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RESEARCH ARTICLE

Revealing the dynamic effects of fossil fuel energy, nuclear energy, renewable energy, and carbon emissions on Pakistan's economic growth

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Abstract

The primary goal of this study was to examine the relationship between fossil fuel energy, electricity production from nuclear sources, renewable energy, CO_2 emissions, and economic growth in Pakistan. Data ranging from 1975 to 2019 were utilized, and the stationarity of this data was verified through the unit root testing. The dynamic connections between variables were investigated by utilizing the linear autoregressive distributed lag technique. Long-run analysis results uncover that fossil fuel energy, renewable energy use, CO_2 emissions, and GDP per capita have a productive relationship with economic progress in Pakistan, whereas electric power consumption, electricity produced from nuclear sources, and energy utilization have an adverse effect on economic growth. Furthermore, the consequences revealed that fossil fuel energy, renewable energy consumption, carbon dioxide emissions, and GDP per capita have a significant linkage to Pakistan's economic growth via short run, whereas we revealed that the variables electric power consumption, electricity produced from nuclear sources, and energy usage have an adversative linkage to Pakistan's economic growth. Feasible progressive policies are required from the Pakistani government to pay more attention for tackling the energy and power sectors' issues in terms of fulfilling the country's energy requirements.

Keywords Fossil fuel energy · Carbon dioxide emissions · Economic growth · Environmental sustainability · ARDL model

Introduction

Environmental sustainability and economic development play an essential role in the energy field. However, promoting economic success, without harming the climate, is a requirement for the sustainable development. Developing nations typically confront several difficulties in fostering the economic development (Fang et al. 2018; Roson and Van der Mensbrugghe 2012; Rehman et al. 2021g). Obsolete infrastructure guarantees that even the industrialized economies continue to use fossil fuel energy to meet the growing demand for more power consumption. Consequently, the economic development in such economies stagnates, increasingly contributing to the generation of harmful gases and excessive fossil fuel use and aggravating the environmental air and land deterioration (Hanif 2018). The global companies use renewable and non-renewable energy sources; however, the paradigm of the sustainable growth that substituted the conventional model of growth over time has diversified the energy needs of the economy. The key energy sources in conventional growth models involve fossil

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fuel energy including gasoline, biomass, and natural gas. It has started to substitute the blueprint for the sustainable development through alternative energies such as wind, solar, and geothermal resources (Akadiri et al. 2019; Tuna and Tuna 2019; Alper and Oguz 2016).

Global prosperity and long-term growth are the ultimate goals of both industrialized and emerging countries. This objective is hampered by a number of obstacles. Even while the degradation of the environment is the most often debated danger to the planned step of sustainable development, there is a complicated link between economic growth and environmental degradation that has to be understood (Alvarado and Toledo 2017; Ahmed et al. 2015; Halkos and Bampatsou 2019; Jamel and Derbali 2016). Global warming and environmental degradation are two important development issues in reaching the sustainable global output and development. Therefore, preserving the environmental quality has been the focus of the national and foreign policy debates in the background of attaining the global imperishable progress in the last few decades. In addition to global warming and air pollution, carbon dioxide emissions have been identified as the primary causes of climate change and are generally recognized as major factors influencing both issues (Başarir and Çakir 2015; Ali et al. 2017; United Nations 2016; Kwakwa et al. 2014).

Pakistan's dependence on thermal energy, which includes imported coal as well as local coal and natural gas, has decreased in the recent years as far as the energy mix is concerned. Pakistan gets two-thirds of its energy from fuel oil and natural gas. Natural gas made up 34.6% of the energy mix, with fuel oil coming second with a share of 31.2%. Renewable energy has a very low share in the energy mix (around 1.1%). In reality, the nuclear energy accounts for 2.7% of the total energy consumption. Coal is another fossil fuel in the Pakistan's energy mix, and it is becoming more important as a source of energy, accounting 12.7% of the total energy mix (GOP 2019). In the Pakistan's electricity sector, petroleum-fired power plants have a life expectancy of more than 30 years and will be removed during the next several years. It is anticipated that in the next few years, furnace oil–based energy will account for less than 1% of the total energy consumption of the country. There are about 186 billion tonnes of coal reserves in Pakistan, which are sufficient to meet the country's long-term energy needs (GOP 2020). In terms of GDP per capita, it presented large fluctuations during the decades, from high growth rates down to negative rates. Pakistan steadily grew after the international financial crisis from 2007–2009, up to 2018 (+3.68%), but then collapsed in 2019 (−1.03%), before the pandemic erupted in 2020 (−1.44%) (GOP, 2020).

In terms of contribution to manufacturing, energy use may result in large carbon emissions that affect the environment. Similarly, the economic development should stimulate innovation in a healthier world according to the energy consumption needs, because an unhealthy environment will only delay the development (Adewuyi and Awodumi 2017). Various studies have been carried to expose the link among economic progress, CO_2 emission, foreign trade, environmental degradation, environmental pollution and trade openness, urban agglomeration, economic globalization, sustainable development, environmental-related technologies, commercial energy distribution, food production, electricity and renewable energy usage, carbonization and atmospheric pollution, and coal energy in power sector (Magazzino 2016; Obradović and Lojanica 2017; Moreau and Vuille 2018; Ssali et al. 2019; Alam and Murad 2020; Rehman et al. 2021a; Murshed et al. 2021; Rehman et al. 2021b; Khan et al., 2022; Rehman et al. 2021c; Rehman et al. 2021d; Cao et al. 2021; Rehman et al. 2021e; Rehman et al. 2021f), but this study's main aim was to explore the association among fossil fuel energy, electricity generated from nuclear sources, renewable energy usage, electric power consumption, CO_2 emissions, energy utilization, and economic growth in Pakistan by utilizing the ARDL model. This research makes a significant addition to the current literature in the areas of energy utilization, carbon emission, environmental sustainability, and economic development, among others.

As a consequence, the remaining sections of the paper are organized as follows: the section "Literature review" presents the findings of previously conducted studies that are relevant to the topic, while the section "Methods and data" uncovers the study methodology and data collection that were used in the analysis of the data. The findings of the research, as well as their interpretation, are provided under the heading "Results and discussion." "Conclusion and policy recommendations" is the last portion of the paper, where ideas and the policy implications are discussed.

Literature review

Sustainable development and climate change mitigation are gravely endangered by the use of fossil fuels, according to several investigations. While the collapse in international fuel prices has boosted a political will to implement reforms in order to subsidize the fossil fuel energy, these recent reforms can be reversed because the fuel prices have bounced. Moreover, they can be reversed particularly if they fail to address the basic mechanisms that cause the low demand for fossil fuel (Schmidt et al. 2017). The core source of atmospheric pollution is carbon dioxide emissions, and CO_2 emissions are mainly caused by the fossil fuel combustion. Environmental degradation is increasing because of the carbon dioxide emissions and climatic variation creates a variety of issues in the emerging economies including inadequate quality of air and water, desert deforestation, and poor quality of survival (Nathaniel et al. 2019; Xue et al. 2014; Pan et al. 2018; Heydari et al. 2019).

Insofar as energy consumption promotes the economic prosperity, increases sales and employment, and improves safety and services, it may become a positive element in achieving the sustainability goals such as poverty eradication. This argument clearly implies that energy utilization leads to the economic progress, and therefore the energy conservation measures would restrict income (Asafu-Adjaye et al. 2016). The primary goal of the industrialized and emerging countries is to promote global prosperity and sustainable development. Many challenges prohibit the achievement of that aim. Although the most prominent contentious challenge is to achieve the targeted level of the sustainable progress, the linkage between the economic development and environmental destruction is complicated. Greenhouse gas (GHG) pollution in the presence of CO_2 emissions is rising and the environmental deterioration is owing to the climatic variation and global warming (Cowan et al. 2014; Gasimli et al. 2019).

Decoupling the increased CO_2 emissions from the global economic growth indicates lower fossil fuel activity. It also reflects the renewable energy usage and energy transition. Indeed, most CO_2 emissions derive from the burning of fossil fuel and hence are dictated by the electricity consumption or energy-intensive practices. Thus, the high demand for energy forecasts high use levels in the electricity generation, industry, and road transport. Nonetheless, changes in the fuel process, including medium carbon or low carbon natural coal, nuclear, or renewable energies, would typically reduce the environmental warming (Apergis et al. 2010; Barreto 2018; Wesseh and Zoumara, 2012; Rehman et al. 2019). Economic development determines climatic variation. Global prosperity encourages industrialization and enhances the utilization of natural resources. All these commercial practices determine natural resource degradation and increase waste volume and threats (Dong et al. 2017; Ahmad and Zhao 2018).

In emerging economies, energy consumption tends to expand at the same pace as demand. According to predictions, this increase will continue. Aside from the need to react to nations' consumption requirements and adapt to the technological advancements, the energy consumption will rise. While a significant percentage of fossil energy sources are used to generate electricity, meeting low levels of renewable energy demand poses possible difficulties in the area of clean energy. In addition, much energy research and national energy policy are moving in this direction. Oil and oil-related instability, import dependence, global crises, and the severe environmental consequences of fossil fuel usage are the most urgent issues (Can and Korkmaz 2019; Bekareva et al. 2017; Amri 2017). Electricity is essential for economic progress, and ensuring that everyone has access to inexpensive, reliable electricity is a significant development goal. In the previous few decades, fossil fuels have exceeded the largest need for energy, but in the future, they would have to offer minimal carbon and potentially zero carbon framework. Decarbonization takes effect in all countries at different rates, based on regional situations (Fankhauser and Jotzo 2018).

Reversing the negative environmental change remains one of the world's biggest problems. GHG and CO_2 emissions have increased annually, because of the huge usage of fossil fuels. The significance of fossil fuels has been recognized both in historical and contemporary growth drivers. Current energy is recognized as a core component of the global development, which provides exposure to accessible, secure, renewable, and efficient electricity.

Methods and data

The study variables used in this analysis include economic growth, fossil fuel energy, renewable energy consumption, electric power consumption, electricity produced from the nuclear sources, CO_2 emission, GDP per capita, and energy utilization. Time series data range is 1975–2019 which is taken from the WDI (World Development Indicators). Figure 1 plot depicts the production and consumption scenario of all variables.

Specification of econometric model with ARDL technique

In order to encounter the relation amid variables, the following model can be stated as:

$$ECG_t = f(FOFEC_t, REEC_t, ELPC_t, CO2e_t, EPNS_t, GDPPCA_t, ENUS_t) \quad (1)$$

In Eq. (1), ECG_t indicates the economic growth, $FOFEC_t$ displays the fossil fuel energy consumption, $REEC_t$ indicates renewable energy consumption, $EPNS_t$ signifies electric power consumption, $CO2e_t$ shows the carbon dioxide emissions, $EPNS_t$ indicates the electricity produced from nuclear sources, $GDPPCA_t$ displays the GDP per capita, and $ENUS_t$ shows the energy usage.

Equation (1) can also be written as:

$$\begin{aligned} ECG_t = {} & \beta_0 + \beta_1 FOFEC_t + \beta_2 REEC_t + \beta_3 ELPC_t + \beta_4 CO2e_t \\ & + \beta_5 EPNS_t + \beta_6 GDPPCA_t + \beta_7 ENUS_t + \varepsilon_t \end{aligned} \quad (2)$$

The logarithmic version of the variables is described in the log-linear model as:

$$\begin{aligned} ECG_t = {} & \beta_0 + \beta_1 LnFOFEC_t + \beta_2 LnREEC_t + \beta_3 LnELPC_t + \beta_4 LnCO2e_t \\ & + \beta_5 LnEPNS_t + \beta_6 LnGDPPCA_t + \beta_7 LnENUS_t + \varepsilon_t \end{aligned} \quad (3)$$

The logarithmic forms of variables are demonstrated in Eq. (3) including fossil fuel energy consumption, electricity produced from nuclear sources, renewable energy consumption, CO_2 emissions, electric power consumption, GDP per

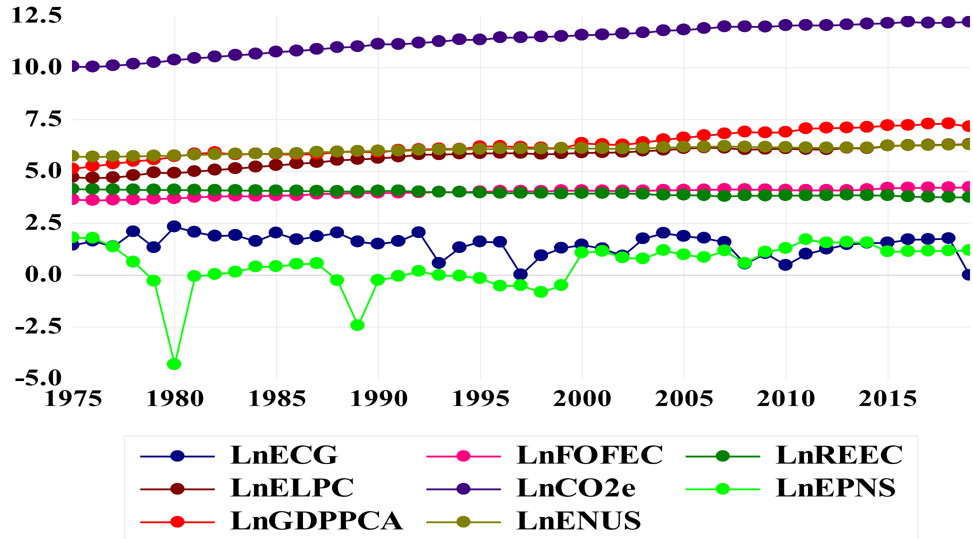

Fig. 1 Plot of variables trend

capita, energy use, and economic growth. t is showing the time dimension and β_1 to β_7 are the model coefficients where β_0 is considered a constant interrupt.

This analysis is established on Pesaran et al. (2001) and Pesaran et al. (1999) ARDL approach to solve the variable interactions by using the long- and short-run estimates. The ARDL method provides more compensation than other techniques and makes no mandatory assumptions. In contrast to other integration methods, all variables must be combined in the same order during the investigation process. In other words, the ARDL process can be used independently. The basic return system is separated in the $I(2)$ and coincidence in $I(0)$ or $I(1)$ order. Secondly, despite the small sample size, the ARDL test is appropriate. The sample size is extremely important. The UECM (unrestricted error correction model) technique validates the ARDL model in both long- and short-term implementations. This paradigm is discussed in two parts: short-term interactions and long-term interactions. The general classification of the variables in the model can be written as:

$$\begin{aligned} \Delta LnECG_t = {} & \pi_0 + \sum_{A=1}^{P} \pi_{1A} \Delta LnECG_{t-i} + \sum_{A=1}^{P} \pi_{2A} \Delta LnFOFEC_{t-i} \\ & + \sum_{A=1}^{P} \pi_{3A} \Delta LnREEC_{t-i} + \sum_{A=1}^{P} \pi_{4A} \Delta LnELPC_{t-i} \\ & + \sum_{A=1}^{P} \pi_{5A} \Delta LnCO2e_{t-i} + \sum_{A=1}^{P} \pi_{6A} \Delta LnEPNS_{t-i} \\ & + \sum_{A=1}^{P} \pi_{7A} \Delta LnGDPPCA_{t-i} \\ & + \sum_{A=1}^{P} \pi_{8A} \Delta LnENUS_{t-i} + \alpha_1 LnECG_{t-1} \\ & + \alpha_2 LnFOFEC_{t-1} \\ & + \alpha_3 LnREEC_{t-1} \\ & + \alpha_4 ELPC_{t-1} + \alpha_5 CO2e_{t-1} + \alpha_6 EPNS_{t-1} + \alpha_7 GDPPCA_{t-1} \\ & + \alpha_8 ENUS_{t-1} + \varepsilon_t \end{aligned} \tag{4}$$

Δ shows the difference operator and P denotes the equation sequence of lags. The description of the long-run relation amid variables can also be stated as:

$$\begin{aligned} \Delta LnECG_t = {} & \beta_0 + \sum_{G=1}^{T} \beta_{1G} \Delta LnECG_{t-i} + \sum_{G=1}^{T} \beta_{2G} \Delta LnFOFEC_{t-i} + \sum_{G=1}^{T} \beta_{3G} \Delta LnREEC_{t-i} \\ & + \sum_{G=1}^{T} \beta_{4G} \Delta LnELPC_{t-i} + \sum_{G=1}^{T} \beta_{5G} \Delta LnCO2e_{t-i} + \sum_{G=1}^{T} \beta_{6G} \Delta LnEPNS_{t-i} \\ & + \sum_{G=1}^{T} \beta_{7G} \Delta LnGDPPCA_{t-i} + \sum_{G=1}^{T} \beta_{8G} \Delta LnENUS_{t-i} + \varepsilon_t \end{aligned} \tag{5}$$

In Eq. (5), T represents the order of the lags; furthermore, given the variables involved, the description of short-run interactions through ECM can be demonstrated as:

$$\begin{aligned} \Delta LnECG_t = {} & \vartheta_0 + \sum_{K=1}^{R} \vartheta_{1K} \Delta LnECG_{t-i} + \sum_{K=1}^{R} \vartheta_{2K} \Delta LnFOFEC_{t-i} \\ & + \sum_{K=1}^{R} \vartheta_{3K} \Delta LnREEC_{t-i} \\ & + \sum_{K=1}^{R} \vartheta_{4K} \Delta LnELPC_{t-i} + \sum_{K=1}^{R} \vartheta_{5K} \Delta LnCO2e_{t-i} \\ & + \sum_{K=1}^{R} \vartheta_{6K} \Delta LnEPNS_{t-i} + \sum_{K=1}^{R} \vartheta_{7K} \Delta LnGDPPCA_{t-i} \\ & + \sum_{K=1}^{R} \vartheta_{8K} \Delta LnENUS_{t-i} + \alpha ECM_{t-1} + \varepsilon_t \end{aligned} \tag{6}$$

The short-run estimation amid variables is stated in Eq. (6), where R shows the lag order.

Results and discussion

Summary statistics of the variables

Table 1 uncovers the summary findings of skewness, Kurtosis, Jarque–Bera, probability, and sum of squares.

Table 1 Summary statistics results

	LnECG	LnFOFEC	LnREEC	LnELPC	LnCO2e	LnEPNS	LnGDPPCA	LnENUS
Mean	1.468	3.978	3.954	5.699	11.337	0.458	6.300	6.027
Median	1.578	4.043	3.950	5.872	11.458	0.624	6.166	6.087
Maximum	2.323	4.229	4.140	6.307	12.211	1.805	7.301	6.278
Minimum	−0.011	3.597	3.743	4.681	10.036	−4.315	5.124	5.700
Std. Dev	0.525	0.176	0.119	0.489	0.683	1.116	0.596	0.172
Skewness	−1.134	−0.738	−0.092	−0.785	−0.448	−2.058	0.148	−0.524
Kurtosis	4.055	2.479	1.702	2.354	1.975	9.187	2.033	2.072
Jarque–Bera	11.738	4.597	3.220	5.414	3.476	103.566	1.918	3.680
Probability	0.002	0.100	0.199	0.066	0.175	0.000	0.383	0.158

Table 2 Correlation among variables

	LnECG	LnFOFEC	LnREEC	LnELPC	LnCO2e	LnEPNS	LnGDPPCA	LnENUS
LnECG	1.000	−0.369	0.366	−0.363	−0.374	−0.182	−0.286	−0.377
LnFOFEC	−0.369	1.000	−0.930	0.992	0.978	0.265	0.902	0.993
LnREEC	0.366	−0.930	1.000	−0.925	−0.965	−0.407	−0.959	−0.954
LnELPC	−0.363	0.992	−0.925	1.000	0.983	0.281	0.902	0.990
LnCO2e	−0.374	0.978	−0.965	0.983	1.000	0.350	0.953	0.984
LnEPNS	−0.182	0.265	−0.407	0.281	0.350	1.000	0.386	0.304
LnGDPPCA	−0.286	0.902	−0.959	0.902	0.953	0.386	1.000	0.913
LnENUS	−0.377	0.993	−0.954	0.990	0.984	0.304	0.913	1.000

Correlation among variables

The correlation amid variables including economic growth, fossil fuel consumption, electricity produced from nuclear sources, renewable energy consumption, carbon emissions, energy use, electric power consumption, and GDP per capita are depicted in Table 2. The outcomes exposed that all variables are linked with one another.

Unit root testing technique

The unit root tests, such as the Phillips-Perron (Phillips and Perron 1988) and augmented Dickey-Fuller (Dickey and Fuller 1979) unit root tests, were used in this work to validate the normality of the variables. The period 1975–2019 has been chosen as the data range for stationary purposes. Both tests certify that in the order of two, none of the variable is integrated. Table 3 displays PP and ADF unit root test consequences at level and at the first difference.

Cointegration test for the validation of bounds testing

The ARDL technique is used in this study to examine the connection between study variables by using the annual data from 1975 to 2019. To perform the ARDL bounds testing for integration valuation, we must choose a suitable lag time by measuring the *F*-statistic based on the Akaike Information Criterion (AIC) lowest value. The consequences of the bounds testing are shown in Table 4. The findings indicate that the measured *F*-statistic assessments are more than 10%, 5%, 2.5%, and 1% of the crucial upper limits in the sequences of 0 and 1.

The robustness among all study variables is determined by using the cointegration test (Johansen and Juselius 1990) with having trace test, max eigenvalue test, and outcomes depicted in Table 5.

Short- and long-run estimations

Table 6 illustrates the ARDL model's short- and long-term results.

Table 6 presents the results of the ARDL model. Outcomes reveal that via short run, the coefficient (3.420) of fossil fuel energy has positive linkage with the economic growth with *p*-value (0.520). Similarly, outcomes also expose that renewable energy consumption, carbon emissions, and GDP per capita have coefficients of 2.607, 0.596, and 0.442 with *p*-values of 0.606, 0.707, and 0.508 that indicates a significant linkage to the economic growth of Pakistan. Furthermore, during the analysis, we found that variables such as electric power consumption, electricity produced from the nuclear sources, and energy usage expose an adversative linkage to the economic growth in Pakistan. Moving to the outcomes of the long-run estimations, they expose that the fossil fuel energy, renewable energy

Table 3 Results of PP and ADF unit root test

		LnECG	LnFOFEC	LnREEC	LnELPC	LnCO2e	LnEPNS	LnGDPPCA	LnENUS
P-P unit root test at level									
[With Constant]	*t*-statistic values (Prob. values)	−4.074 (0.002) ***	−1.470 (0.539) n0	−0.125 (0.940) n0	−2.484 (0.126) n0	−3.519 (0.012) **	−3.649 (0.008) ***	−1.564 (0.491) n0	−1.091 (0.710) n0
[With Constant and Trend]	*t*-statistic values (Prob. values)	−4.752 (0.002) ***	−1.396 (0.848) n0	−2.895 (0.173) n0	−1.139 (0.910) n0	0.207 (0.997) n0	−4.400 (0.005) ***	−2.400 (0.374) n0	−1.634 (0.762) n0
[Without Constant and Trend]	*t*-statistic values (Prob. values)	−1.177 (0.214) n0	3.729 (0.999) n0	−3.358 (0.001) ***	3.549 (0.999) n0	5.921 (1.000) n0	−3.373 (0.001) ***	3.654 (0.999) n0	3.5598 (0.999) n0
At the first difference									
[With Constant]	*t*-statistic values (Prob. values)	−13.141 (0.000) ***	−6.067 (0.000) ***	−6.726 (0.000) ***	−5.751 (0.000) ***	−6.774 (0.000) ***	−11.425 (0.000) ***	−5.528 (0.000) ***	−6.300 (0.000) ***
[With Constant and Trend]	*t*-statistic values (Prob. values)	−12.583 (0.000) ***	−6.457 (0.000) ***	−6.663 (0.000) ***	−6.570 (0.000) ***	−9.759 (0.000) ***	−11.461 (0.000) ***	−5.560 (0.000) ***	−6.374 (0.000) ***
[Without Constant and Trend]	*t*-statistic values (Prob. values)	−12.831 (0.000) ***	−4.568 (0.000) ***	−5.635 (0.000) ***	−4.132 (0.000) ***	−3.162 (0.002) ***	−11.683 (0.000) ***	−4.368 (0.000) ***	−5.064 (0.000) ***
ADF unit root test at level									
[With Constant]	*t*-statistic values (Prob. values)	−4.124 (0.002) ***	−1.498 (0.525) n0	−0.164 (0.935) n0	−2.484 (0.126) n0	−4.621 (0.000) ***	−0.409 (0.896) n0	−1.574 (0.487) n0	−1.093 (0.710) n0
[With Constant and Trend]	*t*-statistic values (Prob. values)	−4.767 (0.002) ***	−1.396 (0.848) n0	−2.803 (0.203) n0	−1.139 (0.910) n0	−0.213 (0.990) n0	−4.518 (0.004) ***	−2.301 (0.424) n0	−1.586 (0.782) n0
[Without Constant and Trend]	*t*-statistic values (Prob. values)	−1.438 (0.138) n0	4.002 (1.000) n0	−3.211 (0.001) ***	4.666 (1.000) n0	7.816 (1.000) n0	0.031 (0.686) n0	3.801 (0.999) n0	3.559 (0.999) n0
At the first difference									
[With Constant]	*t*-statistic values (Prob. values)	−8.925 (0.000) ***	−6.067 (0.000) ***	−6.723 (0.000) ***	−5.676 (0.000) ***	−6.617 (0.000) ***	−2.423 (0.142) n0	−5.536 (0.000) ***	−6.300 (0.000) ***
[With Constant and Trend]	*t*-statistic values (Prob. values)	−8.843 (0.000) ***	−6.469 (0.000) ***	−6.660 (0.000) ***	−6.553 (0.000) ***	−9.348 (0.000) ***	−2.338 (0.403) n0	−5.560 (0.000) ***	−6.374 (0.000) ***
[Without Constant and Trend]	*t*-statistic values (Prob. values)	−9.022 (0.000) ***	−4.383 (0.000) ***	−5.561 (0.000) ***	−2.389 (0.018) **	−1.116 (0.235) n0	−2.083 (0.037) **	−4.465 (0.000) ***	−4.934 (0.000) ***

*, **, and *** signify the level of significant at 10%, 5%, and 1%; "n0" denotes not significant

Table 4 Bounds testing for the recognition of cointegration

F-B test		N-hypothesis: no-level association		
T-S	Value	Signif	$I(0)$	$I(1)$
F-statistic value	(5.582474)	10%	(1.92)	(2.89)
K	(7)	5%	(2.17)	(3.21)
		2.5%	(2.43)	(3.51)
		1%	(2.73)	(3.9)

consumption, carbon dioxide emissions, and GDP per capita have positive coefficients of 3.411, 2.600, 0.594, and 0.441 that show the productive linkage with the economic growth, while the variables electric power consumption, electricity produced from the nuclear sources, and energy utilization have an adversative linkage to the economic growth. Pakistan belongs to those economies that deal with electricity deficits, with no influence on the expansion of the nuclear energy and clean energy use. Therefore, the exposure to electricity is a significant problem for the rural and urban communities because of the absence or rather limited access of less than half of the rural population. Pakistan relies on

Table 5 Cointegration test outcomes (J-J)

T-statistics				Max-eigenvalue statistics			
H- no. of CE(s)	T-S	C-V (0.05)	Prob.**	H- no. of CE(s)	Max-eigen statistic	C-V (0.05)	Prob.**
None*	228.222	159.529	0.000	None*	65.249	52.362	0.001
Max 1*	162.972	125.615	0.000	Max 1*	54.938	46.231	0.004
Max 2*	108.034	95.753	0.005	Max 2	35.894	40.077	0.137
Max 3*	72.139	69.818	0.032	Max 3	29.513	33.876	0.152
Max 4	42.626	47.856	0.141	Max 4	17.669	27.584	0.522
Max 5	24.957	29.797	0.163	Max 5	11.399	21.131	0.607
Max 6	13.557	15.494	0.095	Max 6	8.599	14.264	0.321
Max 7*	4.958	3.841	0.026	Max 7*	4.958	3.841	0.026

*Expressing the denial of hypothesis at the level (0.05). **The probability values

Table 6 Results of short- and long-run estimations

Variables	Coefficients	S-E	T-S	Prob.*
Short run (error correction regression)				
C	– 10.347	47.496	– 0.217	0.828
LnECG(– 1)	– 1.002	0.183	– 5.455	0.000
LnFOFEC	3.420	5.264	0.649	0.520
LnREEC(– 1)	2.607	5.008	0.520	0.606
LnELPC(– 1)	– 1.321	1.944	– 0.679	0.501
LnCO2e	0.596	1.572	0.379	0.707
LnEPNS	– 0.061	0.077	– 0.793	0.433
LnGDPPCA(– 1)	0.442	0.661	0.669	0.508
LnENUS	– 2.395	7.017	– 0.341	0.735
D(REEC)	– 6.824	4.809	– 1.419	0.165
D(ELPC)	2.688	2.230	1.205	0.236
D(GDPPCA)	2.862	1.075	2.660	0.012
CointEq(– 1)	– 1.002	0.126	– 7.924	0.000
Long run				
LnFOFEC	3.411	5.121	0.666	0.510
LnREEC	2.600	5.110	0.508	0.614
LnELPC	– 1.317	2.008	– 0.656	0.516
LnCO2e	0.594	1.625	0.365	0.716
LnEPNS	– 0.060	0.079	– 0.769	0.447
LnGDPPCA	0.441	0.636	0.693	0.493
LnENUS	– 2.388	6.944	– 0.343	0.733
C	– 10.318	47.804	– 0.215	0.830
R^2: 0.633 Adj-R^2: 0.606 S.E. of regression: 0.377 S–S resid: 5.706 L-likelihood: – 17.498 DW-stat: 2.225		Mean-dep. var: – 0.032 S.D. dependent var: 0.601 AIC: 0.977 S-criterion: 1.139 H-Quinn criter.: 1.037		

*The level of significance

fossil fuels to meet its energy needs. However, because of the limited exposure to these resources, it raises the serious problem of carbon emissions. Because of their non-renewable and non-nuclear nature, such sources of energy may be depleted in a matter of days if they are not properly managed. Clean energy and nuclear energy initiatives, in contrast, have a lower economic impact than the fossil fuels. It should also be noted that nuclear power and clean energy would decrease CO_2 emissions, protect the environment, and reduce global reliance on fossil fuels (Zhang et al. 2018; Luqman et al. 2019; Khan et al. 2020).

The world's robust reliance on non-renewable resources has created significant global issues and challenges, such as future non-renewable oil shortages, electricity stability, and environmental concerns. The global economy confronts the danger of increasing energy consumption in order to maintain sustainability and economic development. There is a terrible misconception that carbon fuels deplete the renewable resources. Nevertheless, the environmental effect of the renewable energy is shocking. The large gap between demand and electricity generation, the growing cost, and increased environmental pollution of fossil fuel resources are all urgently necessary to find some cost efficient and environmentally friendly sources of energy. Therefore, the world has recently paid a great attention to the renewable energy development. Power is well recognized as a source of economic growth and social stability, and its potential for the climate change necessitates the use of the green energy (Inglesi-Lotz 2016; Kocaarslan and Soytas 2019; Wang et al. 2018).

For developing successful policies in consequence to decrease the non-renewable energy usage and increase the energy efficiency in the residential sector, the policymakers must be aware of the households' choices regarding the home heating systems. In terms of the environmental impact, the decisions that families make when it comes to heating may have a major impact on the environment (Laureti and Benedetti 2021). Additionally, the local governments and international organizations have made the sustainable energy policy a priority. Energy strategies must address new problems, such as energy poverty, security, justice, energy resilience, and vulnerability, all of which are interconnected issues that need new solutions (Gatto and Busato 2020). Renewable resources are less carbon-intensive and more effective. Because of the adverse environmental effects of GHGs caused by the volatile usage of the fossil fuels, the new requirements in the energy field are becoming increasingly common. The utilization of renewable energy has up surged in the recent years, mostly due to the substantial drops in solar and wind costs. Energy consumption in the developing nations is rising due to varying patterns in infrastructure and population growth. Given the huge disparity between the projected fossil fuel production and energy consumption, all developing nations' energy needs are inadequate. Given the importance and development of the renewable energy, the complex connection between renewable energy usage and economic progress must be recognized as a contribution to a green and sustainable power marketplace (Shukla et al. 2017; Kahouli 2017; Furuoka 2015; Saidi et al. 2017; Pinzón 2018). Figure 2 illustrates the significant linkage among all variables and ECG.

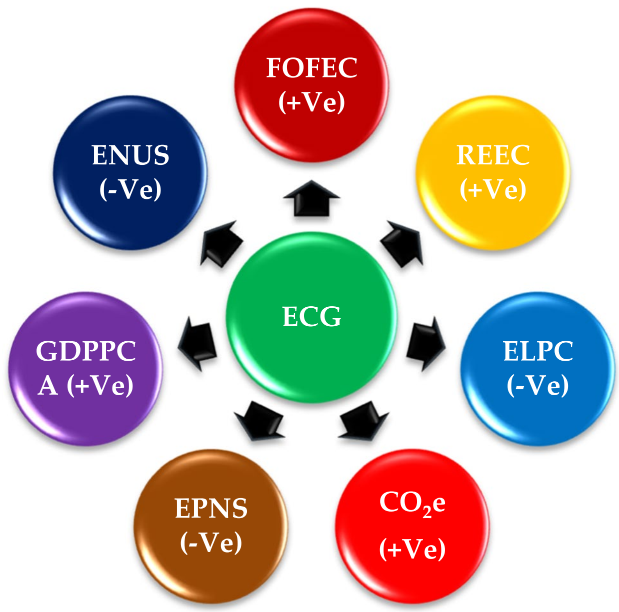

Fig. 2 Long-term linkages of study variables with economic progress (ECG)

Figure 2 uncovered that fossil fuel energy, renewable energy utilization, CO_2 emissions, and gross domestic product per capita exposed a positive impact on the economic progress in Pakistan. Similarly, the variables such as electric power consumption, electricity produced from the nuclear sources, and energy use demonstrated an adverse linkage to the economic development in Pakistan. Furthermore, Fig. 3 illustrates the plot of CUSUM, CUSUM of squares, and recursive estimates.

Conclusion and policy recommendations

In this study, we have examined the association among fossil fuel energy consumption, electricity produced from the nuclear sources, CO_2 emissions, renewable energy consumption, electric power consumption, GDP per capita, energy use, and economic growth in Pakistan. The study data range

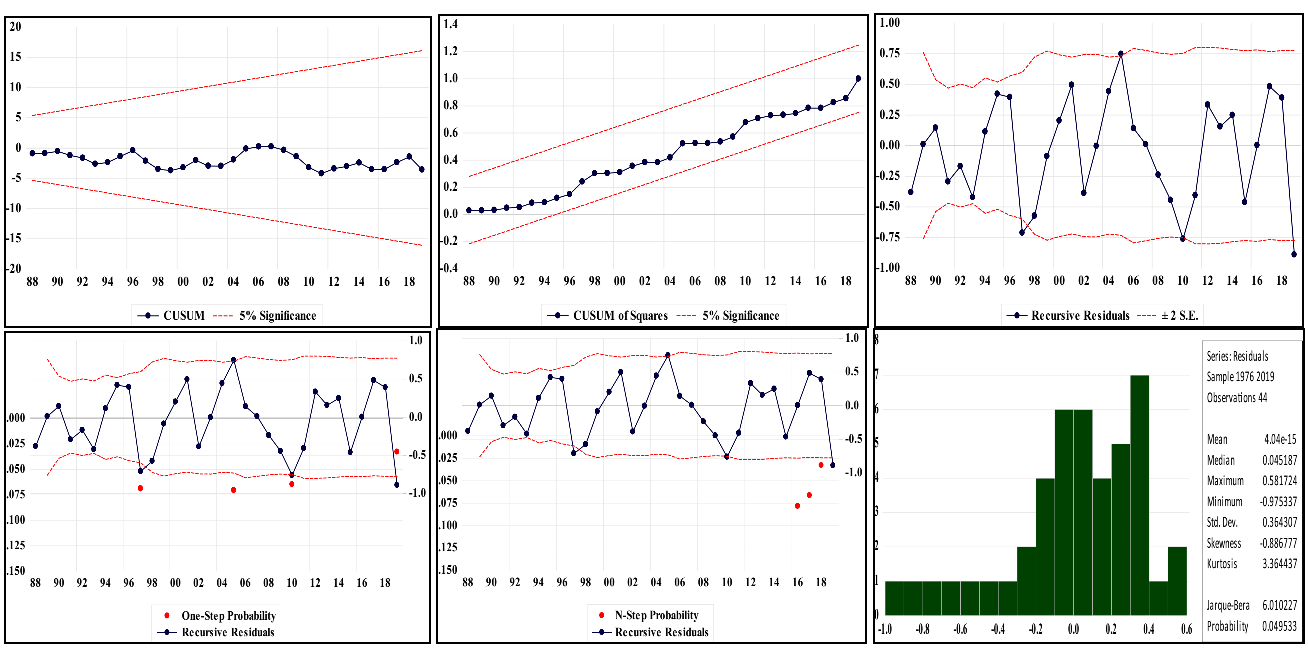

Fig. 3 Recursive plots, CUSUM, and CUSUM of squares

is from 1975 to 2019 and variable stationarity was confirmed through the unit root tests including Phillips-Perron and augmented Dickey-Fuller. The ARDL technique was employed to rectify the dynamic association among the variables. Consequences expose that via long run, the fossil fuel energy, renewable energy consumption, CO_2 emissions, and GDP per capita have a constructive impact on the economic growth, while electric power consumption, electricity produced from the nuclear sources, and energy utilization have a negative connection to the economic growth in Pakistan. Furthermore, short-run outcomes also revealed that the fossil fuel energy consumption, renewable energy consumption, carbon dioxide emissions, and GDP per capita have a substantial positive linkage to the economic growth in Pakistan. During analysis, the variables electricity produced from the nuclear sources, electric power consumption, and energy usage expose the adversative linkage with the economic progress in Pakistan.

To address Pakistan's energy issues, the government of Pakistan must take the necessary efforts to implement practical policies and respond immediately. There is a need to produce interconnected energy networks with common operating principles that offer considerable potential for strengthening the cooperation between new technology, increasing the cost-effective use of the most diverse low-carbon technologies, and improving the energy system sustainability. It was observed that energy sector is largely controlled and operated by the government. In contrast, various policies and efforts must be implemented in directive to expand the presentation of the energy sector. Moreover, significant efforts have been made to increase the engagement of the private sector in the development of the energy sector in order to improve the efficiency of public sector organizations. A new structure can evolve to reorganize the public sector and energy sector institutions in order to build a market where the private firms can operate competitively for supplying the energy.

Furthermore, Pakistan should continue to invest in the energy industry, particularly in natural gas, coal, and hydroelectric power production. Imports will put less of a strain on the country's current account as a result. In order to alleviate the issue of energy scarcity, consumers must be educated about the necessity of making more effective use of the energy supply from a variety of sources. Pakistan has been blessed with an abundance of natural resources. Solar power and coal represent two main sources that stand out as having an enormous potential. To satisfy the increasing energy demand, particularly in warmer areas, the government should prepare to implement and support the solar power projects. Since nuclear energy is used to produce power, the government should start new nuclear projects to keep up with the increasing demand.

This study is not limited, and further research may be conducted by broadening this topic in order to address Pakistan's energy issue and enhance the country's economic growth and development. Further study may look into additional alternative energy sources by enacting new policies and providing financial assistance, building new dams in the country to increase energy generation and economic growth, and installing solar systems to generate electricity from solar panels in order to fulfill increasing demands.

Author contribution Abdul Rehman: conceptualization, investigation, methodology, formal analysis, visualization; writing the original draft; Hengyun Ma and Ilhan Ozturk: investigation, visualization, review and editing; Magdalena Radulescu: editing and made suggestions of the manuscript.

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Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

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