frontiers in Sustainable Energy Policy

TYPE Original Research
PUBLISHED 16 March 2026
DOI 10.3389/fsuep.2026.1766522

EDITED BY
Xiaonan Wei,
China University of Geosciences, China

REVIEWED BY
Izzet Ari,
Social Sciences University of Ankara, Türkiye
Lu Gao,
University of South China, China

*CORRESPONDENCE
Boqiang Lin
✉ bqlin@xmu.edu.cn;
✉ bqlin2004@vip.sina.com

RECEIVED 12 December 2025
REVISED 19 January 2026
ACCEPTED 11 February 2026
PUBLISHED 16 March 2026

CITATION
Raza MY, Lin B and Javed Q (2026) Low-carbon electricity generation through demand and carbon neutrality prediction 2035 of a transitional economy: decomposition and LEAP learning approaches.
Front. Sustain. Energy Policy 5:1766522.
doi: 10.3389/fsuep.2026.1766522

Low-carbon electricity generation through demand and carbon neutrality prediction 2035 of a transitional economy: decomposition and LEAP learning approaches

Muhammad Yousaf Raza[1], Boqiang Lin[2]* and Qasim Javed[3]

[1]School of Economics, Shandong Technology and Business University, Yantai, Shandong, China,
[2]School of Management, China Institute for Studies in Energy Policy, Xiamen University, Fujian, China,
[3]College of Earth and Environmental Sciences, University of the Punjab, Lahore, Pakistan

The precise forecasting of total electricity generation and consumption can provide data support for framing the sustainable development planning of a developing nation. The study framework is composed of two phases: electricity generation and carbon mitigation framework and structure and logical procedures. This study develops decomposition and Long-range Energy Alternatives Planning system methods and analyzes electricity and CO_2 emission mitigation scenarios for 2025–2035 under Energy Vision 2035, including policy implementation, carbon management, and intensity effects. Six main driving factors, including low-carbon structure, electricity generation intensity, energy security, energy intensity, carbon productivity, and CO_2 emissions for four decades, are investigated. The results show that (i) low-carbon electricity presents a rising trend in the current phase, which means the renewable electricity structure is undergoing development; (ii) the carbon production factor shows the Pakistan's economy is improving due to substantial advancements in low-carbon electricity generation, mitigating CO_2 emissions; (iii) electricity demand scenarios show that renewable, hydro, and nuclear electricity are major contributing resources and are lowering CO_2 emissions; (iv) CO_2 emission mitigation scenarios from 2025 to 2035 indicate that CO_2 will be cut by 63.40%, showing that low-carbon electricity resources may produce relative efficiencies in the electricity sector; and, finally, and (v) the development of low-carbon electricity generation and decarbonization could be ensured by regulating carbon mitigation policies and technical development.

KEYWORDS
CO_2 emissions, decomposition analysis, demand scenario, LEAP model, low-carbon electricity generation, Pakistan

1 Introduction

The ever-increasing global climate change evolving worldwide is compelling societies to transition away from fossil fuels and plan pathways to a zero-emission future. To be efficient, the low-carbon transition will need to emerge at an unparalleled speed and scale across all regions and economic sectors (Vrontisi et al., 2020). Obviously, the transition to climate neutrality will pressure nations to undergo a transformation. Several countries around the world have become centers of heavy industry and resource extraction, adding significantly to the carbon footprint (Lu S. et al., 2024). Amid such huge environmental pressures, the low-carbon transition has arisen as a critical means to attain green and sustainable growth in developing countries (Balta-Ozkan et al., 2015). Nevertheless, despite the benefits to various countries, structural change will be marked by short- to long-run growth in energy prices and huge fuel imports (i.e., oil, coal, and gas).

As an emerging country, Pakistan is heavily dependent on resource-based industries, which are responsible for a large share of the country's CO_2 emissions (Lin and Raza, 2020). In addition, Pakistan accounted for 0.6% of global CO_2 emissions in 2018, ranking 27th among the world's CO_2 emitters (International Energy Agency, 2024), highlighting its significant share of the world's emissions. Recently, CO_2 emissions of different sectors (i.e., electricity, industry, transport, residential, commercial, and agriculture) in Pakistan have contributed 53.25, 36.03, 43.61, 17.66, 2.89, and 0.03 $MtCO_2$ (International Energy Agency, 2024). As a developing country, Pakistan uses more fuels every year by importing fossil fuels (88.87%) from the Gulf (Bakhsh et al., 2017), which is contributor to growing CO_2 emissions. CO_2 emissions from the electricity sector reached 155.55 $MtCO_2$, where oil, coal, and natural gas contributed 65, 41.9, and 48.75 $MtCO_2$ in 2024, respectively. Research on a low-carbon electricity transition in Pakistan has excelled at detecting internal factors of energy production, such as low-carbon electricity structure, generation intensity, energy security (ES), energy intensity (EI), carbon productivity, and CO_2 emissions.

The development in low-carbon electricity exemplifies the country's transition from industrial might to sustainable growth, contributing lessons and hope for an eco-friendly future. Heavily dependent on oil, coal, and gas, which has resulted in huge CO_2 emissions, Pakistan has turned toward expanding its low-carbon industry by exploiting low-carbon electricity sources since 2013 (Hydrocarbon Development Institute of Pakistan, 2024). As shown in Figure 1, Pakistan's electricity generation is based on four major sources (i.e., hydro, nuclear, renewable, and thermal electricity), showing that the generation trend is stable and growing steadily, which is evidence of the strong contribution of electricity generation.[1] Recently, it was noted that annual reductions of CO_2 emissions of 36.9-Gt are possible by 2050 using renewable energy, including the previously stated sources (International Renewable Energy Agency, 2021), where solar energy is the most plentiful energy source since it does not depend on direct sunlight. It is the most capable clean energy source, which is supposed to spur countries' social, economic, and environmental growth by replacing traditional energy sources (Hao et al., 2022; Xu et al., 2026). Thus, these sources are leading technologically and are significantly contributing to mitigating CO_2 emissions.

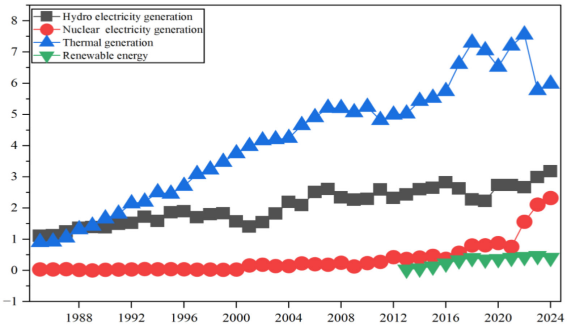

FIGURE 1
Contribution of electricity generation in Pakistan, 1985–2024 (Unit: Mtoe).

Comparative work at this level is rare, and analysis is naturally limited to a single sector or multiple countries. For example, Lin and Zhou (2022) used the entropy-weighted TOPSIS method to estimate the regional population, economic growth, urbanization, industrial structure, and environmental factors in China during the period 2000–2017 and found that all the factors had a significant impact on green development. CserekIyei et al. (2023) analyzed the coal revenues and growth in renewable energy production in Australia using wind, solar, and coal energy from 2017 to 2021. They estimated that a one-megawatt-hour rise in wind and solar energy generation would cause a reduction in coal generation. Sovacool and Valentine (2010) used the predictive framework under economic, policy, and nuclear power factors to evaluate the causality relationship between China and India. They concluded that these countries would fully develop nuclear energy capabilities to the point that it would eventually impact carbon reduction policies and sustainable development. Wang and Yan (2022) used decomposition analysis to determine the effects of various factors in China, such as fossil fuels, ESs, EI, economic growth, and CO_2 emissions between 2000 and 2016. They found that economic growth and population increased CO_2 emissions; however, energy structures have not significantly changed in CO_2 emissions, which will require substitution policies to reduce carbon emissions. Amponsah et al. (2014) examined heat coming from electricity generation, renewable energy technologies, and global emissions using the life cycle assessment method and found that fossil fuel electricity emissions were higher than those of renewable energy sources, with the exception of nuclear-based electricity generation. Li et al. (2024) used the Logarithmic Mean Divisia Index (LMDI) method to analyze the effects of electricity consumption, economic growth, energy efficiency, electricity intensity, fuel emission, and population factors in China in the period 1991–2020. They estimated that economic and fossil fuel factors were spurring CO_2 emissions; however, industrial and energy structures can mitigate CO_2 emissions and sustain economic growth.

Abbreviations: LEAP, Long-range Energy Alternatives Planning System; LMDI, Logarithmic Mean Divisia Index; TEP, total energy production; TEG, total electricity generation; TEC, total electricity consumption; GDP, gross domestic product; CO_2, carbon dioxide; LCS, low-carbon structure; EGI, electricity generation intensity; ES, energy security; CO_2P, carbon productivity; $(EC)_h$, electricity consumption of hydro; $(EC)_t$, electricity consumption of thermal; $(EC)_n$, electricity consumption of nuclear, and renewable; $(EC)_r$, electricity consumption of renewable.

[1] Note that low-carbon electricity generation includes hydro, nuclear, wind, biofuels, and photovoltaic (PV) solar during the estimated period. However, renewable energy is the aggregate of wind, biofuels, and PV solar.

However, this study discusses low-carbon electricity generation (LCEG) using six major driving factors and demand scenarios. To this end, the present research looks at which low-carbon electricity sources are linked with positive or negative designs. Under the country's economic planning framework, the country can forecast and support the relevant transition and decarbonize the electricity system. Thus, the study's core research questions are as follows: What are the low-carbon electricity factors that meet carbon neutrality objectives? What is the LCEG structure? What is the fuel demand and its mitigation projections? Presently, no research has analyzed these questions in a large sample of Pakistan. In an empirical assessment, several studies have concentrated on the analysis of electricity consumption and compared several renewable and social factors, for instance, Raza and Lin (2024), Shahbaz et al. (2024), Khan and Abbas (2016), and Valasai et al. (2017) employed traditional methods to analyze the relationships between energy, economics, and CO_2 emissions at national and sector levels. However, they failed to discuss low-carbon structure (LCS), electricity generation, ES, EI, carbon productivity, and carbon emissions in the country's policy analysis. Therefore, the significance is broadly recognized, and gaps in the literature leave room for further research.

Thus, the current study's contributions are as follows. First, it uses the six major driving factors to investigate LCEG in Pakistan and reveals the driving mechanism from the viewpoint of energy systems over four decades as per the Five-Year National Economic Planning and annual periods from 1985 to 2024. This efficiently fills a gap in current research that has largely depended on econometric models, giving valuable direction for Pakistan and related developing countries experiencing fast industrialization and urbanization. Surprisingly, despite the significance of Pakistan's low-carbon transition, there has been no published empirical study analyzing the association between LCEG factors in the recent period. Second, the study emphasizes the significant national impact of the electricity sector, representing substantial variations in the effects across various factors' contexts and related models. The finding highlights the need for decarbonization policies to be tailored to the specific characteristics of Pakistan, which is of great value for other countries with similar regional differences in economic growth, population and environmental challenges. Third, the study applies two methodologies [i.e., LMDI and Long-range Energy Alternatives Planning system (LEAP)] (Stockholm Environment Institute, 2008). These methods are valuable in estimating decomposing energy with the relative contributions of different factors and develop some changes in energy utilization, its awareness, and in-depth analysis of future energy. Thus, to quantify electricity demand projections, economic policies, and carbon emissions, it is necessary to predict energy demand, for which we employed the LEAP model in conjunction with the LMDI decomposition method, which has produced good outcomes (Wang et al., 2024). The integration between methods will provide an in-depth analysis of CO_2 emission leading factors and reveal threshold effects. Moreover, to forecast electricity demand and CO_2 emissions in the period 2025–2035, first, a time-series method is employed to check consumption patterns, which are identified as the additional mitigation potentials under five electricity consumption scenarios. Trends in a dataset over time will be estimated, and the estimate will be appropriate for predicting future values of data involving electricity consumption from various sources. Compared with past studies on driving factors of electricity-related factors and CO_2 emissions in Pakistan, these factors can provide a more comprehensive and detailed description, especially in the mitigation of CO_2 emissions under Energy Vision 2035 (2014), which focuses on more key issues of energy systems.

The remainder of this study is organized as follows. Section 2 describes the literature review. Section 3 presents the data, and Section 4 outlines the methods used. Empirical results and a discussion are presented in Section 5, while conclusions and policy suggestions are provided in Section 6.

2 Literature review

In the available literature, we found several studies related to energy and the environment at national, regional, and sector levels. Since Grossman and Krueger (1995) ground breaking work, several studies have been done on the interrelationship between economic and environmental factors. For instance, Gong and Zhang (2024) analyzed the role and mechanism of digital finance in China's sustainable growth in the period 2011–2020 and found that digital finance enhanced rural economic growth by changing the energy transition. Raza et al. (2024) employed the translog production model to check energy substitution and nonenergy factors for India and found that capital and energy were good substitutes in a country's economic growth. Boulanouar et al. (2024) used the Environmental Kuznets Curve (EKC) and Autoregressive Distributed Lag (ARDL) methods to examine energy, economic, and CO_2 emission mitigation and found that each factor's coefficient was higher in the short term vs. the long run. Tachega et al. (2024) employed the SMB-DEA and PMG-ARDL methods for Africa from 2010 to 2018 using energy, economics, and environmental quality and found that traditional and renewable energy were efficient at growth rates of 89% and 58%, respectively. In addition, the causes of CO_2 emissions have received substantial attention. For example, Acheampong (2018) used the panel autoregression method to check the causal relationship between 116 countries' economic growth, emissions, and energy consumption over the period 1990–2024. However, they found that CO_2 emissions caused economic growth. Saidi and Hammami (2015) employed the GMM panel model to analyze the impact of economic growth and CO_2 emissions on energy consumption for 58 countries for the period 1990–2012 and found that economic growth had a positive impact on energy use and CO_2 emissions. A similar finding of ASEAN countries was described by Saboori and Sulaiman (2013) using the ARDL method for the period 1971–2009, who determined that there was a significant relationship between energy and CO_2 emissions in all countries. Consequently, based on several findings at various national and regional levels, the energy revolution should be taken to enhance the sustainable use of energy, which will stabilize the estimated models and future framework to achieve sustainable development.

In the empirical literature, several studies (e.g., Lu S. et al., 2024; Hammond and Norman, 2012; Chong et al., 2019; Ozdemir,

TABLE 1 Literature on decomposition analysis and its driving factors at local and international levels.

Author	Country/region	Period	Methods	Factors	Conclusions
Hammond and Norman (2012)	United Kingdom	1990–2007	LMDI-I	Industrial structure, energy intensity, fuel, and electricity-generated emissions	In the manufacturing sector, energy intensity plays an imperative role in enhancing electricity improvement.
Chong et al. (2019)	Malaysia	1978–2014	LMDI and energy allocation analysis	CO_2 emissions, population, GDP, total energy consumption	Population, GDP, and energy intensity are the key driving factors impacting the variations in carbon emissions. However, the contribution of energy efficiency and electricity supply reduces CO_2 emissions.
Lu S. et al. (2024)	World's resource-based cities	2012–2019	Coupling coordination and technology factors	Industrial progress and low-carbon transition	The local industrial structure in these cities mitigates carbon efficiency. However, extra-regional technology does not directly impact progress.
Ozdemir (2023)	Turkey	1990–2020	Tapio decoupling and LMDI methods	CO_2 emissions, economic growth, population, electricity intensity, electricity trade	Population and electricity intensity show a negative impact on CO_2 emissions. Thus, new energy policies can support reducing fossil fuels.
Raza and Lin (2024)	Pakistan	1992–2021	Decomposition, Tapio and mitigation methods	Carbon and fossil fuel trade, fossil fuel intensity, electricity financial factor	Fuel intensity is the main factor in growing CO_2 emissions, while renewable energy is a factor in mitigating CO_2 emissions.
Huang (2020)	Taiwan	2014–2017	LMDI	Residential electricity consumption, air-conditioning, 7,677 households	Air conditioners are the key factors in changing climates. Personal computers and household utilities are the major concerns that cause inefficiency.

2023; Raza and Lin, 2024; Huang, 2020) explored the relationship between various factors, such as EI, CO_2 emissions, gross domestic product (GDP), population, total energy, industrial energy consumption, and residential energy between 1978 and 2020. They suggested a dynamic relationship between energy and social indicators using econometric methods (see Table 1). Furthermore, several studies performed scenario analyses of future energy-related CO_2 emissions in numerous countries. Gan et al. (2013) conducted a quantitative analysis on a low-carbon society, Malaysia, to 2035. They estimated that alternative scenarios would enhance technologies and energy efficiency across various sectors while mitigating CO_2 emissions.

Recently, the rise in extreme weather events coming from globe has brought renewed interest in the need for CO_2 emission mitigation. In focusing on the topic, researchers have concentrated on forecasting CO_2 emissions to measure the influence of socioeconomic development on climate change. Ouedraogo (2017) employed the LEAP model it to investigate the energy demand and the carbon emissions under alternative strategies from 2010 to 2040. Song et al. (2007) analyzed chemical absorption in Korea under the economic and environmental policies at the time and found that these energy-related policies were useful in climate change and helped reduce CO_2 emissions. McPherson and Karney (2014) investigated long-term scenario alternatives for Panama's electricity sectors and found that the electricity composition, marginal cost, global warming, and resource diversity were forecasted under various development pathways. Nieves et al. (2019) analyzed Colombia's energy demand and greenhouse gas (GHG) emissions until 2030 and 2050 and estimated that economic growth and technological substitution of various sectors would be more efficient with greater CO_2 emission reductions in positive scenarios. Huang et al. (2023) employed LEAP and LMDI methods to determine the relationship between China's CO_2 emissions and energy consumption form 2000 to 2060 and found that CO_2 emissions were predicted to peak in 2028 and then fall to achieve carbon neutrality by 2060. Finally, Wang et al. (2024) predicted China's CO_2 emissions in Gansu province before 2030 and achieved carbon neutrality by 2060 using both LMDI and LEAP methods. They proposed that achieving carbon peak neutrality by 2030 would require a 29.53% reduction in EI from 2020, with 46.37 and 64% rises in electricity utilization and green energy generation, respectively. Thus, a huge mitigation of 123.84 Mt can be seen by 2060. Liya and Jianfeng (2018) employed a LEAP analysis for China's environmental and economic effects based on various electric resources during 2012–2050. They found that the natural gas scenario was better than the carbon capture scenario. Wakiyama and Kuramochi (2017) employed an ARMA model to predict CO_2 emissions from electricity in the residential sector of Japan. They determined that Japan could reduce electricity utilization and CO_2 emissions in 2030, which is greater than the Japanese post-2020 mitigation target.

TABLE 2 Description of variables.

Variables/measures	LCEG	TEG	TEP	TEC	GDP	CO_2
Mean	2.5156	6.5431	34.9562	5.1676	167.9300	119.9162
Median	2.3280	6.5197	32.4605	4.8383	138.7123	117.2688
Maximum	5.9076	11.8496	66.1117	9.6016	374.8903	212.4941
Minimum	1.1450	1.9738	12.7358	1.5463	31.1449	38.8532
Standard deviation	1.1512	2.9640	15.7289	2.4851	119.7317	50.4655
Skewness	1.1800	0.2232	0.3934	0.3281	0.3992	0.0652
Kurtosis	4.0851	1.9547	1.9883	1.9145	1.6380	1.7863
Observations	40	40	40	40	40	40
Unit	Mtoe	Mtoe	Mtoe	Mtoe	Billion $	Mt

LCEG includes the electricity generated through hydro, nuclear, wind, biofuels, and PV solar. TEG is the total electricity generated through thermal, hydro, nuclear, wind, biofuels, and PV solar. TEP is the sum of coal, oil, gas, LPG, and electricity including imported energy. TEC is the sum of thermal, hydro, nuclear, renewable, and auxiliary consumption. GDP is the overall gross domestic product, and CO_2 emissions are carbon dioxide emissions using the balances based on IPCC guidelines.

In addition, Fang and Yang (2025) analyzed medium- and long-term energy demand in the Yangtze River Delta using the LEAP model from 2023 to 2060 and found that low-carbon energy would replace the current energy source after 2029. Lu L. et al. (2024) used the LEAP model to determine that GHG emissions for an industrial park would drop from 2020 to 2040 by 17%—30%. Shahid et al. (2025) forecasted fuel demand up to 2041 in Pakistan and found that growing dependence on cleaner energy and domestic resources rather than imported fuels would guarantee ES under sustainable development goals (SDGs). El-Sayed et al. (2023) estimated the Egyptian energy mix case from 2020 to 2050 and determined that low-carbon scenarios have minimum long-term production cost compared to natural gas, nuclear, and other fuels. Finally, Huang et al. (2023) employed LEAP and decomposition analysis for China's CO_2 commitments from 2030 to 2060. According to their investigation, emissions are predicted to rise in 2028, and China will need to cut about 2000 Mt, while other scenarios projected that China would be unbale to attain their carbo peak neutrality goals. Thus, it can be concluded that most earlier studies focused on energy, environment, and economic growth factors, with limited predictions for a specific industry or country. Some studies discussed the energy efficiency of renewable or low-carbon electricity using limited factors, for example, CO_2 emissions, GDP, total energy consumption, total electricity consumption (TEC), EI, and energy generation; however, low-carbon electricity structure, electricity intensity, and carbon production were seldom employed as driving factors in Pakistan, even though these factors may contribute significantly to CO_2 emissions. The argument on the factor relationship and CO_2 emissions has no data presented in the literature; hence, this study aims to fill this gap by analyzing the effects of LCS, electricity generation intensity, ES, EI, carbon productivity, and CO_2 emission factors on LCEG in Pakistan.

3 Data collection

The current study employed annual time-series data of four decades (1985–2024). Given the recent availability of data, we focused on six major variables, including LCEG, total electricity generation (TEG), total energy production, TEC, GDP, and CO_2 emissions. The study employs data for actual scenarios for electricity demand and mitigation based on renewable generation, starting from 2013 to 2024 and then predicted toward Renewable Energy Vision 2035. The data relating to electricity generation, energy production, electricity consumption, and energy production were collected from different annual books of the Hydrocarbon Development Institute of Pakistan (2024). All the energy-related data are organized in million tons of oil equivalent (Mtoe). The data relating to GDP were collected from the World Development Indicators (2025) and arranged in billions of US$. The data relating to CO_2 emissions were collected from the BP Statistical Review of World Energy and are organized in metric tons (Mt) of CO_2. Table 2 presents a description of all the variables involving mean, median, maximum, minimum, standard deviation, skewness, kurtosis, observation, and units. The analysis considers the changes in major variables in which GDP, CO_2, and TEP rank highest in all variables, signifying intense industrialization. The skewness of all variables is positive, showing a right tail. LCEG and TEG ranks lowest in all estimation, reflecting its lower intensity. Positive kurtosis means factors have a sharper peak and heavier tails compared to normal distribution. These differences emphasize the necessity of differentiated policy and decarbonization objectives.

In addition, LCEG and carbon mitigation potential in Pakistan have been changing recently. The study framework provides factor decompositions and their estimations, which are essential for discussing the impact of each factor. The research framework is described in Figure 2.

4 Methodology and scenarios

4.1 The LMDI decomposition method

In the context of LCEG and CO_2 emissions, the key driving factors are measured by employing the LMDI method. To comprehend the effects of electricity generation, we developed a new approach to theoretical decomposition analysis following Ang et al. (1998). In the current study, we employed LMDI and additive

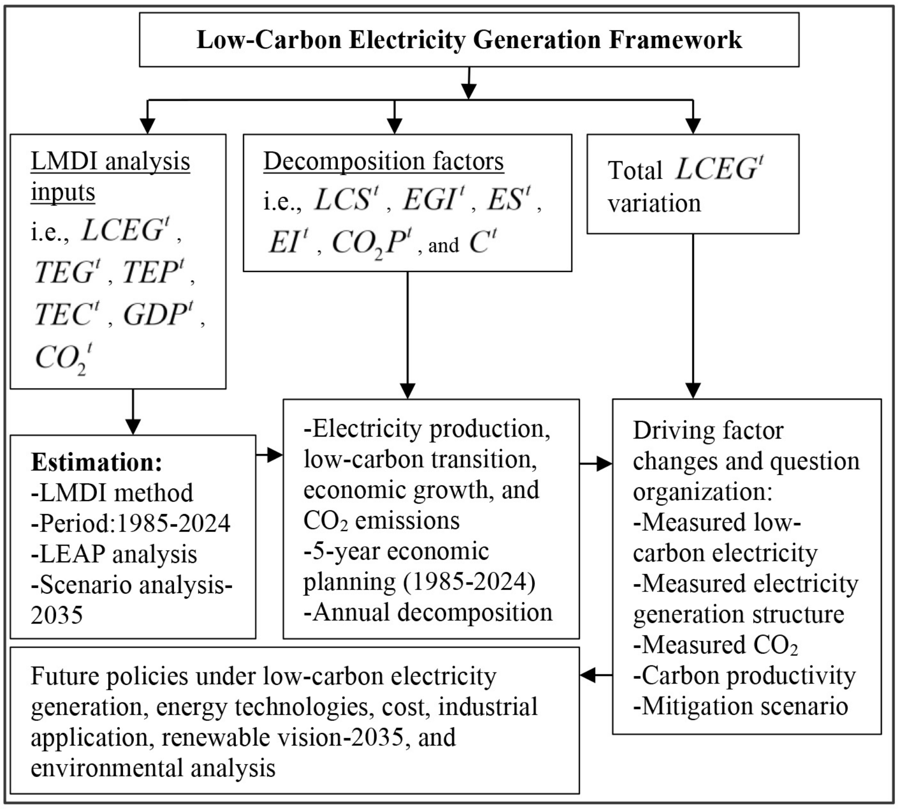

FIGURE 2
Electricity generation and carbon mitigation framework of Pakistan.

methods to investigate low-carbon electricity and its factors' effects at various levels and dimensions. These estimations can be used to approximate the impacts of various indicators that provide useful information to governments and policymakers. Thus, this study analyzes Pakistan's national electricity generation and mitigation potential under the 5-year economic planning period of Pakistan. Technological progress, on the other hand, is another facet that is increasing the efficiency of LCEG to mitigate CO_2 emissions and enhance energy efficiency. The LMDI method has been widely employed to investigate the factors that impact energy utilization, social factors, and CO_2 emissions (Ang, 2004). Electricity is an important source, and there is some degree of substitution effect between electricity generation and socioeconomic factors, for instance, economic growth and the environment. Therefore, the internal structure and electricity sustainability impacts cannot be ignored when analyzing electricity generation factors. This method has several advantages; for example, it can be used to evaluate several issues without residual problems, estimate a zero value, be easily interpreted, and be convenient to apply. For this reason, several studies used this method in different ways, for instance, Zhang et al. (2013) and Li et al. (2024) for China's electricity and CO_2 emissions; Moutinho et al. (2015) for Eastern, Western, Northern, and Southern Europe; and Tang et al. (2024) for Pakistan's coal and economic development. In light of the preceding discussion, the decomposition method is suitable for developing a novel framework for measuring mitigation strategies to develop low-carbon electricity systems. Thus, this method includes decomposing the impacting factors into six major influencing factors: LCS, electricity generation intensity, ES, EI, carbon productivity, and CO_2 emissions. Employing Kaya's (1990) approach, the factors adding to low-carbon electricity and carbon mitigation are analytically estimated as follows in Equation 1:

$$LCEG^t = \sum_i LCEG^t = \sum_i^t \frac{LCEG^t}{TEG^t} \times \frac{TEG^t}{TEP^t} \times \frac{TEP^t}{TEC^t} \times \frac{TEC^t}{GDP^t} \times \frac{GDP^t}{CO_2{}^t} \times CO_2{}^t \qquad (1)$$

where $LCEG^t$, TEG^t, TEP^t, TEC^t, GDP^t, $CO_2{}^t$, and t represent the low-carbon electricity generation, total electricity generation, total energy production, total electricity consumption, gross domestic product, carbon dioxide emissions, and time at the national level. Based on Equation 1, the influencing factors can be described as

$$= \sum_i^t LCS^t \times EGI^t \times ES^t \times EI^t \times CO_2P^t \times C^t \qquad (2)$$

where LCS^t, EGI^t, ES^t, EI^t, CO_2P^t, and C^trepresent the low-carbon structure, electricity generation intensity, energy security, EI, carbon productivity, and carbon emissions. Moreover, each factor in the model includes assumptions that are considered for policy measures. The first factor, $LCS^t = \frac{LCEG^t}{TEG^t}$, shows that if the numerical value is higher, the low-carbon electricity structure will be enhanced. The second factor, $EGI^t = \frac{TEG^t}{TEP^t}$, higher renewable electricity generations intensity will be useful. The third factor, $ES^t = \frac{TEP^t}{TEC^t}$, is called energy security. If the numerical value of ES^t is higher, then the effect of $LCEG^t$ will be at its maximum. Also, the contribution of ES^t to renewable energy highlights the country's energy self-sufficiency, which shows that the positive values reveal an energy production surplus, strengthening ES^t and renewable initiatives. Thus, evaluating renewable energy efficiency is integral to achieving carbon neutrality. The fourth factor, $EI^t = \frac{TEC^t}{GDP^t}$, is called energy intensity. A lower EI^t value is preferred. The fifth factor, $CO_2P^t = \frac{GDP^t}{{CO_2}^t}$, is called carbon production. If the numerical value of CO_2P^t is higher, then the maximum economic growth will be seen with minimum pollution. The sixth factor, C^t, is called the carbon emission factor. If the numerical value is lower, then green development is progressing, which will also show that fuel efficiency and technical enhancements are applicable in mitigating CO_2 emissions. Thus, employing the LMDI method, the change in LCEG from the base year (1985) to the target year (2024) is estimated as

$$\begin{aligned}\Delta LCEG^t &= LCEG^t - LCEG^0 = \Delta LCEG_{LCS} + \Delta LCEG_{EGI} \\ &\quad + \Delta LCEG_{ES} + \Delta LCEG_{EI} + \Delta LCEG_{CO_2P} + \Delta LCEG_C \end{aligned} \tag{3}$$

where Δ shows the change in overall growth in LCEG. However, $\Delta LCEG_{LCS}$, $\Delta LCEG_{EGI}$, $\Delta LCEG_{ES}$, $\Delta LCEG_{EI}$, $\Delta LCEG_{CO_2P}$, and $\Delta LCEG_C$ indicate impacts of low-carbon structure, electricity generation intensity, ES, EI, carbon productivity, and carbon emissions, respectively. Thus, the effects of each factor's decomposition are expressed as in Equations 4–10:

$$\Delta LCEG_{LCS} = \sum \frac{(LCEG^t - LCEG^0)}{(\ln LCEG^t - \ln LCEG^0)} \times \ln\left(\frac{LCS^t}{LCS^0}\right) \tag{4}$$

$$\Delta LCEG_{EGI} = \sum \frac{(LCEG^t - LCEG^0)}{(\ln LCEG^t - \ln LCEG^0)} \times \ln\left(\frac{EGI^t}{EGI^0}\right) \tag{5}$$

$$\Delta LCEG_{ES} = \sum \frac{(LCEG^t - LCEG^0)}{(\ln LCEG^t - \ln LCEG^0)} \times \ln\left(\frac{ES^t}{ES^0}\right) \tag{6}$$

$$\Delta LCEG_{EI} = \sum \frac{(LCEG^t - LCEG^0)}{(\ln LCEG^t - \ln LCEG^0)} \times \ln\left(\frac{EI^t}{EI^0}\right) \tag{7}$$

$$\Delta LCEG_{CO_2P} = \sum \frac{(LCEG^t - LCEG^0)}{(\ln LCEG^t - \ln LCEG^0)} \times \ln\left(\frac{CO_2P^t}{CO_2P^0}\right) \tag{8}$$

$$\Delta LCEG_{C} = \sum \frac{(LCEG^t - LCEG^0)}{(\ln LCEG^t - \ln LCEG^0)} \times \ln\left(\frac{C^t}{C^0}\right) \tag{9}$$

However, the aggregated $LCEG^t$ represents the amount of changeability, as follows in Equation 10:

$$\begin{aligned}&= \frac{(LCEG^t - LCEG^0)}{(\ln LCEG^t - \ln LCEG^0)} \left(\ln\left(\frac{LCS^t}{LCS^0}\right) + \ln\left(\frac{EGI^t}{EGI^0}\right)\right. \\ &\quad \left. + \ln\left(\frac{ES^t}{ES^0}\right) + \ln\left(\frac{EI^t}{EI^0}\right) + \ln\left(\frac{CO_2P^t}{CO_2P^0}\right) + \ln\left(\frac{C^t}{C^0}\right)\right)\end{aligned} \tag{10}$$

4.2 The LEAP model estimation

We integrate the LEAP and LMDI methods to conduct an in-depth analysis of the factors of these emissions. The research applies the LEAP model to measure electricity demand and CO_2 emission mitigation potential of Pakistan's electricity sector. The LEAP-Pakistan model employed in the current study takes into account electricity demand under various fuels (i.e., TEC, hydro, nuclear, thermal, and renewable energy) and CO_2 emission mitigation potential scenarios from each fuel type in Pakistan. The analysis covers the period from 2013 to 2035. The major components of the analysis are various electricity-related fuels and CO_2 emission mitigation under each fuel over the forecasted period. Each level includes the process of energy substitution and efficiency. For this, we employed three scenarios, i.e., electricity forecast [also called business as usual (BAU)], low-demand, and high-demand scenarios. The LEAP model is an energy-environment tool that was developed at the Stockholm Environment Institute (Stockholm Environment Institute, 2008) to measure the impacts of physical, economic, environmental, and technological initiatives. The model is useful and gives wide information on technical characteristics, prices, present practices, and energy production (Jun et al., 2010; Özer et al., 2013). Being a full energy accounting framework, it considers both demand- and supply-side technologies and considers overall system effects. Thus, the LEAP model explains how energy is utilized, substituted, and generated under the limitations of selected energy variables, such as hydro, renewable, nuclear, and thermal. The method is based on a bottom-up electricity generation simulation process, involving production capacity with the capacity factor of various fuels. As per the CO_2 mitigation scenario in the target year 2035, it can be estimated based on low-carbon energy generation. Thus, annual gross electricity production (G) analysis decomposes each fuel, which can be estimated as follows in Equation 11:

$$G_{year} = \sum_i^n g_i \tag{11}$$

where i is the fuel type, n represents the energy employed for the electricity generation, and g_i is the gross electricity generation from fuel i. Moreover, the primary electricity demand for g_i is estimated through the method with the electricity production per unit of electricity consumption (Mtoe), as shown in Equation 12:

$$(EC)_i = \sum_i (g_i * 0.0000010)/\varphi_i \tag{12}$$

where EC is the electricity consumption in Mtoe of fuel i. $(EC)_h$, $(EC)_t$, $(EC)_n$, and $(EC)_r$ denote the electricity consumption of hydro, thermal, nuclear, and renewable. φ_i is the fuel efficiency (%) of fuel i, and 0.0000010 is used for unit conversion as 1Toe = 0.0000010 Mtoe. Thus, various production and consumption fuel types in different scenarios have varying results respecting electricity demand. The logical structure in the LEAP model is presented in Figure 3. The framework is based on baseline, high-demand, and low-demand scenarios. The process can be summarized in four main steps: electricity production as per the demand projection, electricity types, fuel-related CO_2 emissions, and carbon mitigation potential.

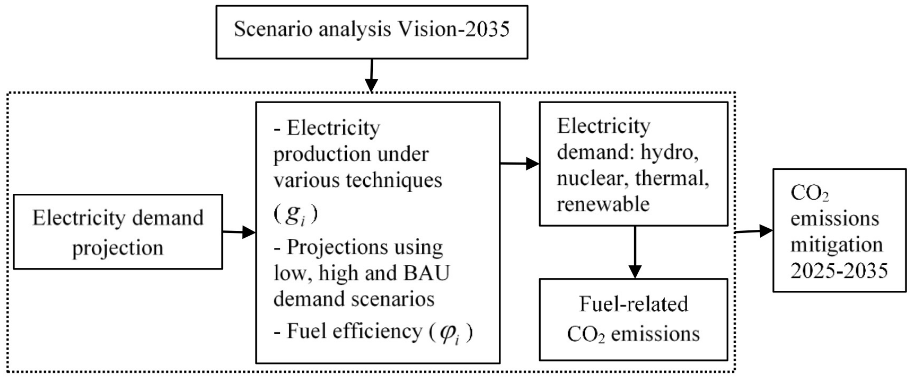

FIGURE 3
Structure and logical procedure of the LEAP model.

TABLE 3 Electricity demand and CO_2 mitigation scenarios.

Scenario name	Scenario description
TEC scenario 1	Use electricity trend from 2013 to 2035. A long-term trend from base year 2013 to forecasted year 2035 is analyzed under Vision 2035.
TEC $(BAU)_i$	TEC scenario at base level from 2013 to 2024 and 2025 to 2035 for long-term prediction with significance level of 5%. The base year and prediction trends include hydro, thermal, nuclear, and renewable electricity.
TEC $(low\ demand)_i$	Lowest demand prediction scenario under the base value from 2013 to 2024 with significance level of 5% to find trend in each fuel.
TEC $(high\ demand)_i$	Long-term prediction under base value from 2013 to 2024 with significance level of 5% to find maximum trend using electricity generation fuels.
CO_2 mitigation scenario	
CO_2 $(EC)_i$ (BAU)	CO_2 emission mitigation scenario: CO_2 $(EC)_i$ (BAU). This scenario assumes by current electricity consumption. CO_2 emission intensity at base level in period 2013–2024. Prediction level starts from 2025 to 2035.
CO_2 $(EC)_i$(low-mitigation)	A common net demand projection for future electricity is expected to be the same in the different scenarios, and individual electricity consumption is confirmed for each scenario. The Vision 2035 development agenda maintains the status quo in electricity consumption regarding the low-carbon trend with technological variations at national and international commitments being developed. Installed capacities are based on highest reduction scenario.

4.3 Scenario criteria for electricity demand and CO_2 mitigation pattern to 2035

Scenarios for electricity demand patterns up to 2035 are fixed under the assumption of the reduction potential of electricity demand in Pakistan, as presented in Table 3. Table 3 shows four types of energy-related scenarios (i.e., TEC scenario 1, TEC-BAU, TEC-low demand, and TEC-high demand scenarios) from the base year 2013 to the current year 2035. Aside from the BAU scenario, three different scenarios, based on common access to modern energy services consistent with the low-carbon energy transition initiatives, are developed. The CO_2 emissions mitigation scenarios are developed to assess pollution reduction under the initiatives of Renewable Energy Vision 2035 of Pakistan. The objective is to see the reduction potential; hence, the low-mitigation scenario is taken up. These scenarios reveal future consumption patterns and how further actions can maintain or reduce the level of electricity combustion by establishing five electricity-related scenarios under BAU, low demand, and high demand from 2013 to 2035 using the LEAP model. A more in-depth description is given in Table 3.

5 Empirical results and discussion

5.1 Factor decomposition of LCEG under economic planning period

This section gives econometric outcomes and a discussion. To obtain relevant outcomes, decomposition and LEAP methods are applied to check the factor effects and predict the mitigation potential of CO_2 emissions. LCEG in Pakistan grew by 4.15% and CO_2 emissions increased by 3.13% from 1985 to 2024. Thus, it is necessary to analyze electricity generation and related factors to investigate the country's sustainability. Furthermore, we employed the decomposition method to estimate the major driving factors, which are directly associated with electricity generation, economic growth, and pollution. These factors are

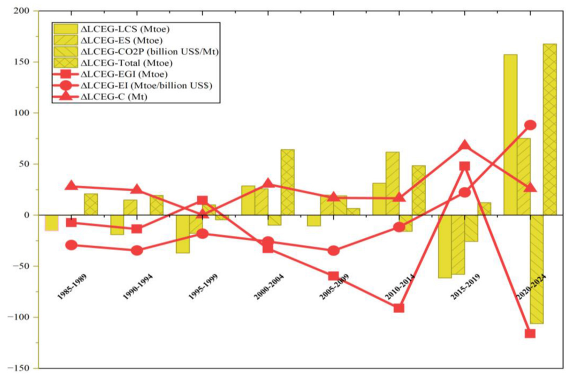

FIGURE 4
Factor’s decompaction analysis based on low-carbon electricity generation under economic development plan of Pakistan.

low-carbon structure ($\Delta LCEG_{LCS}$), electricity generation intensity ($\Delta LCEG_{EGI}$), ES ($\Delta LCEG_{ES}$), EI ($\Delta LCEG_{EI}$), carbon productivity ($\Delta LCEG_{CO_2P}$), carbon emissions ($\Delta LCEG_{C}$), and total factor effects ($\Delta LCEG_{total}$) within the economic planning period (i.e., 1985–1989, 1990–1994, 1995–1999, 2000–2004, 2005–2009, 2010–2014, 2015–2019, 2020–2024, and 1985–2024). Following Equations 4–9, the decomposition results are described in Figure 4.

Figure 4 describes the various driving factors that add to the impact of LCEG. It is obvious that the total effects of $\Delta LCEG_{total}$ during 1985–2024 show an optimistic impact of 415.95 Mtoe. Also, we found that there were positive and significant growing impacts of $\Delta LCEG_{total}$during the planning period excluding 1995–1999. The reduction in TEG during this period was estimated due to the consumption boom, spurring the use of electrical appliances and energy imports (Consortium for Development Policy Research, 2018). The maximum impact was seen in the current planning period (2020–2024), with a growth rate of 167.68 Mtoe, contributing to significant development, while the third planning phase (1995–1999) experienced negative growth of −4.53 Mtoe.

The $\Delta LCEG_{LCS}$ effect shows variations, with the most significant growth rate of 157.20 Mtoe occurring in 2020–2024, making an improved contribution of low-carbon electricity. Recently, the percentage contributions of hydro, nuclear, renewable, and thermal electricity were 25.4%, 8.4%, 6.8%, and 59.4%, respectively (Pakistan Economic Survey, 2023–2024). These are explained by the start of the China-Pakistan Economic Corridor (CPEC) power projects, which have addressed historical gaps in electricity production and enhanced sustainability. However, before 2013, renewable energy was not part of the electricity mix, and even thermal power, a dominant electricity supply source, has declined over the past few decades. For example, the energy sector in Pakistan is the biggest carbon emitter, which has recently increased its renewable energy production capacity from all kinds of renewable energy sources (e.g., solar, wind, biomass, bagasse) (Hydrocarbon Development Institute of Pakistan, 2024). It will try to meet low-carbon electricity demand and sustain the economic development of Pakistan. In addition, the country’s dependence on imported and costly fossil fuels for electricity generation emphasizes the need for a substitution in the fuel mix. For this, Pakistan has set a target to mitigate carbon emissions by 50% by 2030, and clean energy resources will play a dominant role in achieving this objective.

The $\Delta LCEG_{EGI}$effect had positive and negative fluctuations. The optimistic figures for 1985–1989, 1990–1994, and 2015–2019 highlighted the enhancements in electricity generation efficiency by 8.17, 3.04, and 54.13 Mtoe, respectively. However, we found that the maximum period shows a negative share due to technological development and reliance on imported fuel, which is not only affecting the country’s economy but also spurring CO_2 emissions. The renewable electricity era from 2013 onward is a positive sign of growing renewable electricity, which is consistent with the findings of Raza and Lin (2022), who showed that Pakistan could engage in energy substitution, economic development, and inter-fuel substitutions; however, the huge technological costs associated with renewable energy will impact actual progress. The $\Delta LCEG_{ES}$ effect shows that electricity generation is maximally positively significant in most phases, excluding 1985–1989, 1995–1999, and 2015–2019. The positive growth in the 1990–1994, 2000–2004, 2005–2009, 2010–2014, and 2020–2024 planning periods show that there is an energy production excess, strengthening ES and renewable energy production. As shown in Figure 4, the $\Delta LCEG_{ES}$ during the phases 1985–1989, 1995–1999, and 2015–2019 reflects the negative effect by 0.08, 17.77, and 57.91 Mtoe, showing a reduction in EI linked with economic progress. However, the maximum reduction in EI was estimated during the COVID-19 epidemic. It is clear that the EI ($\Delta LCEG_{EI}$) shows a positive effect when ES is negative or show low impact, which shows a negative impact on energy development. Moreover, a positive changeover seemed to occur during 1985–2024, with a positive growth of 32.27 Mtoe/billion US dollars, which suggests that Pakistan still relies on imported energy with an efficient and productive relationship between energy inputs and desired outputs. Thus, the outcomes suggest that achieving the goal with respect to CO_2 emissions mitigation in Pakistan is necessary for a basic energy infrastructure.

Concerning the $\Delta LCEG_{CO_2P}$effect, a mixed trend has been observed. The positive trend during the first three phases (1995-1999; 2000–2004 and 2005–2009) shows that the economy is efficiently progressing with a reduction in CO_2 emissions. It is evident that the country’s economy and pollution reduction have been significant since the start of the renewable energy period (2013) with negative effects, which is also consistent with the study of Qudrat-Ullah (2022), who proposed that Pakistan can significantly achieve CO_2 emissions targets and electricity consumers can save 23% annually on their electricity bills. The CO_2 emission ($\Delta LCEG_{C}$) effect on LCEG shows a maximum aggregated emissions trend by 462.90 Mt during 1985–2024, respectively. As shown in Figure 4, all the economic periods show a positive fluctuation with increasing or decreasing trends. However, it can be seen that during the most recent phase, 2020–2024, there was a reduction in CO_2 emissions of 0.49% to 35.94 Mt. Overall, it is noted that CO_2 emissions remained 462.90 Mt and positively affected LCEG during the period. Finally, it can be seen that the investigated factors are of utmost importance in providing a comprehensive model for understanding and developing low-carbon electricity productivity.

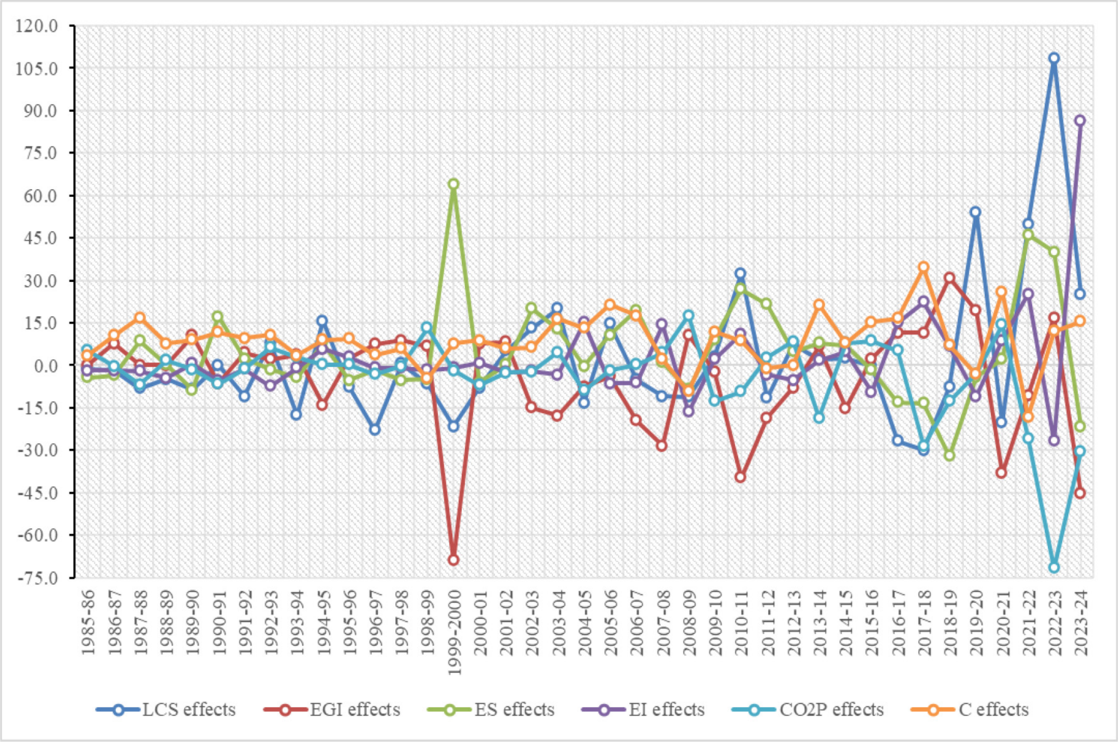

FIGURE 5
Annual decomposition of factor effects of low-carbon electricity generation.

5.2 LCEG and factor decomposition based on annual effects during the period 1985–2024

To further estimate the annual variation in the driving factors, we checked the effects of each factor during the estimated period, as shown in Figure 5. The analysis of each factor provides a mixed direction for the substitution of renewable energy. It is obvious that most of the factors show a wide fluctuation in the current decade because of the renewable contribution and indigenous production. According to the Pakistan Economic Survey (2023–2024), Pakistan is taking initiatives to meet its energy demand and reduce GHG emissions. For instance, several scholars have shown that Pakistan's electricity is the biggest sector in demand and supply, growing energy-related import bills, and growing environmental issues (Lin and Raza, 2020; Tang et al., 2024). For this reason, the government is actively pursuing large-scale renewable energy projects under CPEC and Pakistan's Energy Vision 2035 (Government of Pakistan, 2014) to achieve its global (i.e., Paris Agreement) and local clean energy goals. Despite the positive trends in EI and CO_2 emission mitigation, there has been a possible reduction in the considered factors, suggesting a slow transition toward more sustainable electricity consumption, especially after 2013. For example, there have been variations in the share of low-carbon electricity since 2000, which leads to mitigating CO_2 emissions in the future. The addition of renewable energy efficiency, a sectoral low-carbon energy portfolio, and significant industrial productivity will yield insights into sustainability and efficiency. This analysis will permit policymakers, researchers, and industrialists to make future decisions regarding multiple investments in different aspects.

5.3 Electricity demand and potential scenario

Electricity consumption is the major cause of demand. For this, we employed electricity-related indicators of the considered scenarios, including total electricity demand, hydro, thermal, nuclear, and renewable electricity demand in the period 2013–2035. The scenario analysis takes 2013 as the base year and 2035 as the final year. These inputs are needed to investigate the level of electricity activities as a whole. These demand projection were selected from the base period of 2013 because renewable electricity (i.e., biofuel, solar, and wind) first started in this period (Hydrocarbon Development Institute of Pakistan, 2024), which will provide insights for sound and progressive government policies. All the data are projected up to 2035 in order to predict Pakistan's Energy Vision 2035 (2014). Furthermore, the additional values after 2023–2035 are estimated under Equations 11, 12 with their prediction results under a significance level of 5%. Three scenarios were generated in this model and used in the analysis: baseline scenario, also called BAU, low-demand scenario, and high-demand scenario. However, the low-demand scenario, also called the mitigation scenario, assumes the implementation of more determined energy conservation and emission mitigation actions.

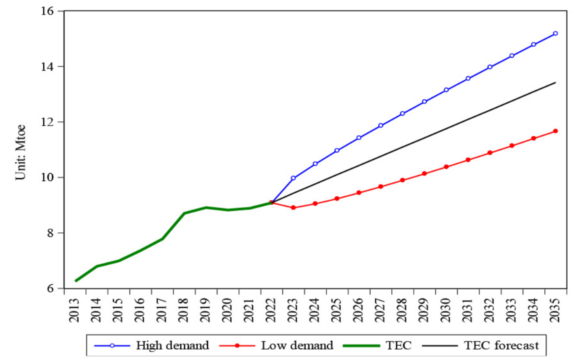

FIGURE 6
Total electricity demand projections of Pakistan.

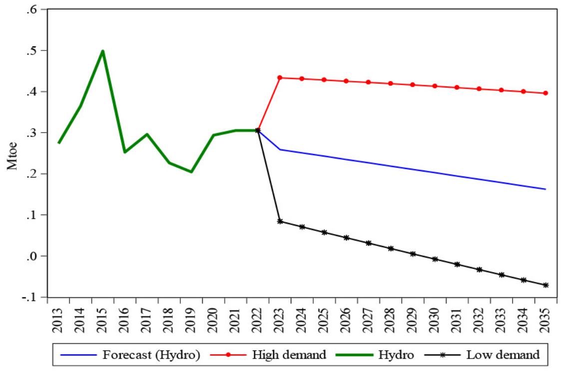

FIGURE 7
Total hydro electricity demand projections of Pakistan.

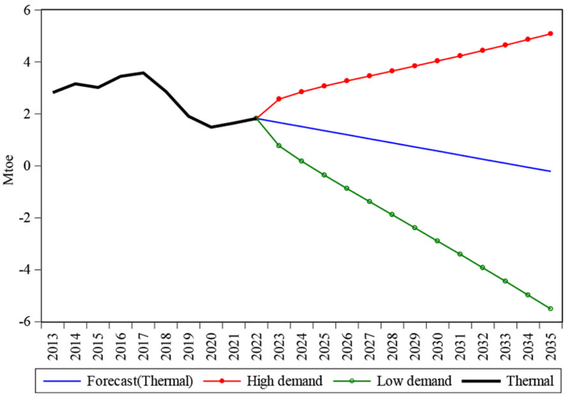

FIGURE 8
Total thermal electricity demand projections of Pakistan.

Thus, the outcomes of each fuel scenario are presented in Figures – . These scenarios will benefit the energy sector and policymakers and give direction for technological and sustainable enhancement.

First, the total electricity demand of Pakistan from 2013 to 2024 is applied (Hydrocarbon Development Institute of Pakistan, 2024) as a criterion to regulate the share of overall consumption and way of growth in forecasting electricity in Pakistan for the study, as shown in Figure 6. As shown in Figure 6, the electricity demand share from 2025 to 2035 shows substantial growth. It is estimated that the share of Pakistan's electricity consumption was 6.25 Mtoe in 2013 and 9.60 Mtoe in 2024, with an average growth rate of 0.53%. During the period between 2025 and 2035, the share of electricity consumption is estimated to add about 0.21%, which means that the share of the electricity sector is consistently growing. The outcomes are consistent and in line with Raza and Lin (2025), who proposed that fuel substitution and structure are useful in growing low-carbon energy. This shows that electricity-related fuel can be further adjusted at the maximum suitability under low-carbon demand.

Second, total hydroelectricity demand shows a zigzag growth pattern from 2013 to 2024, with a growing trend of 0.31%, as shown in Figure 7. Also, Jamil (2020) used the ARIMA model for hydroelectricity consumption prediction for 2030 and determined that no dams will be constructed due to financial issues, which has created a margin between the installed and available potential of hydroelectricity in Pakistan. The hydroelectricity shares from 2025 to 2035 contributed an average growth rate of 0.14%, which means that hydroelectricity contributes significantly over time. The historical measures show that precipitation variations and decreasing water availability have damaged riverine ecology, impaired water security, and influenced hydropower production (Pakistan Economic Survey, 2023–2024). Growth in renewable energy and hydroelectricity from 33 to 62% by 2031 will come through various projects, such as CPEC, and the promotion of local resources, inviting private companies, and building small dams (Integrated Generation Capacity Expansion Plan, 2022).

Third, thermal electricity is similar to hydroelectricity, which on average decreased by 0.58% during 2013–2024, as shown in Figure 8. The thermal electricity share will on average decline by 0.85% between 2025 and 2035, which shows that thermal electricity will decrease due to renewable energy substitution. If we consider the low-demand scenario, thermal electricity will decline by 3% in 2035. For example, the government of Pakistan has decided to add about 6,000 MW of PV solar capacity to quickly reduce pollution from energy generation. The results are consistent with a study by Tahir and Asim (2018), who proposed that this capacity will impact supply and demand of electricity, leading to several hours of power cuts. Consequently, the government should activate its natural resources, including natural gas, solar systems, biomass, and wind, for example, for potential development with the help of international companies.

Fourth, in 1972, Pakistan was the world's 15th nuclear energy producer under Pakistan Atomic Energy. Due to project life cycles, nuclear energy is linked to multiple projects and shows continuous growth. As shown in Figure 9, nuclear electricity demand grew by 4.85% from 2013 to 2024, while demand between 2025 and 2035 will arrive by 0.77%, respectively. This shows that nuclear electricity has the maximum possibility of growing into a future energy source. For instance, nuclear power plants in Pakistan are a reliable source of electricity. These plants can run for a longer time and store enough energy on-site, which can protect against short- and long-run variations and capacity factors. According to Raza and Tang (2024), nuclear energy is clean and has zero GHG

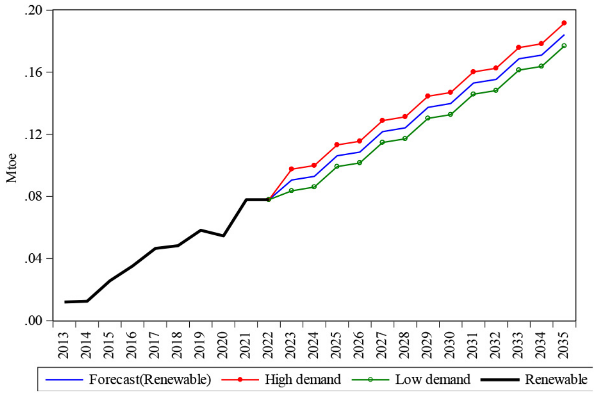

FIGURE 9
Total nuclear electricity demand projections of Pakistan.

emissions. Thus, the low-demand and high-demand scenarios show an increasing and consistent trend over the period. Furthermore, nuclear electricity is the best energy source, which cut about 10 Mt of GHG during 2023; thus, the high-demand scenario is the best choice (Pakistan Economic Survey, 2023–2024), which can be enhanced by several nuclear power plants.

Finally, renewable energy (i.e., solar, wind and biomass) has shown an increasing trend over the period. As presented in Figure 10, Pakistan's renewable energy grew by 7.62% during 2013–2024, because Pakistan's energy sector is paving the way toward transitioning from imported fossil fuels to renewable energy sources, for instance, through substantial investment in solar and wind energy. This is consistent with Shakeel et al. (2016), who found that renewable power generation in 2013 started with a determined goal of removing the gap between generation and consumption. Based on huge investments in renewables, the predictions were estimated at an average growth rate of 0.75% between 2025 and 2035. For example, the government of Pakistan has been concentrating on strengthening the regulatory framework and incentivizing private sector investment in renewable energy that will guarantee ES and climate change mitigation. Moreover, the private power infrastructure board is easing 24 power generation projects, of which 22 are based on renewable energy.

5.4 Fuel-based CO_2 emission mitigation scenario from 2013 to 2035

Based on decomposition results and scenario analysis, it is necessary to adopt a carbon mitigation scenario. The modeling framework is applied to investigate and project the energy demand and CO_2 emission mitigation under the planning for the period 2013–2023. The long-term prediction of energy demand and carbon mitigation is of key importance in Pakistan due to the steady growth in energy needs, the fuel import dependence (i.e., oil, energy technologies, and gas), and the global concerns over energy-induced climate issues. In this scenario, we divide the scenario into five fuels, including TEC, hydro, thermal, nuclear, and renewable electricity. This scenario is adopted to examine CO_2 mitigation from the existing electricity resources in Pakistan. This scenario is imperative because it reduces CO_2 emissions under the condition that the installed power offers a maximum advantage. No power plants are operating under capacity, and all low-carbon electricity consumption sources except thermal are used. In this scenario, we have considered only the mitigation scenario (low-demand scenario), and the carbon reduction of each energy source is described from 2023 to 2035, as shown in Table 4. However, it is obvious that the installed electricity from 2013 to 2022 will not change, and hence carbon emissions from various fuels are expected to decrease due to a rising capacity of low-carbon electricity except thermal electricity (Hydrocarbon Development Institute of Pakistan-HDIP, 2024). Thus, the main outcomes related to CO_2 emission mitigation by fuel type are presented in Table 4. The electricity-related CO_2 emissions were reduced by 6.45% yearly between 2013 and 2035. However, electricity output increases at an average rate of 4.34% per year during the estimated period. For instance, a study by Özer et al. (2013) analyzed Turkey's electricity sector using fossil fuel consumption and investigated the prediction analysis until 2030. According to their analysis, CO_2 emissions will grow due to fossil fuel consumption to meet electricity demand, and mitigation potential is possible in growing renewable energy.

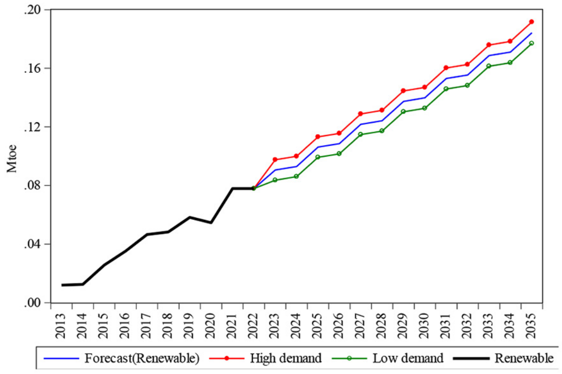

FIGURE 10
Total renewable electricity demand projections of Pakistan.

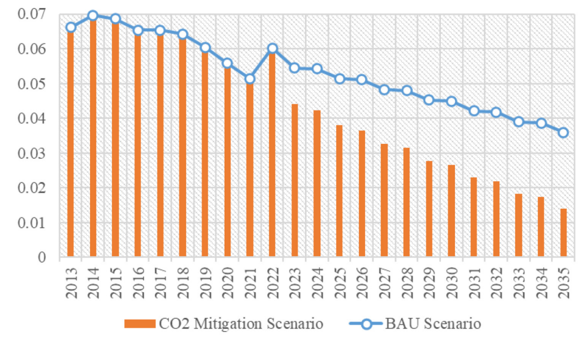

FIGURE 11
CO_2 emission trend for BAU and CO_2 mitigation scenarios based on aggregated low-carbon electricity, 2013–2035 (Unit: $MtCO_2$).

Hence, it can be said that energy models can be developed based on available renewable energy sources to promote energy access, permit a transition to cleaner energy, and reduce pollution for a developing economy.

Figure 11 presents the variation in yearly CO_2 emissions through the prospect of the study for BAU and CO_2 mitigation scenarios. If the maximum share of low-carbon electricity becomes accessible from 2025 onward, the reduction in CO_2 emissions until 2035 is expected to be 68.551%. For instance, a study by Sadiqa et al. (2018), who discussed the electricity transition roadmap for Pakistan's overall energy demand by 2050, found that CO_2 emissions can be significantly reduced, by 100%. Thus, the cumulative CO_2 emissions would be reduced by an average of 0.026 Mt from 2025 to 2035. As shown in Figure 11, the BAU scenario is established first as a benchmark, and a mitigation scenario is established because of the gradual growth share of low-carbon electricity consumption. As shown in Figure 1, the electricity generation of various fuels is increasing as a result of the growing electricity demand and the mitigation potential of CO_2 emissions. Therefore, Pakistan should implement strong renewable energy policies to sustain economic development and mitigate pollution and ES while meeting local and international demand.

6 Conclusion and policy recommendations

6.1 Conclusion

The present research analyzes the major electricity generation and CO_2 emissions in Pakistan, spanning the data from 1985 to 2024, employing LMDI and LEAP models. Based on empirical analysis, the main outcomes are as follows.

First, using the decomposition analysis, the six major factors (i.e., low-carbon structure, electricity generation intensity, ES, EI, carbon productivity, and CO_2 emissions) are divided into the Five-Year Economic Planning period, and then all the factors' effects are analyzed annually. The results prove that aggregated LCEG has a rising impact; however, a positive and growing impact has been observed in the current decade, particularly in the current planning period. Similarly, the low-carbon structure factor provided amazing results during 2020–2024, showing a significant impact on the country's economic and environmental development. The intensity of electricity generation and ES demonstrate technological progress; however, the negative impact of EI has a significant influence on energy technology. This proves that Pakistan can adopt technologies in the energy sector to fight ES, CO_2 emission reduction, and economic sustainability. Carbon production effects show that the economy of Pakistan is improving due to significant advances in LCEG, which is lowering CO_2 emissions. Consequently, a clear reduction, of 23.77%, has been observed in the current phase, showing that Pakistan is committed to renewable agreements, such as the Paris Agreement and Vision 2035 (2014).

Second, electricity demand-based scenarios show that total electricity demand, nuclear, and renewable electricity are increasing in the baseline and high-demand scenarios. This guarantees that the low-carbon electricity will continue to grow and can be a factor in the country's security.

Finally, various electricity sources provide a significant contribution to mitigating CO_2 emissions. As Pakistan is an emerging country and relies heavily on fossil fuels, CO_2 emissions cannot be fully stopped from the baseline scenario. However, we estimated that the mitigation scenario between 2013 and 2035 would reduce emissions by 6.45% annually accompanied by an increasing rate of electricity of 4.34%. Thus, the current study provides relative outcomes for policymakers to put forth national and international-level policies for mitigating long-run CO_2 emissions in the electricity sector of Pakistan, which can be discussed in environmental discussions.

6.2 Policy suggestions

First, based on current results, we noticed that a low-carbon electricity structure was useful for energy efficiency. Thus, the government should pay attention to and encourage long-term investments, renewable energy technologies, and dam reconstruction for hydroelectricity, which will ultimately increase ES and reduce pollution. For example, 250 engineering structures, including dams, ponds, spillways, and drainage systems, are under consideration and can be utilized to increase electricity efficiency.

Second, comparison of scenario analyses suggested that Pakistan could cut CO_2 emissions by 6.45% using low-carbon electricity up to 2035. To do this, ES efforts can be increased by various electricity-consuming sectors or by substituting fossil fuel electricity for low-carbon electricity-generating resources, i.e., hydro, nuclear, wind, biofuels, and photovoltaic (PV) solar by following the long-term goals of the Paris Agreement to achieve net zero emissions in the second half of the century.

Finally, we could not find low-carbon electricity costs or sectoral information. Thus, further study and scenarios can be investigated in comparing costs and sectoral progress. Energy models support monitoring energy indicators, measuring the time effects of energy consumption, and evaluating progress on SDGs. Moreover, energy prediction models use machine learning with a focus on renewable energy, load, and cost forecasting. These prediction models will be employed to formulate policies with extrinsic inputs (i.e., population, income, growth factors, and

TABLE 4 CO_2 emissions mitigation scenario by electricity fuel type, 2013–2035 (unit: Mt).

Time	EC	$(EC)_h$	$(EC)_t$	$(EC)_n$	$(EC)_r$	Total	Growth rate (%)
2013	0.04304	0.00188	0.01943	0.00168	0.00008	0.06611	–
2014	0.04478	0.00241	0.02080	0.00156	0.00008	0.06962	5.31866
2015	0.04361	0.00311	0.01883	0.00292	0.00016	0.06863	−1.42552
2016	0.04173	0.00143	0.01955	0.00238	0.00020	0.06529	−4.87013
2017	0.04123	0.00157	0.01895	0.00334	0.00025	0.06533	0.06863
2018	0.04458	0.00116	0.01466	0.00360	0.00025	0.06425	−1.65914
2019	0.04576	0.00105	0.00978	0.00350	0.00030	0.06040	−5.99811
2020	0.04260	0.00142	0.00718	0.00437	0.00026	0.05583	−7.56097
2021	0.03842	0.00132	0.00713	0.00424	0.00034	0.05144	−7.85647
2022	0.04362	0.00147	0.00876	0.00598	0.00037	0.06020	17.01687
2023	0.03733	−0.00020	0.00226	0.00436	0.00037	0.04412	−26.70767
2024	0.03716	−0.00034	−0.00098	0.00602	0.00038	0.04224	−4.26020
2025	0.03699	−0.00047	−0.00391	0.00488	0.00043	0.03791	−10.24218
2026	0.03682	−0.00061	−0.00667	0.00654	0.00045	0.03653	−3.65269
2027	0.03665	−0.00075	−0.00930	0.00547	0.00050	0.03257	−10.83654
2028	0.03648	−0.00088	−0.01186	0.00713	0.00051	0.03139	−3.64002
2029	0.03632	−0.00102	−0.01435	0.00610	0.00056	0.02761	−12.01788
2030	0.03615	−0.00116	−0.01679	0.00777	0.00057	0.02654	−3.87769
2031	0.03598	−0.00129	−0.01919	0.00676	0.00063	0.02289	−13.76716
2032	0.03581	−0.00143	−0.02155	0.00843	0.00064	0.02189	−4.34251
2033	0.03564	−0.00157	−0.02388	0.00744	0.00069	0.01832	−16.31205
2034	0.03547	−0.00170	−0.02619	0.00910	0.00070	0.01739	−5.11928
2035	0.03531	−0.00184	−0.02847	0.00813	0.00075	0.01388	−20.18579
Average	–	–	–	–	–	4.34952	−6.45127

technologies) to measure energy utilization patterns. Also, to review the additional mitigation potential of the current scenario under Energy Vision 2035, further studies should be conducted on the mitigation potential of electricity consumption in other sectors and overall energy demand. Also, electricity demand forecasts are based on economic growth and population; hence, these factors might provide efficient results.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

MR: Conceptualization, Data curation, Formal analysis, Methodology, Software, Writing – original draft, Writing – review & editing. BL: Conceptualization, Formal analysis, Methodology, Project administration, Writing – original draft, Writing – review & editing. QJ: Conceptualization, Data curation, Methodology, Software, Writing – original draft, Writing – review & editing.

Funding

The author(s) declared that financial support was received for this work and/or its publication. This work was supported by the National Natural Science Foundation of China (Key Program No. 72133003) and National Natural Science Foundation of China (General Program, No. 721574188).

Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declared that generative AI was not used in the creation of this manuscript.

Any alternative text (alt text) provided alongside figures in this article has been generated by Frontiers with the support of artificial intelligence and reasonable efforts have been made to ensure accuracy, including review by the authors wherever possible. If you identify any issues, please contact us.

Publisher's note

References

Acheampong, A. O. (2018). Economic growth, CO_2 emissions and energy consumption: what causes what and where? *Energy Econ.* 74, 677–692. doi: 10.1016/j.eneco.2018.07.022

Amponsah, N. Y., Troldborg, M., Kington, B., Aalders, I., and Hough, R. L. (2014). Greenhouse gas emissions from renewable energy sources: a review of lifecycle considerations. *Renew. Sustain. Energy Rev.* 39, 461–475. doi: 10.1016/j.rser.2014.07.087

Ang, B. W. (2004). Decomposition analysis for policymaking in energy: which is the preferred method? *Energy Policy* 32, 1131–1139. doi: 10.1016/S0301-4215(03)00076-4

Ang, B. W., Zhang, F. Q., and Choi, K. H. (1998). Factorizing changes in energy and environmental indicators through decomposition. *Energy* 23, 489–495. doi: 10.1016/S0360-5442(98)00016-4

Bakhsh, K., Rose, S., Ali, M. F., Ahmad, N., and Shahbaz, M. (2017). Economic growth, CO_2 emissions, renewable waste and FDI relation in Pakistan: new evidences from 3SLS. *J. Environ. Manage.* 196, 627–632. doi: 10.1016/j.jenvman.2017.03.029

Balta-Ozkan, N., Watson, T., and Mocca, E. (2015). Spatially uneven development and low carbon transitions: insights from urban and regional planning. *Energy Policy* 85, 500–510. doi: 10.1016/j.enpol.2015.05.013

Boulanouar, Z., Essid, L., and Omri, A. (2024). Achieving carbon neutrality in emerging markets: the dual impact of energy transition investments on economic growth and carbon emissions. *Int. Rev. Econ. Finance* 96:103709. doi: 10.1016/j.iref.2024.103709

Chong, C. H., Tan, W. X., Ting, Z. J., Liu, P., Ma, L., Li, Z., et al. (2019). The driving factors of energy-related CO_2 emission growth in Malaysia: the LMDI decomposition method based on energy allocation analysis. *Renew. Sustain. Energy Rev.* 115:109356. doi: 10.1016/j.rser.2019.109356

Consortium for Development Policy Research (2018). Available online at: https://www.cdpr.org.pk/wp-content/uploads/2025/06/Power-Shortages-in-Pakistan.pdf (Accessed December 1, 2025).

Csereklyei, Z., Manchester, J., and Ancev, T. (2023). Coal generator revenues and the rise of renewable generation: evidence from Australia's national electricity market. *Energy Policy* 178:113580. doi: 10.1016/j.enpol.2023.113580

El-Sayed, A. H. A., Khalil, A., and Yehia, M. (2023). Modeling alternative scenarios for Egypt 2050 energy mix based on LEAP analysis. *Energy* 266:126615. doi: 10.1016/j.energy.2023.126615

Fang, X., and Yang, L. (2025). Medium and long-term energy demand forecasting in the Yangtze River Delta based on the LEAP-SJZA model under the "dual carbon" goals. *Energy* 335:38270. doi: 10.1016/j.energy.2025.138270

Gan, P. Y., Komiyama, R., and Li, Z. (2013). A low carbon society outlook for Malaysia to 2035. *Renew. Sustain. Energy Rev.* 21, 432–443. doi: 10.1016/j.rser.2012.12.041

Gong, Q., and Zhang, R. (2024). Digital finance as a catalyst for energy transition and sustainable rural economic growth. *Financ Res. Lett.* 71:106405. doi: 10.1016/j.frl.2024.106405

Government of Pakistan (2014). "Vision 2035. Pakistan 2035, one nation-one vision," in *Planning Commission*. Islamabad: Ministry of Planning, Development and Reforms. Government of Pakistan. Available online at: https://www.sdpi.org/publications/files/Pakistan%20Energy%25 (Accessed December 5, 2025).

Grossman, G. M., and Krueger, A. B. (1995). Economic growth and the environment. *Q. J. Econ.* 110, 353–377. doi: 10.2307/2118443

Hammond, G. P., and Norman, J. B. (2012). Decomposition analysis of energy-related carbon emissions from UK manufacturing. *Energy* 41, 220–227. doi: 10.1016/j.energy.2011.06.035

Hao, D., Qi, L., Tairab, A. M., Ahmed, A., Azam, A., Luo, D., et al. (2022). Solar energy harvesting technologies for PV self-powered applications: a comprehensive review. *Renew. Energy* 188, 678–697. doi: 10.1016/j.renene.2022.02.066

Huang, Y., Wang, Y., Peng, J., Li, F., Zhu, L., Zhao, H., et al. (2023). Can China achieve its 2030 and 2060 CO_2 commitments? Scenario analysis based on the integration of LEAP model with LMDI decomposition. *Sci. Total Environ.* 888:164151. doi: 10.1016/j.scitotenv.2023.164151

Huang, Y. H. (2020). Examining impact factors of residential electricity consumption in Taiwan using index decomposition analysis based on end-use level data. *Energy* 213:119067. doi: 10.1016/j.energy.2020.119067

Hydrocarbon Development Institute of Pakistan (2024). *Pakistan energy yearbook. Ministry of energy (Petroleum Division).* Hydrocarbon Development Institute of Pakistan. Available online at: https://hdip.com.pk/contents.php?cid=32 (Accessed November 15, 2025).

Hydrocarbon Development Institute of Pakistan-HDIP (2024). *Pakistan Energy Yearbook. Ministry of Energy (Petroleum Division). Hydrocarbon Development Institute of Pakistan*. Available online at: https://hdip.com.pk/contents.php?cid=32

Integrated Generation Capacity Expansion Plan (2022). Available online at: https://www.brecorder.com/news/40224272#:~:text=The%20IGCEP-2022%20builds%20on%20the%20plans%20laid%20down,energy%2C%20including%20hydel%2C%20Thar%20coal%2C%20wind%2C%20and%20solar (Accessed November 10, 2025).

International Energy Agency (2024). Available online at: https://www.iea.org/data-and-statistics/data-tools/energy-statistics-data-browser?country=PAKISTANandfuel=CO2%20emissionsandindicator=CO2BySector (Accessed November 7, 2025).

International Renewable Energy Agency (2021). *World Energy Transitions Outlook: 1.5°C Pathway*. Available online at: https://www.irena.org/publications/2021/Jun/World-Energy-Transitions-Outlook (Accessed October 21, 2025).

Jamil, R. (2020). Hydroelectricity consumption forecast for Pakistan using ARIMA modeling and supply-demand analysis for the year 2030. *Renew. Energy* 154, 1–10. doi: 10.1016/j.renene.2020.02.117

Jun, S., Lee, S., Park, J. W., Jeong, S. J., and Shin, H. C. (2010). The assessment of renewable energy planning on CO_2 abatement in South Korea. *Renew. Energy* 35, 471–477. doi: 10.1016/j.renene.2009.07.024

Kaya, Y. (1990). *Impact of Carbon Dioxide Emission Control on GNP Growth: Interpretation of Proposed Scenarios.* Paris: IPCC Energy and Industry Subgroup, Response Strategies Working Group.

Khan, M. A., and Abbas, F. (2016). The dynamics of electricity demand in Pakistan: a panel cointegration analysis. *Renew. Sustain. Energy Rev.* 65, 1159–1178. doi: 10.1016/j.rser.2016.06.054

Li, L., Raza, M. Y., and Cucculelli, M. (2024). Electricity generation and CO_2 emissions in China using index decomposition and decoupling approach. *Energy Strategy Rev.* 51:101304. doi: 10.1016/j.esr.2024.101304

Lin, B., and Raza, M. Y. (2020). Analysis of energy security indicators and CO_2 emissions. A case from a developing economy. *Energy* 200:117575. doi: 10.1016/j.energy.2020.117575

Lin, B., and Zhou, Y. (2022). Measuring the green economic growth in China: influencing factors and policy perspectives. *Energy* 241:122518. doi: 10.1016/j.energy.2021.122518

Liya, C., and Jianfeng, G. (2018). Scenario analysis of CO2 emission abatement effect based on LEAP. *Energy Procedia* 152, 965–970.

Lu, L., Chen, Y., Feng, Q., Li, W., and Chen, D. (2024). Long-range energy demand and greenhouse gas emissions analysis using the LEAP Model: a case study of building ceramic industrial park. *Energy Sustain. Dev.* 83:101594. doi: 10.1016/j.esd.2024.101594

Lu, S., Li, J., Zhang, W., and Xiao, F. (2024). Towards sustainable development in resource-based cities: assessing the effects of extraregional technology and investment on the low-carbon transition. *J. Environ. Manage.* 364:121388. doi: 10.1016/j.jenvman.2024.121388

McPherson, M., and Karney, B. (2014). Long-term scenario alternatives and their implications: LEAP model application of Panama? s electricity sector. *Energy Policy* 68, 146–157. doi: 10.1016/j.enpol.2014.01.028

Moutinho, V., Moreira, A. C., and Silva, P. M. (2015). The driving forces of change in energy-related CO_2 emissions in Eastern, Western, Northern and Southern Europe: the LMDI approach to decomposition analysis. *Renew. Sustain. Energy Rev.* 50, 1485–1499. doi: 10.1016/j.rser.2015.05.072

Nieves, J. A., Aristizábal, A. J., Dyner, I., Báez, O., and Ospina, D. H. (2019). Energy demand and greenhouse gas emissions analysis in Colombia: a LEAP model application. *Energy* 169, 380–397. doi: 10.1016/j.energy.2018.12.051

Ouedraogo, N. S. (2017). Africa energy future: alternative scenarios and their implications for sustainable development strategies. *Energy Policy* 106, 457–471. doi: 10.1016/j.enpol.2017.03.021

Ozdemir, A. C. (2023). Decomposition and decoupling analysis of carbon dioxide emissions in electricity generation by primary fossil fuels in Turkey. *Energy* 273:127264. doi: 10.1016/j.energy.2023.127264

Özer, B., Görgün, E., and Incecik, S. (2013). The scenario analysis on CO_2 emission mitigation potential in the Turkish electricity sector: 2006–2030. *Energy* 49, 395–403. doi: 10.1016/j.energy.2012.10.059

Pakistan Economic Survey (2023–2024). *Ministry of Finance, Government of Pakistan.* Islamabad: Ministry of Finance, Government of Pakistan. Available online at: http:// http://www.finance.gov.pk/survey/chapters_24/Pakistan_ES_2023_24_pdf (Accessed September 23, 2025).

Qudrat-Ullah, H. (2022). A review and analysis of renewable energy policies and CO_2 emissions of Pakistan. *Energy* 238:121849. doi: 10.1016/j.energy.2021.121849

Raza, M. Y., and Lin, B. (2022). Energy efficiency and factor productivity in Pakistan: policy perspectives. *Energy* 247:123461.

Raza, M. Y., and Lin, B. (2024). Energy transition, carbon trade and sustainable electricity generation in Pakistan. *Appl. Energy* 372:123782. doi: 10.1016/j.apenergy.2024.123782

Raza, M. Y., and Lin, B. (2025). Energy elasticity and technological substitution possibilities in Pakistan's cement sector: a production approach towards 2035. *Energy* 339:139139. doi: 10.1016/j.energy.2025.139139

Raza, M. Y., Lin, B., and Javed, Q. (2024). Fuel substitution possibilities, factor productivity, and technological progress in the industrial sector of India. *Front. Sustain. Energy Policy* 3:1351785. doi: 10.3389/fsuep.2024.1351785

Raza, M. Y., and Tang, S. (2024). Nuclear energy, economic growth and CO_2 emissions in Pakistan: evidence from extended STRIPAT model. *Nucl. Eng. Technol.* 56, 2480–2488. doi: 10.1016/j.net.2024.02.006

Saboori, B., and Sulaiman, J. (2013). CO_2 emissions, energy consumption and economic growth in Association of Southeast Asian Nations (ASEAN) countries: a cointegration approach. *Energy* 55, 813–822. doi: 10.1016/j.energy.2013.04.038

Sadiqa, A., Gulagi, A., and Breyer, C. (2018). Energy transition roadmap towards 100% renewable energy and role of storage technologies for Pakistan by 2050. *Energy* 147, 518–533. doi: 10.1016/j.energy.2018.01.027

Saidi, K., and Hammami, S. (2015). The impact of CO_2 emissions and economic growth on energy consumption in 58 countries. *Energy Rep.* 1, 62–70. doi: 10.1016/j.egyr.2015.01.003

Shahbaz, M., Kuziboev, B., Pícha, K., Abdullaev, I., Minani, L. M., and Jumaniyazova, S. (2024). Mediating role of energy uncertainty for environmental management in electricity generation: the evidence from Pakistan. *Energy Nexus* 16:100327. doi: 10.1016/j.nexus.2024.100327

Shahid, M., Ullah, K., Imran, K., and Ali, A. (2025). Towards energy efficiency in Pakistan: an analysis of increasing integrated fuel demand using LEAP forecasting and backcasting. *Fuel* 396:135247. doi: 10.1016/j.fuel.2025.135247

Shakeel, S. R., Takala, J., and Shakeel, W. (2016). Renewable energy sources in power generation in Pakistan. *Renew. Sustain. Energy Rev.* 64, 421–434. doi: 10.1016/j.rser.2016.06.016

Song, H. J., Lee, S., Maken, S., Ahn, S. W., Park, J. W., Min, B., et al. (2007). Environmental and economic assessment of the chemical absorption process in Korea using the LEAP model. *Energy Policy* 35, 5109–5116. doi: 10.1016/j.enpol.2007.05.004

Sovacool, B. K., and Valentine, S. V. (2010). The socio-political economy of nuclear energy in China and India. *Energy* 35, 3803–3813. doi: 10.1016/j.energy.2010.05.033

Stockholm Environment Institute (2008). *LEAP Long-Range Energy Alternatives Planning System; User Guide for Leap Version*. Available online at: http://www.energycommunity.org/documents/Leap2008UserGuideEnglish.pdf (Accessed September 15, 2025).

Tachega, M. A., Chen, Y., Agbanyo, G. K., Ahmed, R., Appiah, A., and Mintah, C. (2024). Energy efficiency, economic growth, and natural resource rent: a trilemma analysis of environmental sustainability in Africa. *Energy* 307:132693. doi: 10.1016/j.energy.2024.132693

Tahir, Z. R., and Asim, M. (2018). Surface measured solar radiation data and solar energy resource assessment of Pakistan: a review. *Renew. Sustain. Energy Rev.* 81, 2839–2861. doi: 10.1016/j.rser.2017.06.090

Tang, S., Raza, M. Y., and Lin, B. (2024). Analysis of coal-related energy consumption, economic growth and intensity effects in Pakistan. *Energy* 292:130581. doi: 10.1016/j.energy.2024.130581

Valasai, G. D., Uqaili, M. A., Memon, H. R., Samoo, S. R., Mirjat, N. H., and Harijan, K. (2017). Overcoming electricity crisis in Pakistan: a review of sustainable electricity options. *Renew. Sustain. Energy Rev.* 72, 734–745. doi: 10.1016/j.rser.2017.01.097

Vrontisi, Z., Fragkiadakis, K., Kannavou, M., and Capros, P. (2020). Energy system transition and macroeconomic impacts of a European decarbonization action towards a below 2°C climate stabilization. *Clim. Change* 162, 1857–1875. doi: 10.1007/s10584-019-02440-7

Wakiyama, T., and Kuramochi, T. (2017). Scenario analysis of energy saving and CO_2 emissions reduction potentials to ratchet up Japanese mitigation target in 2030 in the residential sector. *Energy Policy* 103, 1–15. doi: 10.1016/j.enpol.2016.12.059

Wang, X., and Yan, L. (2022). Driving factors and decoupling analysis of fossil fuel related-carbon dioxide emissions in China. *Fuel* 314:122869. doi: 10.1016/j.fuel.2021.122869

Wang, Z., Huang, C., Zhang, Y., Zhong, F., and Li, W. (2024). Tackling carbon peak and carbon neutrality challenges: a method with long-range energy alternatives planning system and Logarithmic Mean Divisia Index Integration. *Energy* 311:133465. doi: 10.1016/j.energy.2024.133465

World Development Indicators (2025). Available online at: https://data.worldbank.org/indicator (Accessed August 10, 2025).

Xu, T., Ding, C. J., and Ahmed, A. D. (2026). The dark side of green innovation policy on energy consumption: from technology substitution effect perspective. *Energy Policy* 208:114894. doi: 10.1016/j.enpol.2025.114894

Zhang, M., Liu, X., Wang, W., and Zhou, M. (2013). Decomposition analysis of CO_2 emissions from electricity generation in China. *Energy Policy* 52, 159–165. doi: 10.1016/j.enpol.2012.10.013