonrenewable energy to renewable energy. (4) Two investment scenarios show significant results and suggest that nonrenewable energy substitution for renewable energy has the potential to lessen CO_2 emissions without reducing the economy. Finally, energy substitution is possible from technical perspectives and inputs show strong convergence differences in technical progress. Comprehensive capital growth, technological progress, and low-carbon technological efforts can be a better fit for attaining carbon-reduction and sustainable economic growth.

Keywords Translog production function · Non-renewable energy · Renewable energy · Economic development · Pakistan

Introduction

Maximum economic doings in Pakistan are driven by energy, which encourages industrial and commercial doings intending to provide fundamental social welfare. Indeed, energy is not only an imperative contributor to the economy but also gives enthusiastic support to major economic sectors, i.e., agriculture, industrial, transport, household, commercial, and other government. The energy crisis, energy security, and economic growth (EG) have become crucial parameters for boosting carbon dioxide emission (CO_2E) in a region or a country. Interestingly, Pakistan is facing these issues.

Recently, the CO_2Es have grown continuously with fossil fuel energy consumption, as shown in Pakistan's fossil fuel and CO_2Es time series in Fig. 1. After 2008, nonrenewable energy (NRE) decreased by 0.90, 0.15, and 1.21 Mtoe in 2009, 2011, and 2012, respectively, but a little positive change of 1.09 and 0.15 Mtoe was detected in 2010 and 2014. Also, CO_2Es were reduced because of an increasing trend in renewable energy (RE) by 0.32, 0.22, 0.03, 0.002, and 0.53 Mtoe during 2009–2013. Furthermore, the emissions were reduced because of reducing oil, coal, and gas consumption in the major sectors (Pakistan Energy Yearbook (PEYB 2019)). Therefore, Pakistan has ensured the development of renewable energy technologies (RETs), i.e., coal, gas, and clean sources of energy, with the help of the China-Pakistan Economic Corridor (CPEC n.d.), Visions 2025–2035 (Vision 2025–2035 2014). A few remarkable studies, for example, Lin and Raza (2020a, b, c, 2021) and Raza et al. (2021), have clamored for a rise in

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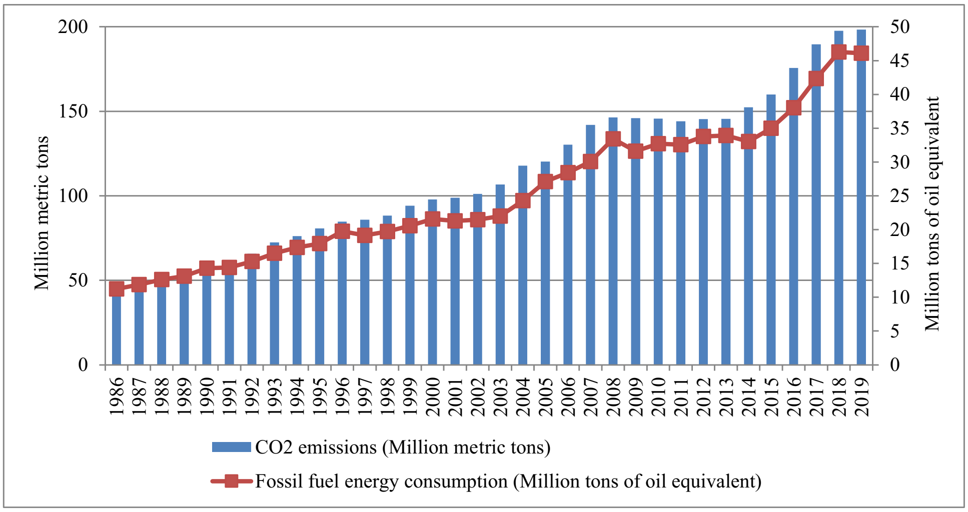

Fig. 1 Pakistan's fossil CO_2 emissions from 1986 to 2019. Source: Pakistan Energy Yearbook; BP Statistical Review of World Energy

RE in Pakistan's energy mix. These descriptions propose RE growth as a crucial policy track for energy prospects. Thus, RE could be substituted with NRE is a challenge based on the present energy structure. Having the world's 28th largest coal reserve of 185.175 billion tons and 3000–3300 sunshine hours per year (Lin and Raza 2019), Pakistan can use its cheap energy sources to improve energy security and mitigate CO_2Es, though the coal could be consumed using clean coal technologies. In this case, the RE impact on the economy and CO_2E mitigation can be checked, which is the main target to answer the questions.

To protect the atmosphere, the world society is determined to bind the global temperature to 2 °C until the present century under Intended Nationally Determined Contribution (INDC) (Commission 2015). Many countries presented this to the Conference of Parties (COP-21) for pollution mitigation in Paris. INDC also found its roots within Pakistan (Lin and Raza 2019). For the sustainable energy future of Pakistan, it proposes techniques to enhance RE objectives, inspects the limitations of the present framework, cost reduction mechanism, and technical obstacles, and highlights the potency of private investment in renewables for rural and off-grid electrification (International Renewable Energy Agency (IRENA 2018)). Thus, Pakistan is in an ideal situation to be considered regarding such transformation, seeing its ecological and renewable policies. Moreover, Pak-INDC largely enunciates the main difficulties of the country, which are expected to strengthen in the future as an outcome of climate-caused changeability and natural hazards (Pak-INDC n.d.). It involves the total CO_2Es and forecasts by considering the current and upcoming socioeconomic parameters, i.e., demographic movements, energy demands, mitigation, and adaptation measures. Also, EG, with a rise in population, has historically stayed a challenge for successive administrations. Uncertainty in energy has been another stumbling issue to enhance incomes for social and industrial development. Therefore, the Government of Pakistan (GOP) has started various financial and non-financial assistance programs of different types and sets to cater to the economic and societal protection of the poor and susceptible parts of society. The long-run national adaptation and road maps are provided in Table 1.

As per objectives, existing research analyzes whether Pakistan can move away from NRE to RE production. RE source[1] will be the greatest opportunity for lessening pollution and rising economy, energy security, and employment possibilities. Poverty will decline because the maximum population depends on natural resources (Zeb et al. 2014). The 99.7% of global CO_2E production countries move to 100% clean, nuclear, wind, water, and solar no later than 2050, with at least 80% renewables by 2030 (World Economic Forum (WEF 2020)). For example, RE assets as a job motor increased by 55% jobs in Germany since 2004 (Frondel et al. 2010). Pakistan has plentiful RE resources to fill the gap between energy demands. However, it is restrained by a few components: policy, regulation, and societal, economic, technological, industrial, and informational obstacles (Lin and Raza 2020a, b, c). For this, the study pays the translog production function to first give measurements for the association between RE, NRE, and real GDP. The approximations are then applied to measure energy factors' output and substitution elasticity. Second, the study reflects on the conditions of RE growth based on critical findings and the economy. Third, the study analyzes the CO_2 mitigation scenarios based on NRE reduction from 2017 to 2019. Also, the study uses the most updated and available data for Pakistan

[1] In this study, RE is taken as pollution-free energy. The RE includes all the electricity, including hydro, nuclear, renewable, and imported electricity (from various countries). RE does not include fossil fuel-related energy. NRE includes oil, gas, Liquified Petroleum Gas (LPG), and coal.

Table 1 Long-run national adaptation related to Pakistan's socio-economic, mitigation and energy needs (Pak-INDC n.d.)

Serial no	Adaptations
1	To construct a Climate-Resilient Society (CRS) and economy by guaranteeing that climate alters are disseminated within the social and economic vulnerable divisions
2	To support and adapt CRS, Pakistan will follow pains up to 2030 that state agriculture, water, and framework susceptibility
3	Circulation and transmission damages are identified to be critical in the country. Changes within the grid's productivity would save costs and reduce CO_2 emissions
4	Enhancing the effectiveness of coal-based energy generation using clean coal technologies
5	Improve water management and irrigation, high sustainable development and policy documentation
6	Energy Standards and Labeling (ESL) for industrialists, traders, and elevation for consumers should arise through modern technologies
7	Technological knowledge, fitting, maintaining wind, and solar energy sources should be ensured
8	Capacity development to monitor and confirm development on the implementation of ESL
9	Consciousness-raising and provision of incentives for efficient vehicle operations

to analyze the measure of the potential occurring among the various factors. Fourth, the study estimates the convergence difference in technological progress among pairs of input factors. Finally, the research proposes practical policy suggestions for the development of future energy security.

The study applies a trans-log production function because the model is a second-order approximation of any production function and becomes any function by the parametric transformation. It also improves each factor's level; therefore, the trans-log production function has variable substitutability. This research could not apply the trans-log cost function because variables have no prices or cross-price, such as energy prices, wages, and rents. Moreover, the production function has several advantages; for instance, (i) it measures the input elasticities, (ii) it discusses the independent variables as a factor in the model, and (iii) it estimates the substitutability among the factors between zero to infinite, and functional forms impose no boundaries or restrictions on the production process. This model does not only merely help as the best choice to investigate the substitution issue between RE and NRE but also establishes a definite theoretical association between factors. Besides, the present research adds to the literature not only regarding the method but also on RE challenges in Pakistan. Therefore, this study is more valuable because it assists as a source for an upcoming study to be done.

The research's motivation and contribution are (a) compared to emerging countries (i.e., China, India, Europe, and the USA); Pakistan's proportion of production inputs is relatively different, which causes extensive energy consumption and CO_2Es. Pakistan's RETs can enhance sustainable energy and could be helpful in local and global industries (Lin and Raza 2020a, b, c). Thus, the energy and nonenergy factors are essential for a country's energy planning, economic progress, and carbon reductions. That is, each energy policy directed to RE production in a country should investigate the individuality of the economy and its energy framework. As energy remains to be an imperative factor of production in a developing economy, there is a need for modeling to give further information on sustainable energy changeover and economic progress nexus. For this, we employed the trans-log production method, which offers the best opportunity to do so. It states a certain theoretical association between energy and non-energy factors and therefore investigates the output and substitution possibilities among energy-related inputs. The relevant analysis is very advantageous seeing the global environmental policies that have obtained recognition in the current decades (e.g., The Paris Agreement, CPEC, Vision-2035). Given that the current studies, particularly on Pakistan, have not yet undertaken substitutability between RE and NRE factors, the present study fills the literature gap. This will contribute to RE issues in Pakistan and also serve as the basis for future research. (b) We found very limited studies concerned with RE and NRE substitution and energy consumption in Pakistan; for example, few studies on RE, both qualitative and quantitative, have been conducted (Raza et al. 2020; Raza 2023), though the elasticity of substitution possibility between them has not been attempted yet. Moreover, the used techniques in these researches do not openly define a theoretical association between input–output (Raza et al. 2021). (c) With the rising demand for energy supply in various sectors, forecasts should be made to compare this condition with the required supply. These predictions should be not only reliant on the energy input trends but also impact the degree of fuel substitution with passaging time. Therefore, the energy demand using energy techniques might be more suitable if the substitution elasticities are deliberated. Thus, limiting the CO_2Es requires the applicability of RE resources and RETs. (d) Previously, most studies in Pakistan focused on transportation, industries, and studies in general, but the current study focused on the substitution relationship between RE and NRE in terms of economic development from 1986 to 2019, which had never been explored previously. Finally, the study intends to determine the degree of

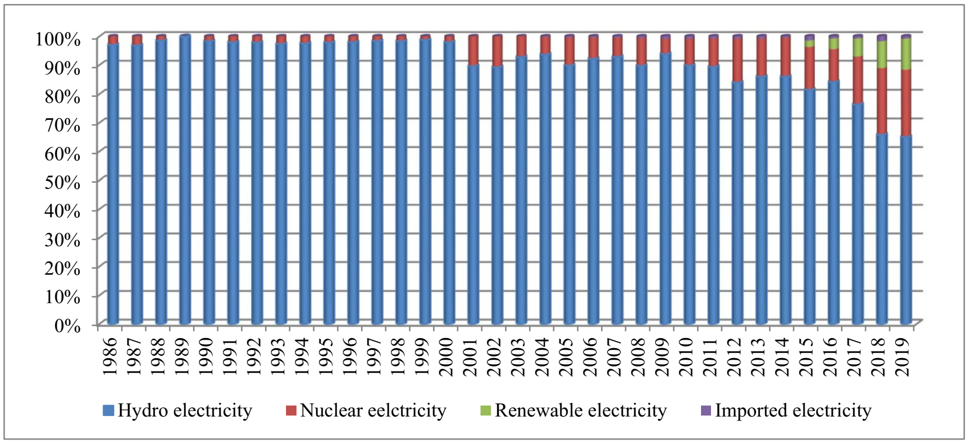

Fig. 2 The percentage share of installed electricity generation volume from 1986 to 2019. Source: Pakistan Energy Yearbook

substitutability between energy-related factors to support conversion, CO_2E reduction scenarios, and technical progress between energy and nonenergy factors. Moreover, this study is applicable in this light and helps to give an awareness of Pakistan's RE visions to raise the RE consumption with the EG under Pakistan's renewable energy (Visions 2025–2035 2014).

The remaining part is as shadows: The "RE potential, RETs, promotion, challenges, and economic growth" section narrates the RE potential, RETs, promotion, challenges, and economy. The "Literature overview" section shows the literature review. The "Model construction and measurement procedure" section covers the data description. Method and estimations are discussed in the "Data collection and description" section. The "Estimated outcomes and discussion" section provides the results and discussions. Conclusions and policy suggestions are described in the "Conclusion and policy suggestions" section.

RE potential, RETs, promotion, challenges, and economic growth

The primary commercial energy supplies have decreased from 86 to 84 Mtoe because of a decrease in the supply of oil by 19.8% and LPG by 9.5%, while there is a significant rise in RE by 21.4%, Liquified Natural Gas (LNG) by 18.9%, coal by 18.4%, and 0.3% in nuclear energy as compared to the previous year 2017 (PEYB 2019). Pakistan is situated in a sunny belt and has long sunlight hours with tremendous segregation levels. According to PEYB (2019), the total share of RE has been counted by 12.1%. Many solar energy plants are in progress in various provinces because the normal sunlight hours are about 3000–3300 h/year, with 6–7 h per day (Sadiq 2018). For this, CPEC (worth $33.8 billion in energy-related projects) and some private energy companies are constructing solar energy plants (Lin and Raza 2019; PES 2019).

As per the Pakistan Bureau of Statistics (2017), 59.45% of Pakistan's population lives in rural areas, which are concerned with food supply and agriculture growth. Despite attaining a national electrification rate of 70%, only 54.39% of rural people have electricity access, while 45.61% do not have access to electricity (Statistical Review of World Energy (SRWE 2019)). RE has become a convenient choice because of the many limitations of joining the rural populace to the country grid. Furthermore, policy makers have concentrated on some issues boosted by global organizations and agreements, i.e., Conference of Parties (COP)-21, IRENA, and Visions 2025–2035 to guarantee CO_2E mitigation. This suggests that the large-scale distribution of RETs is a specific step toward sustainable development.

Based on Pakistan's RE growth, the agenda is as follows: RE and RETs framework is embodied in the custody energy Visions and National Climate Change Policy-2012. All the consequences are made based on electricity utilization and production. The action plan is based on IRENA (2018), which strengthens RE targets; limitations of the current grid structure emphasize the best mechanisms to lessen prices, alleviate technology, and highlight the potential for private investment in RE. Towards our estimation, the agenda lies in the context of RE use, and their development in Pakistan is geared to energy supply and its consumption. Thus, check the overall installed electricity generation volume, as shown in the installed electricity generation time series in Fig. 2. This presents the overall share of available electricity in Pakistan. The country's RE consumption in various sectors shows a growing trend, which is proof of the strong contribution of RE. The RE consumption of different sectors is presented, as shown in Fig. 3. Finally, the share of RE consumption and real GDP in Pakistan shows a significant trend, as shown in the growth period in Fig. 4.

Pakistan's electricity generation is hydro- and nuclear electricity-based (Fig. 1). Renewable electricity (solar, biomass, wind, etc.) accounts for an insignificant share and only started in 2015. To fulfill the energy requirement,

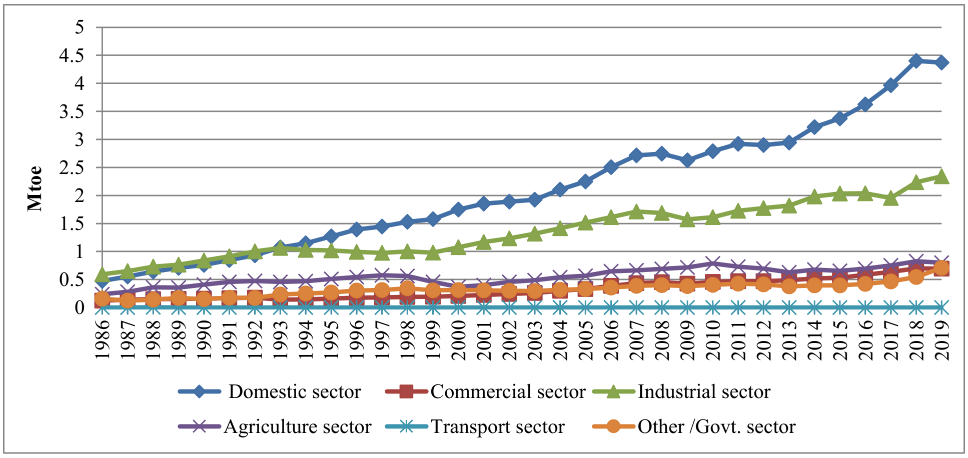

Fig. 3 Sector-wise final renewable energy consumption from 1986 to 2019 (Sector-wise or industrial renewable energy consumption is based on hydel, thermal, nuclear, renewables, and imported electricity. Collective clean energy is considered renewable energy because of the friendly environment. RE used in the production sectors, i.e., commercial, industrial, transport, agriculture, and other Government sectors are analyzed to compare the real GDP situation (Fig. 4). Maximum RE is consumed by the household sector, which is not concerned with production and does not impact Pakistan's economy. Therefore, we have excluded household RE consumption.). Source: Pakistan Energy Yearbook

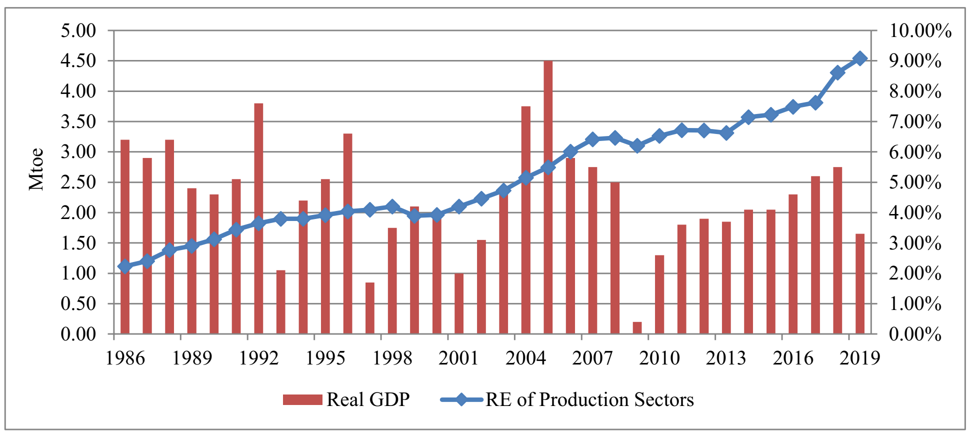

Fig. 4 Share of RE utilization and real GDP in Pakistan from 1986 to 2018. Source: Pakistan Energy Yearbook; Pakistan; Pakistan Bureau of Statistics

Pakistan started importing electricity after 2003. Renewable electricity generation increased by 21.4%, nuclear generation increased by 0.3%, and electricity imports decreased by 12.4% during 2019 (PEYB 2019), though the annual compound growth rate of electricity consumption grew by 5.6%. The sectors play a crucial role in energy transformation towards maximum renewables (Fig. 3). The household sector has the highest electricity consumed, followed by the industrial, agriculture, commercial, other govt., and transport sectors. Reality confirms that maximum renewable electricity is mainly hydropower-based and that a large quantity is spent in the non-production divisions.

A quite increasing movement is shown between real GDP and renewable electricity (Fig. 4). Simply, the ups and downs of renewable electricity utilization are comparable with real GDP with a small gap. As per the Pakistan Economic Survey (PES (2019)), Pakistan's real GDP growth was contracted by 0.4% because of the COVID-19 crisis. Based on these facts, renewable electricity use influences the country's economy. Therefore, the GOP stresses using household and ecologically RE generation resources because substitutes and RETs are the highest preferences for the GOP. Other factors, i.e., labor, capital, and NRE, also highly influence the output fluctuation.

Literature overview

Along with the EG of Pakistan and NRE consumption, CO_2Es have continuously increased over the last decade. As INDC found CO_2E roots within Pakistan (Commission 2015). In 2019, Pakistan's CO_2Es from fossil fuel combustion reached 198.30 Mt (SRWE 2019). For this, the GOP has created a favorable circumstance for the sustainability of the

Table 2 A literature review nexus based on energy use and EG in Pakistan since 2008

Author	Duration	Methods	Findings
Khan and Ahmad (2008)	1972–2007	VECM	Long-run: real income per capita → gas utilization, domestic price ≠ gas demand Short-run: real income per capita ↔ indigenous cost
Zahid (2008)	1971–2003	VECM	EC → GDP Pakistan, Sri Lanka, Nepal: Coal → GDP, GDP → EC, petroleum → GDP
Khan and Qayyum (2009)	1970–2006	ARDL	For agriculture, household, and industry EC: Long-run: income ↔ price elasticities Short-run: income ↔ price elasticities
Shahbaz et al. (2012)	1972–2011	VECM	RE, NRE → EG; labor, capital → EG; RE, NRE, capital ↔ EG
Tang and Shahbaz (2013)	1972–2010	VECM	Agriculture, manufacturing, and services sectors: EC → real output in all sectors. EC ≠ output of agriculture sector
Satti et al. (2014)	1974–2010	VECM	EG ↔ coal utilization
Ahmed et al. (2015)	1971–2011	GC	EG → energy consumption
Komal and Abbas (2015)	1972–2012	GMM	EG and urbanization → energy use; energy prices → energy utilization; EG ↔ energy consumption
Lin and Ahmad (2017)	1990–2014	LMDI	Per capita GDP and populace → CO_2Es; Carbon intensity, energy intensity, and fuel substitutions → reduce emissions
Rehman et al. (2019)	1990–2015	PAK-TIMES	Coal → CO_2Es
Raza and Shah (2019)	1981–2017	ARDL	Short-run: GDP ↔ coal, unemployment, populace, fiscal deficit Long-run: GDP ↔ coal consumption
Lin and Raza (2020a, b, c)	1978–2017	LMDI	Population, activity effects, GDP → CO_2Es; carbon intensity and energy intensity → lessen CO_2E
Raza and Lin (2020)	1984–2018	LMDI, TDA	Carbon coefficient → lessening CO_2E; GDP → raising CO_2Es. CO_2E presents an expensive coupling → EG
Lin and Raza (2020a, b, c)	2012–2040	MARKAL	Energy supply will reduce slightly while aggregative RE will grow by 28%. Net energy import proportion dependence would increase by 5.838 times, and vulnerability index and net oil import proportion would reduce by 1.276 and 1.105 under the base case. CO_2Es would rise by 407.49 Mt in 2040
Lin and Raza (2021)	1999–2018	LMDI, I-O	Industrial structure → coal utilization; energy intensity, mixed energy → energy output; EG factor → coal consumption; energy intensity, energy mix, and industrial trend → coal utilization
Lin and Raza (2021)	1989–2018	ID, TDA	EG → EC because of industrial, agriculture, and household divisions. Agriculture sector shows weak decoupling while other energy-concentrated sectors show an expensive decoupling

ARDL autoregressive distributed lag, *VECM* vector error correction model, *GC* granger causality, *EC* electricity consumption, *LMDI* logarithmic mean Divisia index, *I-O* input–output, *ID* index decomposition, *TDA* Tapio's decoupling approach

→ ↔ ≠ presents unidirectional bidirectional and no impact

RE division in Pakistan to harness the output of household RE resources (PES 2019). Therefore, a study on factors (i.e., RE, NRE, real GDP, labor, and capital) is essential for Pakistan's EG and CO_2E mitigation.

Generally, existing research arises under literature that analyzes the nexus between energy utilization and EG. For this, we update the literature to represent studies that emphasize Pakistan; that apply the trans-log production function approach. The specific studies on Pakistan (i.e., country-wise or multi-country studies) have provided proof that confirms different forms of outcomes. The outcomes and details of each study (since 2008) are provided in Table 2. It can be seen that there is an absence of a particular conclusion on the association between energy consumption, EG, and environmental pollution, and this is debatable because of the different methods.

As the energy demand increases, much research that goes beyond the energy estimation growth nexus has recently occurred. These studies applied the trans-log production function, which measures the relationship between energy, GDP, and substitution among the input factors. For example, Smyth et al. (2011, 2012) for China's steel and iron sector; Lin and Wesseh (2013) for the Chinese chemical industry; Lin and Xie (2014) for the Chinese transport sector; Lin et al. (2016) for Ghana energy economy; Lin et al. (2017) for Brazil energy; and Lin and Ankrah (2019) for Ghana RE growth are the multi-country studies that focused on inter-factor and inter-fuel substitution, and Wesseh and Lin (2021) analyzed electricity market effects on CO_2E and social welfare. They found that in the reverse order between clean energy output and high load, the time pricing method gives better possibilities for CO_2Es reduction than storage

Table 3 A literature review nexus based on energy utilization and EG in multi-countries since 2005

Author	Duration	Country	Methodology	Findings
Wang et al. (2014)	2001–2010	China	DEA	Declining trend for China's energy efficiency was estimated during 2001–2005. Overall, an increasing trend was found from 2005 to 2010 because of technical progress
Jin (2007)	1971–2001	South Korea	Rebound effect	At macroeconomic level: Home appliances → energy proficiency
Welsch and Ochsen (2005)	1976–1994	West Germany	Trans-log production function	Technical variation → increase power conservation and energy share
Suh (2015)	1948–2011	US	Trans-log production function	No substitution ≠ energy, capital in the 1960s; since 2000, energy substitutes ↔ capital
Li and Lin (2016)	2012	China	Two-stage estimation method	Substitutability ↔ fuels, production factors
Guidolin and Guseo (2016)	1960–2016	Germany	Innovation diffusion framework	RE → reduction of nuclear energy Highly in word-of-mouth → energy change. Diffusion of nuclear energy → negative crosses word-of-mouth
Liu and Lin (2017)	2003–2012	China	Trans-log cost function	RE, NRE ↔ input factor's energy in construction sector Technology → negative role in energy, 3% CO_2Es could be lessened in construction sector
Wesseh and Lin (2018)	1980–2014	Egypt	Trans-log causality model	Energy ↔ EG Technology → reduces CO_2Es
Rehfeldt et al. (2020)	2015, 2030, 2050	European Union	Cross-cutting and Special process	Technology → reduces 34% CO_2Es by 2030; high energy cost → minimum EG

DEA data envelopment analysis, *DOLS* dynamic ordinary least square

devices. They estimate that RE and NRE have driven EG for the previous decade and that China, Brazil, and African countries have the potential to substitute RE and NRE.

We observed some studies that analyzed inter-factor and inter-fuel substitution in various sectors concentrating on Pakistan. For example, Lin and Ahmad (2016) examined the transport sector's energy substitutability, Lin and Raza (2020b) estimated the energy and non-energy factors to estimate the input elasticity and substitution elasticity of the transport division, and Raza et al. (2021) analyzed the chemical sector's energy and non-energy factors. These researchers focused on fuel consumption and total energy consumption in various sectors and investigated the substitutability among the factors. However, these studies have nothing to do with RE in Pakistan. Studies and reviews have tried to estimate the nexus between energy use and EG in national and multi-countries (Tables 2 and 3). It has been reviewed that EG and energy utilization are linked to each other; for instance, Khan and Ahmad (2008); Zahid (2008); Khan and Qayyum (2009); Shahbaz et al. (2012); Tang and Shahbaz (2013); Satti et al. (2014); Ahmed et al. (2015); Komal and Abbas (2015); Lin and Ahmad (2017); Rehman et al. (2019); Raza and Shah (2019); Raza and Lin (2020); and Khan et al. (2020) found no consensus on causality between energy consumption and EG. Few studies on multiple countries, for example, Wang et al. (2014); Jin (2007); Welsch and Ochsen (2005); Suh (2015); Li and Lin (2016); Guidolin and Guseo (2016); Liu and Lin (2017); Wesseh and Lin (2018); and Rehfeldt et al. (2020) found a similar consensus because these studies suffer from the issue of omitted variable bias. The trans-log production function also studies evidence that the association between energy and EG exists and then analyzes the substitution effect among various input factors.

Energy is an imperative factor of production and EG; better modeling is needed to deliver more information. It can be understood via previous studies; maximum studies evaluated the substitution between overall energy and economic factors using trans-log production methods, which proves that the substitution elasticity fluctuates with a production function. However, no one has estimated the association between RE, NRE, and nonenergy factors, particularly in Pakistan. Thus, this function proposes the best possible and is valid for scholars, academics and GOP, which fulfills the literature gap and helps as a basis for upcoming research.

Model construction and measurement procedure

Model framework

The trans-log production function was first proposed by Christensen et al. (1973) along with characteristics reliant on variable estimation, elasticity, inclusiveness, square response surface framework, and measure substitution elasticity among the influences. This method has benefits; for instance, (1) it measures the elasticities between inputs, and (2) it can replicate the boundary of controlled variables to discuss the model's factors. Furthermore, Berndt and Wood (1975) and Raza et al. [5] used the trans-log production technique to find the substitution elasticity and complementarity. Furthermore, in the field of energy economics, this method has been valuable in estimating the input factor's possibilities, factor substitutability, product development, technical change, aggregation, and production efficiency.

By definition, the trans-log production function is a 2nd-order differential estimation at a definite point, where functional forms levy no limitations or restrictions on the production process. In short, no conditions are placed on the first and second differentiation estimation points. Therefore, these motives make the trans-log production function the best option for this research than the other estimations, i.e., Cobb–Douglas, constant elasticity of substitution (CES), etc. Many researchers, i.e., Lin and Wesseh (2013); Lin and Xie (2014), and Raza et al. (2021) have practiced this method for different countries and estimated the perfect substitution among the various factors, but this study concentrated on the substitutability among RE and NRE for Pakistan. Furthermore, the defined model is estimated as

$$
\begin{aligned}
l\ln Y_t = {} & \alpha_0 + \alpha_K \ln K_t + \alpha_L \ln L_t + \alpha_{RE} \ln RE_t \\
& + \alpha_{NRE} \ln NRE_t + \alpha_{K.L} \ln K_t \times \ln L_t \\
& + \alpha_{K.RE} \ln K_t \times \ln RE_t + \alpha_{K.NRE} \ln K_t \\
& \times \ln NRE_t + \alpha_{L.RE} \ln L_t \times \ln RE_t \\
& + \alpha_{L.NRE} \ln L_t \times \ln NRE_t + \alpha_{RE.NRE} \ln RE_t \\
& \times \ln NRE_t + \alpha_{K.K}(\ln K)^2 + \alpha_{L.L}(\ln L)^2 \\
& + \alpha_{RE.RE}(\ln RE)^2 + \alpha_{NRE.NRE}(\ln NRE)^2
\end{aligned} \tag{1}
$$

where Y_t shows the real GDP. K_t, L_t, RE_t, and NRE_t present capital, labor, renewable energy, and nonrenewable energy, and t is the time, respectively. ln is the natural logarithm, $\alpha_{K.L}$, $\alpha_{K.RE}$, $\alpha_{K.NRE}$, $\alpha_{L.RE}$, $\alpha_{L.NRE}$, and $\alpha_{RE.NRE}$ are technically determined parameters (i.e., i and j). Based on each factor's output elasticity, we estimate the output of each factor using Eqs. (2)–(5).

$$
\begin{aligned}
\phi_{Kt} = {} & \left(\frac{d \ln Y_t}{d \ln K_t}\right) \\
= {} & \alpha_K + 2\alpha_{K.K} \ln K_t + \alpha_{K.L} \ln L_t \\
& + \alpha_{K.RE} \ln RE_t + \alpha_{K.NRE} \ln NRE_t \rhd 0
\end{aligned} \tag{2}
$$

$$
\begin{aligned}
\phi_{Lt} = {} & \left(\frac{d \ln Y_t}{d \ln L_t}\right) \\
= {} & \alpha_L + 2\alpha_{L.L} \ln L_t + \alpha_{L.K} \ln K_t + \alpha_{L.RE} \ln RE_t \\
& + \alpha_{L.NRE} \ln NRE_t \rhd 0
\end{aligned} \tag{3}
$$

$$
\begin{aligned}
\phi_{REt} = {} & \left(\frac{d \ln Y_t}{d \ln RE_t}\right) \\
= {} & \alpha_{RE} + 2\alpha_{RE.RE} \ln RE_t + \alpha_{RE.K} \ln K_t \\
& + \alpha_{RE.L} \ln L_t + \alpha_{RE.NRE} \ln NRE_t \rhd 0
\end{aligned} \tag{4}
$$

$$
\begin{aligned}
\phi_{NREt} = {} & \left(\frac{d \ln Y_t}{d \ln NRE_t}\right) \\
= {} & \alpha_{NRE} + 2\alpha_{NRE.NRE} \ln NRE_t + \alpha_{NRE.K} \ln K_t \\
& + \alpha_{NRE.L} \ln L_t + \alpha_{NRE.RE} \ln RE_t \rhd 0
\end{aligned} \tag{5}
$$

One objective of the study is to analyze the substitutability between RE and NRE contributions to create the expression among the input influences. The substitution elasticity can be stated as follows: it is the proportion of the % change in the share of contributing factors to the % change in the marginal rate of technical substitution. The substitution degree between the factors changes from [0-∞] in which "0" means "2" factors cannot replace one another at all. This situation happens when there is a fixed portion in the production isoquant, i.e., a combination of capital and labor. ∞ shows that the production factors are accurately replaced by each other. To estimate productivity and energy efficiency is very important for the higher EG (Wang et al. 2017). Thus, the substitution elasticity between the factors is estimated by using Eq. (6).

$$
\sigma_{ij} = \frac{\%\Delta\left(\frac{X_{it}}{X_{jt}}\right)}{\%\Delta\left(\frac{P_{jt}}{P_{it}}\right)} \tag{6}
$$

where σ_{ij} shows the technical determined parameters of i and j. If Pakistan's firms are made advanced and are cost-reduced, Eq. (7) can be modified as

$$
\sigma_{ij} = \frac{\%\Delta\left(\frac{X_{it}}{X_{jt}}\right)}{\%\Delta\left(\frac{MP_{jt}}{MP_{it}}\right)} = \frac{d\left(\frac{X_{it}}{X_{jt}}\right)}{d\left(\frac{MP_{jt}}{MP_{it}}\right)} \times \frac{\left(\frac{MP_{jt}}{MP_{it}}\right)}{\left(\frac{X_{it}}{X_{jt}}\right)} \tag{7}
$$

where MP_{ij} are the marginal productivity of various inputs. Elasticities between i and j factors from Eq. (8) can be estimated:

$$\sigma_{ij} = \left[1 + \frac{-\alpha_{ij} + \left(\frac{\phi_i}{\phi_j}\right)\alpha_{jj}}{-\phi_i + \phi_j} \right]^{-1} \tag{8}$$

Thus, the pair of factor's substitutions between K-L, K-RE, K-NRE, L-RE, L-NRE, and RE-NRE can be calculated in Eq. (11) by using Eq. (9):

$$\sigma_{K.L} = \left[1 + \frac{-\alpha_{K.L} + \left(\frac{\phi_K}{\phi_L}\right)\alpha_{LL}}{-\phi_K + \phi_L} \right]^{-1} \tag{9}$$

$$\sigma_{K.RE} = \left[1 + \frac{-\alpha_{K.RE} + \left(\frac{\phi_K}{\phi_{RE}}\right)\alpha_{RE.RE}}{-\phi_K + \phi_{RE}} \right]^{-1} \tag{10}$$

$$\sigma_{K.NRE} = \left[1 + \frac{-\alpha_{K.NRE} + \left(\frac{\phi_K}{\phi_{NRE}}\right)\alpha_{NRE.NRE}}{-\phi_K + \phi_{NRE}} \right]^{-1} \tag{11}$$

$$\sigma_{L.RE} = \left[1 + \frac{-\alpha_{L.RE} + \left(\frac{\phi_L}{\phi_{RE}}\right)\alpha_{RE.RE}}{-\phi_L + \phi_{RE}} \right]^{-1} \tag{12}$$

$$\sigma_{L.NRE} = \left[1 + \frac{-\alpha_{L.NRE} + \left(\frac{\phi_L}{\phi_{NRE}}\right)\alpha_{NRE.NRE}}{-\phi_L + \phi_{NRE}} \right]^{-1} \tag{13}$$

$$\sigma_{RE.NRE} = \left[1 + \frac{-\alpha_{RE.NRE} + \left(\frac{\phi_{RE}}{\phi_{NRE}}\right)\alpha_{NRE.NRE}}{-\phi_{RE} + \phi_{NRE}} \right]^{-1} \tag{14}$$

where σ_{KL}, σ_{KRE}, σ_{KNRE}, σ_{LRE}, σ_{LNRE}, and σ_{RENRE} show substitution between the input factors.

Estimation strategy

Seeing the economic performance of data, the model suffers from multicollinearity (Fig. 5 and Eq. 2). Therefore, we must investigate whether there is a relationship between "2" or more of the input factors. For example, according to Lin and Atsagli (2017) and Raza et al. (2021), we assume the Pearson correlation estimation, multicollinearity, and the VIF (Variance Inflation Factor) techniques to identify the degree of multicollinearity for each factor. To reduce the ambiguity and correlation misleading, we estimated VIF with correlation analysis, which specifies how much the variance (σ^2) of an analyzed regression coefficient rises if independent variables are interrelated. As per the rule of thumb, if the value of VIF is > 10, the multicollinearity degree is supposed to be higher, but if the VIF is close to 1 or < 10, it is considered preferable. All VIFs show high values among factors and confirm the presence of multicollinearity, as shown in Table 4. To reduce the multicollinearity issue, we assumed the ridge regression method suggested by Hoerl and Kennard (1970) for our calculation. This method is employed because of its suitability, diminishes the mean square and is an effective technique with extensive applications. This method is obtained by estimating $\left(\acute{X}X + kI\right)\hat{\beta} = h$; where $h = \acute{X}Y$, $\hat{\beta} = \left(\acute{X}X + kI\right)^{-1}$ h, I is the identity matrix, and k is the ridge parameter that satisfies $k \geq 0$. Commonly, it is essential to detect the ridge solution for a range of [0–1]. Small and positive values develop the problem situation and lessen the σ^2. Mostly, while biased, the smallest ridge σ^2 measure frequently consequences in a lower mean square error when matched to least-squares measures. Hoerl and Kennard (1970) gave the name ridge regression to his method because of the similarity of its mathematical calculation to methods he employed before, i.e., "Ridge analyses" for graphically presenting the characteristics of second-order respond surface equation in many independent variables. Based on econometric literature, numerous techniques for obtaining the optimum ridge parametric value have been projected. Therefore, the present study employs the ridge plot based on various coefficients, which is common. The $\hat{\beta}\ i$ coefficient is then drawn regarding the k-values, and the optimum value is considered at the point where the $\hat{\beta}\ i$ coefficients look steady.

Data collection and description

The research includes the variables (i.e., labor, capital, output value, RE, and NRE) and their sources. Labor and real GDP statistics were taken from the Pakistan Economic Surveys;[2] capital information was obtained from World Development Indicators. RE and NRE consumption data were assessed from Pakistan Energy Yearbooks.[3]

[2] All labor and economic data books can be accessed from http://www.finance.gov.pk/survey.html.

[3] All labor and economic data books can be accessed from: https://hdip.com.pk/contents.php?cid¼432.

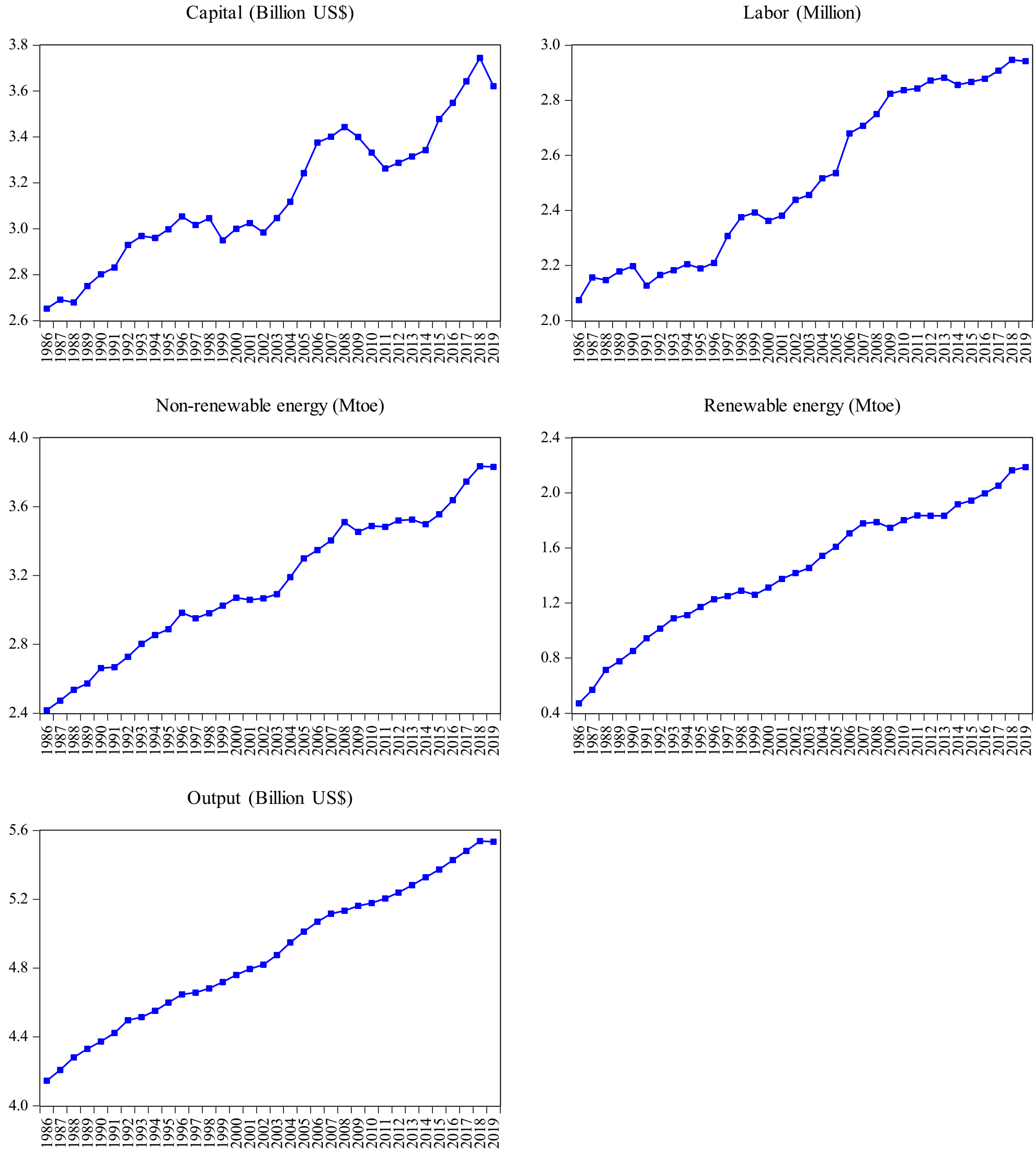

Fig. 5 Trends of the entire variables from 1986 to 2019

Table 4 Correlation and VIF analysis of all logarithmically converted variables

Variables	*K*	*L*	*RE*	*NRE*	VIF
K	1	0.929 (000)	0.967 (000)	0.975 (000)	209496.00
L	0.929 (000)	1	0.954 (000)	0.967 (000)	111422.50
RE	0.967 (000)	0.954 (000)	1	0.994 (000)	1467126.00
NRE	0.975 (000)	0.967 (000)	0.994 (000)	1	2768611.00

Correlation is significant at the 1% (000) level

Considering that statistics on NRE and RE consumption are separately observable for Pakistan, therefore, we estimated the energy consumption data in two ways: RE consumption (i.e., hydro, nuclear, renewable, and imported electricity) and NRE consumption (i.e., oil, gas, LPG, and coal) were separated to estimate the clear output. It should be noted that Lin and Ahmad (2016) and Raza et al. (2021) used similar calculations for Pakistan. Also, all the main sectors, which add to Pakistan's economy, consume electricity (RE) in their processes. Therefore, RE as a substitution for energy is sensible and suitable.

Pakistan's labor estimation is analyzed by $((\text{labor force employed}/\text{total population}) * \text{active population})$ The gross capital formation (GCF) values were composed in constant 2010 US$ to remove the influence of inflation. Numerous researchers estimated capital data by applying the perpetual inventory technique because of non-availability. To measure capital stock comprising capital rental price Jorgenson (1995) and perpetual inventory method Goldsmith (1951), which several scholars have applied; for instance, Lin and Wesseh (2013); Lin and Xie (2014); and Lin and Ankrah (2019) have employed this method to different countries. Inventories are stocks of goods given by firms to encounter temporary or unpredicted variations in production or sales and "work in progress." Therefore, we used this method to find out the capital stock. This method is used because of its popularity, supportable outcomes, and best results. Hence, only a few researches have deliberated on Pakistan's energy, transport sector, and chemical sector. However, no research has been recently estimated on the nexus between RE, NRE and real GDP. We choose the real GDP because it tracks the total values of goods and services estimating the quantities. Also, it is a more accurate measure of the change in production levels from one period to another period. Using a perpetual inventory process, the time capital stock is estimated by using Eq. (15), and the initial capital stock is estimated in Eq. (16).

$$K_t = K_{t-1} \times \left(1 - \delta_t\right) + I_t \tag{15}$$

where K_t is the current capital stock, K_{t-1} is the previous year's stock, I_t is the capital investment in time t, and δ_t is the capital's depreciation rate. Following the studies of Smyth et al. (2012) and Lin and Ankrah (2019), there was a supposed 5% depreciation rate for the various countries. A similar depreciation rate was practiced by Lin and Ahmad (2016), Lin and Raza (2020b), Raza et al. (2021), and Ma (2023) for Pakistan's various sectors and China. Hence, K_0 is as follows:

$$K_0 = {}^{I_0}\!/_{(g+\delta)} \tag{16}$$

Table 5 Statistics of all variables

Statistics	Output	*K*	*L*	*RE*	*NRE*
Units	Billion US$	Billion US$	Million	Mtoe	Mote
Mean	142.380	12.889	24.229	4.6719	25.2610
Std. Dev	56.743	3.909	7.294	2.02366	9.96254

Table 6 Degree of multicollinearity

Variables	R^2
K	0.953
L	0.942
RE	0.988
NRE	0.933

where K_0, I_0, g, and δ present initial capital stock, initial capital investment, average capital growth, and capital depreciation, respectively. The data set was transformed into a natural logarithm for easy measurement and understanding. To estimate the data for five variables used in this study is arranged. The unit of energy-related data is measured by million tons of oil equivalents (Mtoe). The data relating to output and capital is converted into billion US$ while labor data is converted into million.

Variable units, means and standard deviations are provided in Table 5. The corresponding standard deviation and means values start from 0.29 to 0.46 and from 1.44 to 4.87. The trends of all variables beyond the time are used in this study, as shown in Fig. 5. The objective is to test the likelihood of association amongst the explanatory parameters, thus proposing the need to examine the relationship among independent variables.

Estimated outcomes and discussion

Estimation of ridge trace

Given many parameters in our trans-log formulation, we start with an analysis of multicollinearity in the statistics by applying the Kmenta (1967) method. As per Kmenta, an idealized multicollinearity degree measurement is obtained by regressing individual predictor parameters on the residual explanatory variables. The estimated coefficient of determination (R^2) from regression can be applied to estimate the multicollinearity degree in the data, as shown in Table 6. Thus, the obtained values of R^2 are correlated with 0.953, 0.942, 0.988, and 0.933 for *K*, *L*, *RE*, and *NRE* (Table 6). The outcomes propose very extreme multicollinearity, hence, an issue in the study.

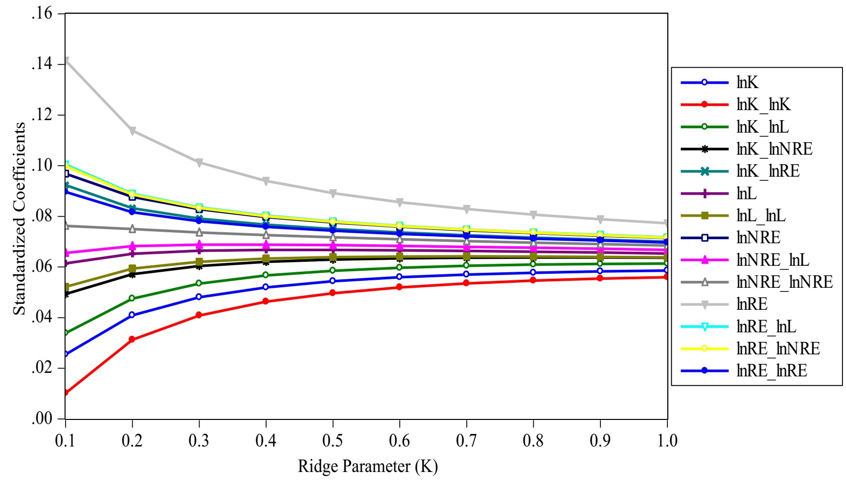

Fig. 6 Estimation of ridge trace graph [*k*-values of 0 to1] of the coefficients based on ridge regression

Table 7 Ridge regression estimates

Variables	Coefficient	Std. error	*t*-statistics	*P*-value	VIF
lnK	0.05529*	0.03630	1.52316	0.07584	0.08119
lnL	0.06667**	0.03306	2.01684	0.03242	0.09271
lnRE	0.08721**	0.02890	3.01735	0.00495	0.07033
lnNRE	0.07667***	0.03083	2.48722	0.01361	0.02985
lnK.lnL	0.05917**	0.03509	1.68627	0.05779	0.02802
lnK.lnRE	0.07425***	0.03132	2.37039	0.01695	0.01910
lnK.lnNRE	0.06320**	0.03395	1.86145	0.04272	0.02303
lnL.lnRE	0.07705***	0.03075	2.50573	0.01315	0.01597
lnL.lnNRE	0.06846**	0.03262	2.09861	0.02797	0.02452
lnRE.lnNRE	0.07688**	0.03078	2.49744	0.01336	0.01658
lnK.lnK	0.05088*	0.03784	1.34461	0.10087	0.09487
lnL.lnL	0.06406**	0.03372	1.89957	0.03995	0.09713
lnRE.lnRE	0.07367**	0.03145	2.34267	0.01785	0.01658
lnNRE.lnNRE	0.07132**	0.03196	2.23148	0.02194	0.01877
Constant	3.1042				
Model diagnostics					
Ridge parameter *K*	0.55				
R-square	0.98930				
F-statistics	147.01			0.0000	

***, **, and * show 1%, 5%, and 10%

The outcomes bound us to apply the ridge regression technique (Table 5 and 6). Generally, the advantages of ridge regression are as follows: it reduces the multicollinearity issue by incorporating a minor statistic to the diagonal of the amount which is correlated, the ridge estimator is reliable and has smaller σ^2 than an OLS estimator, standardization in ridge regression, and recurring estimation on ridge regression is that because of subjective technique. Therefore, we consider it would be the most suitable econometric method since coefficient measures for multiple linear regression methods depend hugely on the individuality of the method terms. We approved $k=0.55$ as the ridge parameters since it is about at this value that the coefficients of the factors look too balanced, as shown in the ridge trace plot between ridge parameters [0.10–1.00] and standardized coefficients (Fig. 6).

Ridge regression analysis

The ridge regression ($k=0.55$) shows that all the coefficients are reliable with the economic theory, as shown in Table 7. The VIF values of all parameters are <10, which proposes that the value of k is appropriate. All the estimated parameters' coefficients seem significant, which shows a practical description and increasing return to scale (Table 7). The current discussion depends on the key parameters that are the primary drivers of Pakistan's EG to permit the model description to be appropriate. Also, Lin and Atsagli (2017) examined interfuel substitution and found mixed outcomes for Ghana; Lin et al. (2017) found significant outcomes for Brazil; Raza et al. (2021) found maximum positive results for Pakistan's chemical sector. Therefore, existing factors are sensible, and the Eq. (2) consequences fit the model.

In Pakistan's economic framework, the applied variables (i.e., K and L) are analyzed in this research. However, it must be kept in mind that our investigation, importantly, emphasizes RE and NRE. Capital and labor positively and significantly influence Pakistan's economy (Table 7). Specifically, a 1% raise in capital and labor increases the economy by 0.055% and 0.666%. Interestingly, a 1% rise in RE and NRE increases the economy by 0.087% and 0.766% and is significant. Although, the squared terms of both RE and NRE show a positive and significant influence on the economy. The RE impact is slightly higher by 0.23% than NRE, so as the RE utilization rises; its impact on the economy strengthens by 0.073%. Also, a positive impact of NRE and a positive impact of $(NRE)^2$ increase the economy by 0.076% and 0.071%. Thus, it can be noted that both RE and NRE are imperative for Pakistan's economy, which is consistent with (Lin and Raza 2020a, b, c, 2021). As noted in footnote 1, the RE contains the maximum part of energy in Pakistan (i.e., electricity including hydro, nuclear, renewable, and imported electricity). Furthermore, the interaction relationship between K-RE and L-RE describes an optimistic and significant value of 0.0742 and 0.0770, saying that the right capital investment in *RE* will boost Pakistan's economy and labor by 0.074% and 0.077%. The model's R^2 is 0.98, and the standard error of all parameters is < 0.05, suggesting the model's goodness of fit (Table 7). Also, the t-values show a positive and significant direction of the difference in sample means (Table 7). The significance level (F-statistics is 147.01 (0.000)) is good, showing the model's suitability. All the coefficients are positive and lie in the range of zero to one, which is in line with economic reality. Also, the significant contribution of RE in the industrial, government, household, agriculture, and commercial sectors has made a significant output. This is why new RE commitments, i.e., CPEC with the worth of $33.8 billion for energy-related projects (CPEC), clean coal power projects (7560 megawatts) and clean energy (2790 megawatts), Pakistan's RE Visions 2025–2035, Pakistan-China Joint Energy Working Group (JEWG) in 2011, Pakistan-Iran electricity agreement in 2012, and Central Asia-South Asia power project ($1.16 billion) would export over 1000 megawatts of electricity to Pakistan. Likewise, installing wind, hydro, solar, and biogas power plants can make Pakistan an Asian Pioneer in cleaner energy because of its natural resources. The production divisions, i.e., industrial, agriculture and commercial consume less RE (Fig. 3), which could be substituted with the household sector. The K-NRE output is lower than the output of K-RE because Pakistan has invested much in RE projects during the last decade, including clean coal technologies, hydro, and RE (Lin and Raza 2020a, b, c; INDC 2015). Another reason is that

Table 8 Analysis of output elasticity and substitution between RE and NRE from 1986 to 2019

Year	Output elasticities of RE and NRE		Elasticity of substitution between RE and NRE
	ϕRE_t	ϕNRE_t	$\sigma RE_t.NRE_t$
1986	0.699141	0.767235	0.824398
1987	0.727181	0.790901	0.828974
1988	0.751707	0.809595	0.834099
1989	0.771689	0.826448	0.837093
1990	0.794575	0.849211	0.838196
1991	0.805336	0.854171	0.842332
1992	0.830839	0.877200	0.844847
1993	0.851756	0.897266	0.846093
1994	0.860367	0.907404	0.845439
1995	0.873143	0.918007	0.847177
1996	0.894380	0.940771	0.846919
1997	0.900268	0.942543	0.849543
1998	0.915560	0.956155	0.850959
1999	0.908778	0.955181	0.847348
2000	0.921345	0.966900	0.848209
2001	0.933010	0.972807	0.851876
2002	0.941114	0.978536	0.853462
2003	0.954908	0.990346	0.854929
2004	0.985362	1.019775	0.856149
2005	1.013960	1.049491	0.856083
2006	1.053057	1.082158	0.860277
2007	1.072134	1.099276	0.861611
2008	1.088073	1.120663	0.858954
2009	1.079955	1.111684	0.859280
2010	1.086654	1.117394	0.859902
2011	1.086988	1.115579	0.861042
2012	1.093292	1.124064	0.859984
2013	1.096484	1.127148	0.860088
2014	1.106609	1.129592	0.864257
2015	1.126146	1.149339	0.864359
2016	1.146323	1.170406	0.864116
2017	1.171907	1.197917	0.863423
2018	1.205976	1.228433	0.865521
2019	1.199615	1.221528	0.865730
Average	0.9690	1.0078	0.8521
Standard deviation	0.1436	0.1318	0.0108

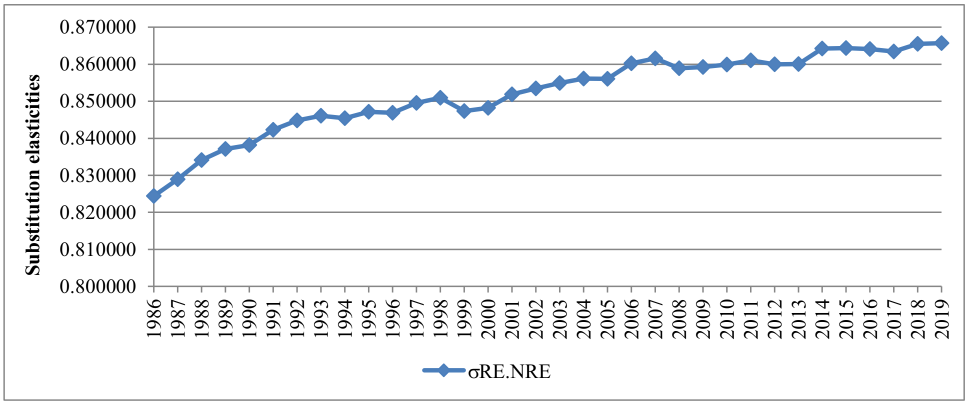

Fig. 7 Elasticity of substitution between RE and NRE from 1986 to 2019

the NRE supply reduced (i.e., 19.8% oil and 9.5% LPG and RE, LNG, coal, and nuclear electricity increased by 21.4%, 18.9%, 18.4%, and 0.3% (PEYB 2019).

Output elasticity and elasticity of substitution between RE and NRE factors

We investigated the output elasticities of RE and NRE of input factors by using Eqs. (5)–(6). Columns (2)–(3) present the RE and NRE output elasticity, as shown in Table 8. The output elasticities are found to be elastic, while the results of NRE show the maximum degree of responsiveness. These elasticities are called marginal products regarding output, which approximates how much output fluctuates because of a unit rise in a particular factor. It is beneficial in respect of concluding resource allocation over the period. Moreover, the output elasticities of RE (starts from 0.699 to 1.199), while that of NRE are positive (starts from 0.767 to 1.221) with a mixed decreasing trend. Averagely, the output elasticities of RE and NRE are 0.969 and 1.007, while the standard deviation of both elasticities is counted as 0.144 and 0.132, respectively. This analysis shows that the annual fluctuation in the RE "34" years has encouraged optimistic and greater EG than the NRE, which is consistent with Lin and Ankrah (2019).

Also, we then estimated substitution between RE and NRE by using Eqs. (9) and (14). All the input pairs are substitutes, but the substitution consequence between RE and NRE is of great concern to Pakistan's energy economy. This is because of environmental issues that NRE utilization might cause in the future. Moreover, the Paris Agreement adopted by 196 parties, including Pakistan, at COP-21 is a legally binding global treaty on climate change. The major objective is to retain a global temperature rise this century well below 2 °C and try to limit the temperature rise even further to 1.5 °C above pre-industrial levels (Commission, 205). Therefore, the idea of substituting NRE (i.e., oil, coal, and gas) has received great attention from many countries. Thus, to give experimental support for sustainable RE development, we estimate substitution elasticity between two energy kinds (RE and NRE), as shown in Table 8 (column 4). The RE and NRE substitution elasticity for the thirty-four-year trend is provided in Fig. 7. All the values of substitution elasticity between $\sigma RE_t.NRE_t$ are found to be positive (0.824–0.865) with a positive average and standard deviation of 0.852 and 0.0108. This presents that RE and NRE are substitutes, and the value is close to "1," stable, and positive. It can be seen that substitution elasticity only suggests a potential of "2" input factors being substitutes. The indication of its measurement is theoretic; therefore, there must be practical valuation in the form of its possibility before the policy suggestions. For example, Wesseh et al. (2013) analyzed petroleum and electricity to be substitutes for Liberia and found that both are substitutes. The opportunity is limited in practice because some important issues are linked with RETs, which is the cause of weak substitution; Lin et al. (2016) estimated the substitution from electricity to petroleum and found that the enhancement of the technology to renewable energy production will be successful over future; Lin and Ankrah (2019) found the substitution between nonrenewable and renewable energy for Ghana and found that there is a weak substitution. Finally, the study is also reliant on Gyamfi et al. (2015) for Ghana and

Table 9 NRE reduction and its impacts on CO_2E mitigations

Year	RE consumption (Mtoe)	CO_2 emission reduction (Mt)
	Scenario 1: Increase RE capital investment by 5%	
2017	8.1689	22.1604
2018	9.1435	20.6381
2019	9.3602	21.1858
	Scenario 2: Increase RE capital investment by 10%	
2017	8.5579	23.2157
2018	9.5789	21.6209
2019	9.8059	21.1858

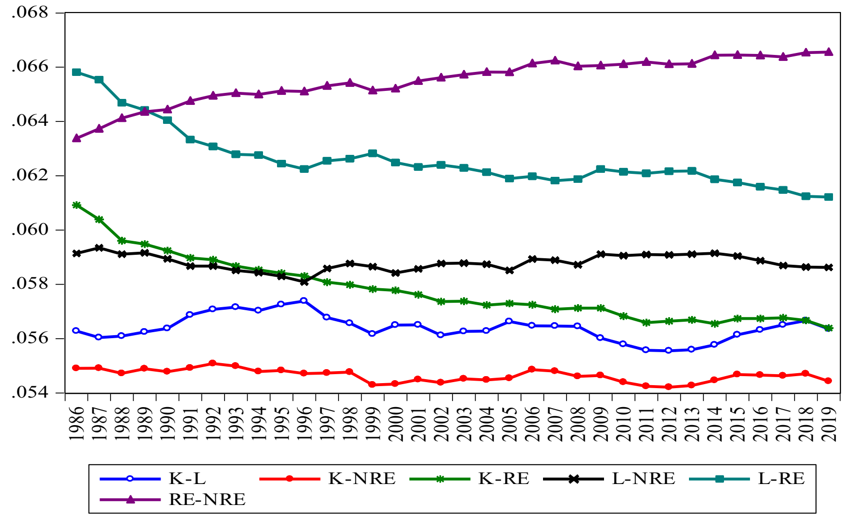

Fig. 8 The difference in TP between the pair of factors from 1986 to 2019

Lin and Ahmad (2016) and Raza et al. (2021) for Pakistan based on grave limitations. Moreover, the study suggests that inter-fuel substitution is not only the solution; relatively, the substitution should be sustained by technological development and employment of highly skilled labor.

Scenario analysis

The outcomes of RE substitution are further applied in scenario investigation. These scenarios estimate the RE consumption and their impacts on CO_2Es, as shown in Table 9. The scenarios we estimated correspond to a 5% and 10% rise in capital investment linked to the RE (in lessening investment in petroleum products) during 2017, 2018, and 2019. The outcomes propose that a 5% and 10% rise in investment is associated with NRE-lessening technologies (Table 9). This would result in a corresponding decrease in fossil fuel use by 8.17, 9.14, and 9.36 and 8.56, 9.58, and 9.81 Mtoe for 2017, 2018, and 2019 years, respectively. In the reduction in fossil fuel, the level of CO_2Es under the 5% investment scenario declines by 22.16, 20.63, and 20.22 Mt corresponding to the 2017, 2018, and 2019 years, respectively. Under the 10% investment scenario, a corresponding reduction in CO_2E levels is found by 23.22, 21.62, and 21.18 Mt for similar periods. The outcomes propose that substituting petroleum for RE has the potential to lessen CO_2Es in Pakistan without negatively impacting the level of EG. Also, the substitution is proportional, which means that the subsequent rise in RE consumption as an outcome of a decrease in fossil fuel consumption corresponds to the magnitude of petroleum reduction and its contribution to EG. Moreover, environmental advantages are adopted, and hence, the cost savings from environmental clean-up should offset the costs linked with technology switching. Thus, the results propose that investment in RETs is more critical because Pakistan is more reliant on fossil fuel imports (Lin and Raza 2020a, b, c). It is also worth mentioning that Pakistan is substituting huge NRE for RE. According to PEYB (2019), the total petroleum products import declined by 34% and the import of crude oil refineries was reduced by 13.2%, with a decreased bill of US$1.3 billion. Electricity installed capacity grew from 33,554 to 35,114 MW and 4682 GWh generated RE from solar, wind, bagasse, etc. Thus, clean energy projects will lessen the current account deficit and cheap energy from indigenous resources. More interestingly, Pakistan, being a high-fuel importing country, reduces its dependence on imports and will also improve energy security. Therefore, it is necessary to estimate the technical progress to check the current situation.

Analysis of the difference in technical progress of pairs of input factors

This analysis includes the utilization of the aggregate trans-log production function in addition to a combination of the previously estimated output elasticities and coefficients from Eq. (1). Many researchers applied this analysis to find out the technological progress of the energy and non-energy factors, for instance, Lin and Wesseh (2013) and Lin et al. (2017). The function used for estimation is given as:

$$TP_{ij} = \frac{\alpha_i}{\phi_i} - \frac{\alpha_j}{\phi_j} \tag{17}$$

where TP_{ij} shows the difference between technical progress of input factors i and j; α_i and α_j are the measured coefficients from Eq. (2); ϕ_i and ϕ_j are the output states of technical knowledge.

Based on Eq. (17), a positive TP_{ij} demonstrates that the state of TP for input "*i*" is faster than input "*j*." A negative TP_{ij} shows that the state of TP for input "*j*" is faster than the input "*i*." If TP_{ij} is "0", it infers there is equality in TP for inputs "*i*" and "*j*." All the input sets express an optimistic difference in TP, as shown in Fig. 8. Besides, there exist but few differences found in the relative TP of particular Except for K-L, RE-NRE, and L-NRE, the TP_{ij} of the other pair of inputs little declines in appropriate times (Fig. 8). In general, our outcomes suggest that TP of renewable-nonrenewable energy is faster than that of capital-labor. Similarly, Lin and Wesseh (2013) found the faster TP between oil and coal to electricity for China's chemical industry. Moreover, the evidence of convergence proposes that there is a possibility to substitute RE with NRE.

Conclusion and policy suggestions

Conclusion

The present study tried to investigate the economic impact of renewable energy, output elasticity and elasticity of substitution among the particular energy in Pakistan production technology. The ridge regression method is employed to control the multicollinearity issue in the data. The results indicate the following:

(1) The output is initially led by capital and labor with the significant contributions of both renewable and non-renewable energy. The output return of RE and NRE shows an optimistic consequence with rising returns to scale; however, the NRE provided mixed but decreasing rates during the studied period. The significant impact of clean energy on output is surprising, seeing that a maximum quantity of renewable energy goes into the production process, i.e., in agriculture, industrial, and commercial sectors. Non-renewable energy also positively impacts economy because Pakistan was initially reliant on fossil fuels. The significant development in RETs and maximum diversion in the key production sectors (especially the household sector to the industrial and agriculture sectors) has significant output. It also proves that Pakistan relies more on RE than NRE increasingly during the estimated period.

(2) The renewable and non-renewable energy are substitutes, which presents the changeover possibility between energy factors. Substitution between renewable and non-renewables shows a positive change between 0.824 and 0.865, indicating that Pakistan is moving from non-renewable to renewable energy. In addition, the issues linked with renewable energy involve but are limited to maximum capital investment and low energy content. Also, the elasticity of substitution suggests the potential of two input factors being alternated. For sustainable growth, research still acknowledges the renewables' potential and economic status, if and only if, the problem of cost, site, and scale are dealt with.

(3) The scenario analysis presents evidence of non-renewable energy reduction and its impacts on CO_2Es. Under the current 5% and 10% scenarios, the CO_2 emissions would decline by 20.22% and 21.8%, which presents that the RE has the best opportunity to mitigate carbon emissions in the future. The outcome further suggests that investment in RETs and indigenous energy resources, including renewables and clean coal technologies, would substitute for imported coal and oil products.

(4) Finally, the results show a robust convergence difference in technological progress among all the inputs. All the outcomes show a convergence between 0.55 and 0.67, showing optimistic results between all the factors (i.e., K-L, K-RE, K-NRE, L-RE, L-NRE, and RE-NRE). However, the technological progress between RE-NRE presents the maximum contribution during the period, especially after 2000. It concludes that, with the progress of research and development in renewable energy technology, there is the possibility of renewable energy replacing the main fossil fuel energy source of Pakistan, which will help accelerate the CO_2E mitigation agenda.

Policy recommendations

These results have important policy implications for Pakistan to relieve the pressure of carbon reduction. First, energy substitution and conservation policies on fuel would result in maximum consumption of clean fuel (considered to be cleaner), and this will have no negative impact on economic development. Simply, policymakers in Pakistan can impose taxes and quotas on fossil fuels and link less environmental damage without running the risk of suffering an economic recession. Second, substitution policies may be needed to enhance the volumes of smaller industries to levels that would raise their capacities to regulate convenient structural changes linked with the substitution in technologies coming from inter-fuel substitution. Currently, cutting oil consumption by 19.8% and increasing renewable and nuclear electricity generation by 21.4% and 0.3%, respectively, boost substitutability over time (PEYB 2019). Third, Pakistan's slower but optimistic rate of technological progress implies that the country has a huge opportunity to reduce CO_2Es by improving energy productivity through innovations in various energy technologies, primarily the sunny belt, gas mines, and clean coal technologies, as part of the CPEC and Pakistan Energy Visions 2025–2035. For example, at domestic and international levels, Pakistan and China are trying to enlarge their trade, economy, and energy security through SinoPak cooperation, One-Belt-One-Road, and CPEC under different projects (Raza and Lin 2022). These projects will significantly impact energy bills, economic growth, climate change, and human life, which will also satisfy the Paris Agreement. The low-carbon projects will be settled down on the availability of resources, for instance, the average sunshine hours in Pakistan are 3000–3300 h per year, 29th biggest gas mines in the world and coastal areas. These frameworks can play a significant role in domestic renewable energy and technology and ultimately reduce pollution.

Finally, the study is not without limitations. Future research can be carried out if recent figures are available. The trans-log production technique is actually not a cure-all technique in resolving each issue in the model. For this, the reverse causality among factors and the trans-log causality method can be employed. From the policy perspective, ensure research towards cost–benefit analysis and the availability of renewable energy sites.

Author contribution MYR: conceptualization, methodology, data curation, software, writing—original draft preparation, and validation. MC: methodology, data curation, software, writing—original draft preparation, and validation.

Funding This paper is supported by the Doctors Start Funding Project (No. BS202137) of Shandong Technology and Business University, Yantai, Shandong, 255000, China.

Data availability Data will be made available on request.

Declarations

Ethics approval This article does not contain any studies with human participants or animals by any of the authors.

Consent to participate All authors are informed and provided consent for this submission.

Consent for publication All authors have approved the manuscript and declare that this is an original contribution and none of the material in this paper is under consideration for publication elsewhere.

Competing interests The authors declare no competing interests.

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