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Achieving "clean" or "green" energy initiatives and a sustainable future in the conundrum of urbanisation and technological innovation

Abdul Rehman

College of Economics and Management, Henan Agricultural University, Zhengzhou, 450002, China

e-mail: abdrehman@henau.edu.cn

ORCID: 0000-0001-7809-5124

Hengyun Ma

College of Economics and Management, Henan Agricultural University, Zhengzhou, 450002, China

e-mail: h.y.ma@163.com

ORCID: 0000-0003-4405-3078

Wasi Ul Hassan Shah

School of Management, Zhejiang Shuren University, Hangzhou, 310015, China

e-mail: wasiulhassanshah@zjsru.edu.cn

ORCID: 0000-0003-1470-4861

Enea Constanța

Faculty of Economics, Constantin Brâncuși University of Târgu-Jiu, 210185, Romania

e-mail: constanta_enea@yahoo.com

ORCID: 0000-0002-8397-6572

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Abstract

Aim: The aim of this research was to examine the impact of renewable energy consumption (RE), technological innovation (TI), urbanisation (UR), and trade (TR) on carbon dioxide emissions (CE) in Pakistan, utilising an asymmetric (NARDL) approach to understand the dynamics of these factors in influencing environmental quality.

Methodology: The study employed the asymmetric Nonlinear Autoregressive Distributed Lag (NARDL) approach to analyse the relationship between energy consumption, urbanisation, technological innovation, trade, and carbon emissions in Pakistan. Additionally, the robustness of the results was verified using the Robust Least Squares (RLS) and Generalised Method of Moments (GMM) techniques to assess the persistence of the variables over time.

Results: The study found that renewable energy consumption and urbanisation had a negative impact on environmental quality, both in the short and long term. Technological innovation, on the other hand, had a positive impact on environmental quality in the short and long-run estimations. However, the results from robust least squares and GMM analysis indicated that renewable energy use, urbanisation, and trade negatively impacted environmental quality, while technological innovation emerged as a significant factor for improvement.

Implications and recommendations: The findings suggest that while renewable energy use and urbanisation contribute negatively to environmental quality, technological innovation can help mitigate these adverse effects. Policymakers should focus on creating favourable legislation that promotes the adoption of green technologies and renewable energy sources. Encouraging further advancements in technological innovation in the green energy sector is crucial for achieving environmental sustainability in Pakistan.

Originality/Value: This study provides valuable insights into the role of renewable energy, technological innovation, urbanisation, and trade in shaping carbon emissions in Pakistan, using an innovative asymmetric modelling approach. The research contributed to the literature on environmental economics by emphasising the importance of technology and energy consumption in the fight against global warming.

Keywords: CO_2 emissions, technological innovation, energy use, trade, environmental sustainability

1. Introduction

Technological innovation is essential for reducing emissions and enhancing energy efficiency. Moreover, technological advancement is crucial for optimising the use of traditional and sustainable energy sources. Innovations in energy conversion technologies also significantly boost the development of other renewable energy sources. This technological development in the energy industry augments the efficacy of renewable energy sources, hence amplifying the potential supply of clean energy to meet future energy requirements. Given the increasing need for energy, it is unavoidable that renewable energy will become the primary energy source for future generations. Furthermore, it offers a means for more sustainable energy production with less environmental and ecological impact (Adebayo et al., 2021; Sun et al., 2022). The integration of renewable energy sources is a powerful tool in the quest for energy diversity, whilst decreasing reliance on fossil fuel energy signifies greater resilience against fossil fuel energy. The costs associated with the implementation of renewable energy are a major obstacle. Unlike the costs associated with fossil fuel-based energy, other financial challenges must be addressed, including the need for improved infrastructure, higher operating expenses, and initial start-up costs. The financial sector is crucial in operating the economic system by generating capital and facilitating transparent transactions and capital management. An integrated monetary framework is essential for facilitating the smooth movement of investments and enhancing the operational efficiency of enterprises, thereby fostering economic development (Ali et al., 2022; Qayyum et al., 2021; Mawardi et al., 2024).

Global developed and developing economies are facing challenges caused by global warming, mostly as a result of the inadequate control of GHG emissions in the atmosphere. The extensive usage of fossil fuels is the main culprit in GHG emissions and environmental degradation, hence it is essential to augment the proportion of renewable energy in the overall energy supply to effectively mitigate these emissions, particularly carbon dioxide. Based on previous research by Ahmed N. et al. (2022) and Shu et al. (2023), it is believed that government funding for renewable energy is essential to boost innovations in technology needed to greatly increase the production and distribution of eco-friendly energy. Energy has had a significant impact on national economic and political agendas, as well as on bilateral ties and the establishment of legal regulations, ever since it became an indispensable aspect of human existence. Countries possessing energy resources have formulated and executed various energy policies. Conversely, several countries with restricted options for energy sources have successfully established new positions in the energy sector and have had significant influence in shaping global policy, thereby avoiding marginalisation from the international community (He et al., 2019; Li & Solaymani, 2021). Environmental indicators, such as changes in weather patterns and increasing temperatures, provide clear evidence of the on-going degradation of the global ecosystem. To address these environmental issues and secure a sustainable future, global leaders, including lawmakers and authorities are collaborating to discover inventive alternatives. Economists and environmentalists have reached a consensus that the escalation of investment between developed and underdeveloped countries, especially in recent decades, has heightened global climate issues (Ahmed Z. et al., 2022; Aydin et al., 2023).

A crucial existential dilemma that the world now confronts is the task of reducing atmospheric carbon dioxide levels and mitigating other consequential effects of global warming, all while preserving economic development. The escalating human influence on Earth, driven by the pursuit of economic development, has resulted in the expansion of the overall land and water area necessary for ecosystems to provide sufficient resources and process waste (IPCC, 2018). The ecosystem can use renewable energy and recycle it perpetually. These energy sources are considered the most important due to their plentiful and environmentally friendly attributes. Furthermore, expansion in renewable energy generation is a method to sustain and support economic growth. Regarding renewable energy and modern technologies, clean energy policies should be seen not just as a defensive measure but as a means to address the increasing demands of communities, including enhancing energy generation and mitigating the effects of global fossil fuel usage.

Renewable energy primarily contributes to addressing social and environmental benefits, such as enhancing educational and job prospects, as well as eliminating poverty and gender discrimination (Ceglia et al., 2022). Utilising renewable energy sources has the promise of being more effective in mitigating pollution and the release of carbon dioxide compared to the use of fossil fuels that are not sustainable. Consequently, it mitigates the impact of global warming and other types of environmental degradation. However, urbanization also has a significant impact on carbon emissions. Urban areas are the primary sources of greenhouse gas emissions, but they also play a key role in mitigating CO_2 emissions. Urbanisation fosters economic growth, facilitates energy use, and contributes to CO_2 emissions (Guo et al., 2018). The primary drivers behind the rise in the usage of energy and the release of carbon emissions are urbanisation and the restructuring of industry (Yu et al., 2018). Although Pakistan is implementing substantial initiatives to meet its energy demands while concurrently striving to diminish greenhouse gas emissions, the government is actively seeking substantial investments in renewable energy to fulfil its clean energy goals. In this context, it has executed multiple initiatives, encompassing strategic planning and adaptive measures, in order to address the requirements of both current and future generations, thus adopting a holistic approach to alleviate the detrimental impacts of climate change. Moreover, it is essential for developed economies to recognise their obligations by adopting environmentally sustainable production methods, fostering green growth, and dedicating resources to offset climate-related damages experienced by developing countries (GOP, 2024). Pakistan has made significant advancements in technology and the development of the Internet to propel itself into a new era of digital dominance, and is adopting connectivity and innovation through various initiatives. It is strategically positioned to emerge as a significant contender in the global digital landscape due to investments in infrastructure and the cultivation of an ecosystem that fosters innovation and growth. A new epoch of digital transformation is emerging in the nation, presenting exhilarating opportunities for progress, development, and prosperity. Technological advancements and heightened internet usage have generated new prospects for business expansion, employment, and economic enhancement (GOP, 2023).

This research examined the correlation between technological innovation, urbanisation, and carbon emissions, which are crucial elements in attaining sustainable growth and establishing a low-carbon economy. The trend of globalisation has expedited the urbanisation process, resulting in a significant influence on carbon emissions. Conversely, the growth of economic development has resulted in more energy use, benefiting residents' living standards but also causing environmental degradation. Hence, the adoption of green growth is crucial in order to mitigate environmental degradation concerns, including specific hazards such as agricultural output, climate change, rising sea levels, water scarcity, and volatile weather patterns. Consequently, the significance and technological advancement of renewable energy have grown in recent years. Earlier academic studies in this domain mostly concentrated on examining the complex correlation between clean energy, progress in technology, and environmental quality. However, the researchers often used combined data from many economies, revealing notable differences within the analysed clusters and a higher likelihood of intricate relationships among these categories and their respective economies. To address this challenge, this study employed innovative methods to evaluate the interaction between the variables. The significance of understanding the difference between international energy policy and unforeseen occurrences rests in the fact that both forces simultaneously impact the national economy. This research is the pioneer in exploring the interaction of green energy, urbanisation, technological progress, and trading on carbon emissions in Pakistan, as well as the intricate connections between these factors, and makes a distinctive contribution to the existing literature. The authors employed the Nonlinear Autoregressive Distributed Lag (NARDL) framework to comprehensively scrutinise the connection between green energy, urbanisation, technological innovation, trade, and carbonisation. This analysis also utilised the RLS technique and GMM to check the robustness of the series. By prioritising the primary causes associated with carbon emissions, researchers expected gaining a more thorough knowledge of the specific activities required for successfully reducing CO_2 levels.

2. Comprehensive literature review

Global economic and environmental forums have acknowledged the risk of environmental degradation to sustainable consumption and production (Arora & Mishra, 2023). Policymakers widely agree that the adverse impacts of carbon dioxide emissions have been aggravated by the widespread adoption and use of carbon-intensive technologies. Several countries have responded by enacting strict laws and aggressively promoting the development of eco-friendly technology by both private and public organizations (Alhorr et al., 2014; Panicker, 2024).

Reliance on fossil fuels undeniably exposes humanity to the risk of energy shortages and increased threats to human well-being due to environmental challenges, whilst renewable energy is globally recognised as a viable alternative energy choice. Renewable energy production is a crucial factor for enhancing environmental quality, alongside demand management and energy efficiency. The rapid growth of urbanisation and population presents a significant concern over the growing need for energy, thus the only solution to tackle the existing environmental risks is to enhance energy output. Alternative energy sources support sustainable growth by facilitating the alignment of economic and environmental objectives (Safi et al., 2021; Hye et al., 2023; Imran et al., 2024). Implementing environmental improvement policies and adopting sustainable energy sources are crucial for enhancing the overall environmental condition. Energy from renewable sources is essential for mitigating carbon dioxide emissions, advancing sustainability, and decreasing reliance on other economies, therefore the use of sustainable energy sources is vital in tackling concerns about energy stability and ecological deterioration. Green energy is crucial for fulfilling energy requirements and can enhance current energy systems, rectify market disparities, and alleviate environmental damage. Environmental consequences indicate that the extensive use of renewable energy is now a vital component in the global shift towards a civilisation characterised by decreased carbon emissions. The transition from fossil fuels to alternative energy sources may mitigate existing and future energy disparities while facilitating decarbonisation, improving energy security, and promoting economic development (Vural, 2020; Saleem et al., 2022; Diallo, 2024).

In the past decade, developing countries have seen remarkable expansion and have become a dominant force in the context of the global economy. Rising living standards, less poverty, and upgraded infrastructure are all hallmarks of a flourishing economy. Nevertheless, the process of growth has intrinsic repercussions, particularly when nations persistently choose artificial extravagance over the preservation of the natural environment. Research by Raza et al. (2023) showed that technological progress and the expansion of alternative power sources significantly reduce the environmental impact. Growth in the economy, foreign investment, and urbanisation all have a major impact on the ecological footprint. Nonetheless, poor institutional quality has a negative effect on the connection between technological innovation, renewable energy, and ecological impact. Jiang et al. (2023) also studied environmental sustainability from a particular angle, highlighting the significance of building a knowledge-based economy as a means to a green economy. The existing literature proves that the information sector's dedication to R&D and its role in guaranteeing sustainable growth are important factors. In addition, the research results show that funding conservation and efficiency programmes may help reduce carbon emissions. Carbon emissions are inversely related to factors including reducing political risks, encouraging environmentally friendly innovation, promoting the use of renewable energy, and making exports easier. Salman et al. (2019) found that income and imports had a negative impact on consumption-dependent carbon emissions, whereas according to Mpeqa et al. (2023), carbon emissions are negatively affected by trade in goods. Furthermore, it has been shown that energy use and population density contribute to increased carbon emissions. However, the innovative use of ecologically beneficial energy sources significantly impacts the release of carbon emissions into the atmosphere. Moreover, enhancing energy efficiency through modern technologies further helps reduce carbon emissions.

As a result of the pressing need to fight global warming and decrease dependence on fossil fuels, major shifts are occurring in the world's energy environment. The role of the economic system in driving this transition has been significant, particularly as the adoption of renewable energy and sustainable technology has grown in recent times. With a focus on the influence of financial markets, it seeks to chart investment trends and future possibilities for clean technology and green energy. Renewable energy investment has led to a substantial upsurge in recent years due to the combination of declining prices, supportive policies, and rising interest from investors (Li, 2023; Sun et al., 2023; Liu et al., 2023). However, there is a general consensus that using technological breakthroughs is a key way to improve energy efficiency, thereby helping to lower energy consumption including entire consumption as well as dependency on fossil fuels. In light of apprehensions regarding environmental deterioration and the scarcity of energy resources, economies world-wide are progressively embracing technological advancements that prioritise ecological sustainability and energy efficiency. The rise of eco-innovation can be ascribed to significant spending in research and development endeavour. This transition has facilitated the economic shift from reliance on fossil fuel energy to more environmentally friendly and long-term power sources. Thus, advancements in technology, particularly in the realm of eco-innovation, have emerged as a driving force in fostering sustainable economic expansion (Li & Ullah, 2022; Alvarez-Herranz et al., 2017; Borgi et al., 2024).

It is important to move resources from fossil fuels to other energy sources in order to achieve long-term economic growth. Businesses and individuals are becoming more interested in using green energy sources because of the unstable changes in oil costs and the need to buy more energy. Dependence on environmental innovation will serve as a means to overcome the current renewable energy problem. Renewable energy is a highly desirable substitute for mitigating pollution, ensuring energy security, and fostering sustainable economic development. Due to their reliance on natural resources, developing countries benefit from job creation through environmental innovation initiatives (Huang et al., 2022; Can & Ahmed, 2023; Shan et al., 2021; Lu et al., 2024). Attaining sustainable economic growth has emerged as a crucial objective for numerous global economic powers. The significance of innovation has been receiving increasing focus in discussions concerning economic expansion and sustainable progress. Innovation in environmental technology may help solve the issue of economic growth causing significant harm to the environment (Hübler et al., 2012). Enhancing technological innovation has the potential to improve energy efficiency and facilitate the utilisation of clean energy sources, thereby contributing to increased production efficiency and the attainment of sustainability objectives. It is imperative to investigate the influence of technological progress on renewable energy within this specific context as such research is essential for assessing the impact of technological advancements and renewable energy sources on greenhouse gas emissions. The primary aim is to ascertain whether the innovation and green energy initiatives of the selected economies have succeeded in reducing carbon emissions to the anticipated levels, thereby enhancing environmental quality. Key objectives include minimising carbon emissions and fostering economic growth. In some economies the emergence of innovation may represent a viable strategy for achieving these objectives (Jiang & Khan, 2023; Adebayo et al., 2023; Wang et al., 2020; Nguyen & Le, 2024).

The extensive use of ecologically detrimental industrial manufacturing technology and fossil energy sources intensifies environmental deterioration. These activities emit carbon dioxide into the atmosphere, which contributes to the greenhouse effect and pollution. To ensure a positive future for generations to come, it is essential to evaluate and reorganise worldwide development thoroughly. This should include a significant shift towards green technology and a focus on intense consumption rather than widespread consumption. Furthermore, the issue of air pollution is a critical concern regarding the negative consequences on ecosystems caused by human actions. In order to effectively decrease greenhouse gas emissions, it is necessary to implement existing low-emission technologies and encourage the development of new technologies through innovation. Consequently, there has been a growing emphasis on strategies to encourage innovation, specifically on the involvement of governments in this endeavour. However, this study focused on examining how renewable energy consumption, urbanisation, technological progress, and trade impact environmental quality in Pakistan. Based on the analysis, the authors formulated the following hypotheses:

H1: Renewable energy is considered to have a negative effect on environmental quality.
H2: It is considered that urbanisation has a detrimental influence on the environment.
H3: Technological innovation is expected to significantly lower CO_2 emissions and enhance environmental quality.

3. Methodology and data

This research employed the NARDL technique to examine the connection among the parameters using yearly time series data obtained from the primary source, WDI (https://data.worldbank.org/country/pakistan). The paper provides an extensive overview of the variables employed, including CO_2 emissions (kt), renewable energy consumption (% of total final energy consumption), urbanisation (% of total population), technological innovation (patent applications of residents and non-residents), and trade (% of GDP). These variables were analysed in the context of Pakistan, using data from 1990 to 2020. The time series trend of all variables is shown in Figure 1, indicating both increasing and adverse patterns for carbon emissions, renewable energy consumption, technological innovation, urbanisation, and trade, respectively.

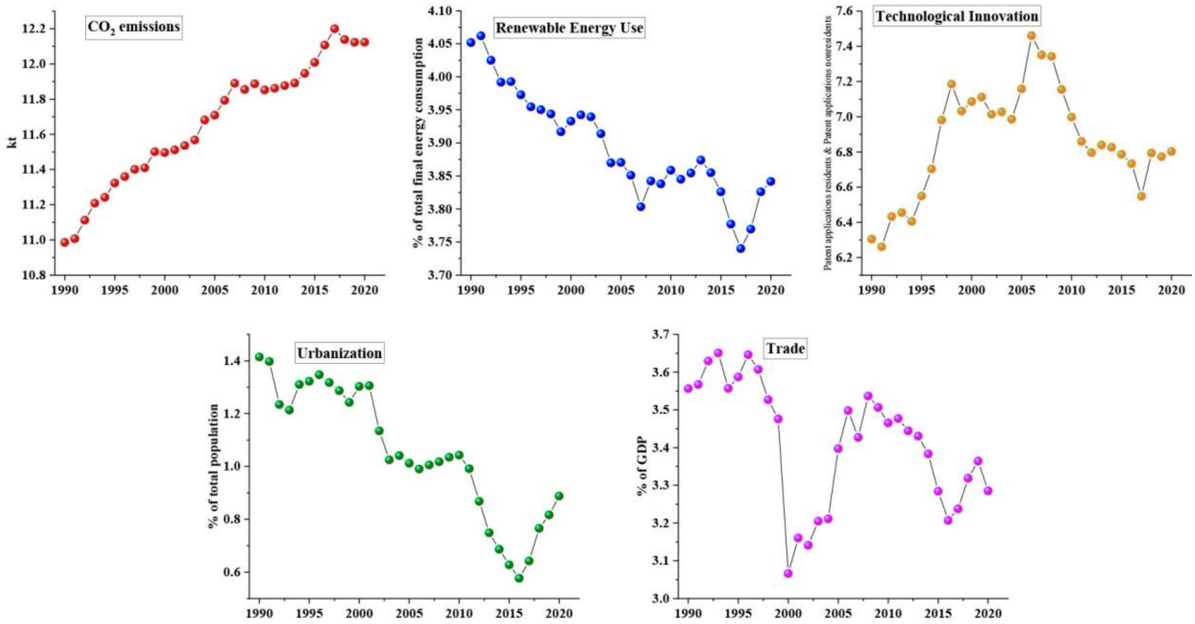

Fig. 1. Annual time series patterns of the studied variables

Source: authors' own work.

Figure 2 illustrates the framework of the econometric approach used for the variables to uncover the nexus. Firstly, this study conducted basic statistical analyses, such as descriptive analysis and a correlation matrix, to determine if the variables are associated and then employed other econometric techniques.

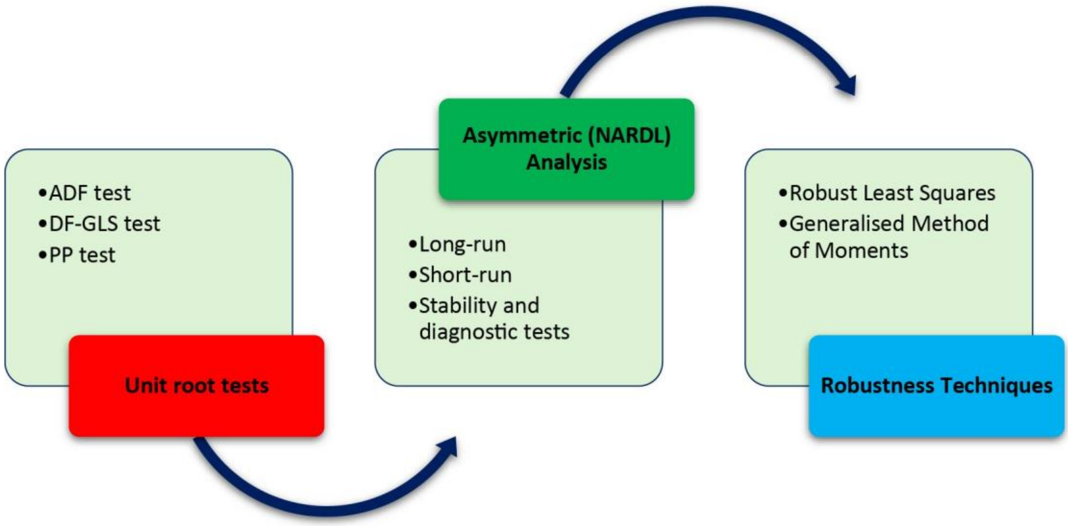

Fig. 2. Methodological framework of the study

Source: authors' own work.

3.1. Model specification

Numerous research studies have been carried out using different methodologies to comprehend the association between different variables. Murad et al. (2019) examined the interaction between energy use, pricing, innovation in technology, and economic growth in Denmark using time series data. The interrelationships between these variables were investigated using the ARDL approach. Using wavelet statistical techniques, Adebayo & Kirikkaleli (2021) provided fresh insights into the relationships between technological advancement, renewable energy, economic growth, globalisation, and CO_2 emissions in

Japan. Additionally, Acheampong et al. (2022) examined the effects of transportation infrastructure and technological innovation on economic growth, energy consumption, and carbon emissions in the EU using annual time series data and the dynamic approach of the system of generalised method of moments. Wang et al. (2023) used advanced panel econometric tests in their research, including the augmented mean group (AMG) and the common correlated effects mean group (CCEMG) estimator. Their goal was to investigate how changes in technology, financial development, renewable and non-renewable energy sources, and foreign investment affected the ecological footprints of rising EU countries. Using the GMM panel framework, Ganda (2024) looked at energy consumption, technological innovation, financial growth, rents from natural resources, and the interaction between these factors in the BRICS countries. The investigation also discovered a substantial inverse association between technological innovation and natural resource availability, as well as a negative correlation between financial development and the availability of natural resources. This study challenges the general assumption that natural resources hinder economic progress, asserting that the opposite is evident. An asymmetric (NARDL) strategy that integrates robust least squares and GMM methodologies was used to analyse the relationship between renewable energy, technological innovation, urbanisation, and trade. The authors examined an annual dataset and observed an expanding economy in Pakistan, hence a model could be constructed to analyse the interconnections among the variables.

$$\text{Carbon Emission}_t = f\begin{pmatrix}\text{Renewable Energy Consumption}_t,\ \ldots \\ \text{Technological Innovation}_t, \text{Urbanization}_t, \text{Trade}_t\end{pmatrix}. \quad (1)$$

The equation (1) could be further expanded in the following manner:

$$\text{CE}_t = f(\text{RE}_t, \text{TI}_t, \text{UR}_t, \text{TR}_t). \quad (2)$$

The variables in equation (1) were elucidated as follows: CE denotes the CO_2 emissions, RE signifies the utilisation of renewable energy, UR represents the process of urbanisation, and TR indicates the extent of trade. Furthermore, the Greek-letter notation used for regression coefficients across the model equations is explained in Table 1. Thus the equation (2) can be expressed in the following form:

$$\text{LCE}_t = \tau_0 + \tau_1\text{LRE}_t + \tau_2\text{LTI}_t + \tau_3\text{LUR}_t + \tau_4\text{LTR}_t + \varepsilon_t, \quad (3)$$

where LCE_t represents the logarithmic form of CO_2 emissions released during time period t, LRE_t characterises the logarithm of renewable energy use in relation to time t, LUR_t denotes the logarithm of urbanisation during time t, and LTR_t signifies the logarithm of trade in relation to time t. In the equation, τ_0 represents the constant, whereas τ_1, τ_2, τ_3, and τ_4 are the coefficients, where ε_t determines the error term.

Table 1. Greek letter families for regression coefficients across the model equations

Symbol family	Equation	Role
$\tau_0, \tau_1 - \tau_4$	(3)	Level and log-linear OLS
$\xi_1 - \xi_5, \alpha_0 - \alpha_4$	(4)	ARDL ECM (short-run, long-run)
$\beta_1 - \beta_5, \lambda_0$	(5)	ARDL ECM with explicit ECT
$\varphi_1 - \varphi_9, \varsigma_0 - \varsigma_8, \gamma_0$	(8), (9)	NARDL (short-run, long-run, ECT)
$\delta_0 - \delta_4$	(10)	GMM

Source: authors' own work.

3.2. Asymmetric model specification

The study applied an asymmetrical technique known as the NARDL (Nonlinear Autoregressive Distributed Lag) model, which is an extension of the symmetric Autoregressive Distributed Lag (ARDL) model proposed by Pesaran et al. (2001). To capture both the short and long-term impacts of the study, first the ARDL approach coupled with the error correction term was demonstrated, thus the error correction form of the autoregressive distributed lag technique was:

$$\Delta CE_t = \xi_0 + \sum_{j=1}^{p_1} \xi_{1j}\, \Delta CE_{t-j} + \sum_{j=0}^{p_2} \xi_{2j}\, \Delta RE_{t-j} + \sum_{j=0}^{p_3} \xi_{3j}\, \Delta TI_{t-j} + \cdots$$
$$+ \sum_{j=0}^{p_4} \xi_{4j}\, \Delta UR_{t-j} + \sum_{j=0}^{p_5} \xi_{5j}\, \Delta TR_{t-j} + \alpha_0 CE_{t-1} + \alpha_1 RE_{t-1} + \cdots$$
$$+\alpha_2 TI_{t-1} + \alpha_3 UR_{t-1} + \alpha_4 TR_{t-1} + \varepsilon_t. \quad (4)$$

Where "p" denotes the lag order. The equation (4) can be written in terms of error correction as:

$$\Delta CE_t = \beta_0 + \sum_{j=1}^{p_1} \beta_{1j}\, \Delta CE_{t-j} + \sum_{j=0}^{p_2} \beta_{2j}\, \Delta RE_{t-j} + \sum_{j=0}^{p_3} \beta_{3j}\, \Delta TI_{t-j} + \cdots$$
$$+ \sum_{j=0}^{p_4} \beta_{4j}\, \Delta UR_{t-j} + \sum_{j=0}^{p_5} \beta_{5j}\, \Delta TR_{t-j} + \lambda_0 ECT_{t-1} + \varepsilon_t. \quad (5)$$

In equations (4) and (5), the symbols $\xi_1 - \xi_5$ and $\beta_1 - \beta_5$ represent the coefficients for the short term, while $\alpha_0 - \alpha_4$ represent the coefficients for the long term, namely the residual term. To verify the long-term presence of cointegration in equation (5) using F-test results, the NARDL approach challenges the usual assumption in cointegration analysis that all variables in the model should have the same degree of integration. According to Pesaran et al. (2001), the F-test can be employed to verify the precision of long-term forecasts and the distinct impacts of these forecasts on the stated parameters. After confirming cointegration, long-run elasticities were recovered by normalising the long-run level coefficients $\alpha_1, \ldots, \alpha_4$ by $-\hat{\alpha}_0$. The outcomes of Shin et al. (2014) differed from the impacts seen in renewable energy consumption, technological innovation, urbanisation, and trade. These effects may be described by the breakdown of positive and negative factors ($\mathrm{RE^+}_t; \mathrm{TI^+}_t; \mathrm{UR^+}_t; \mathrm{TR^+}_t$) shown below.

$$\mathrm{RE^+}_t = \sum_{j=1}^{t} \max\,(\Delta \mathrm{RE}_j,\ 0);$$
$$\mathrm{TI^+}_t = \sum_{j=1}^{t} \max\,(\Delta \mathrm{TI}_j,\ 0);$$
$$\mathrm{UR^+}_t = \sum_{j=1}^{t} \max\,(\Delta \mathrm{UR}_j,\ 0);$$
$$\mathrm{TR^+}_t = \textstyle\sum_{j=1}^{t} \max\,(\Delta \mathrm{TR}_j,\ 0). \quad (6)$$

The selected variables ($\mathrm{RE^-}_t; \mathrm{TI^-}_t; \mathrm{UR^-}_t; \mathrm{TR^-}_t$) were decomposed for negative shocks.

$$\mathrm{RE^-}_t = \sum_{j=1}^{t} \min\,(\Delta \mathrm{RE}_j,\ 0);$$
$$\mathrm{TI^-}_t = \sum_{j=1}^{t} \min\,(\Delta \mathrm{TI}_j,\ 0);$$
$$\mathrm{UR^-}_t = \sum_{j=1}^{t} \min\,(\Delta \mathrm{UR}_j,\ 0);$$
$$\mathrm{TR^-}_t = \sum_{j=1}^{t} \min\,(\Delta \mathrm{TR}_j,\ 0). \quad (7)$$

Equations (6) and (7) outline the impact of renewable energy use, technological innovation, urbanisation, and trade, both positive and negative. The model's asymmetrical appearance can be described in the following manner:

$$\Delta CE_t = \varphi_0 + \sum_{j=1}^{p_1} \varphi_{1j}\, \Delta CE_{t-j} + \sum_{j=0}^{p_2} \varphi_{2j}\, \Delta RE_{t-j}^{+} + \sum_{j=0}^{p_3} \varphi_{3j}\, \Delta RE_{t-j}^{-} + \sum_{j=0}^{p_4} \varphi_{4j}\, \Delta TI_{t-j}^{+} + \cdots$$
$$+ \sum_{j=0}^{p_5} \varphi_{5j}\, \Delta TI_{t-j}^{-} + \sum_{j=0}^{p_6} \varphi_{6j}\, \Delta UR_{t-j}^{+} + \sum_{j=0}^{p_7} \varphi_{7j}\, \Delta UR_{t-j}^{-} + \sum_{j=0}^{p_8} \varphi_{8j}\, \Delta TR_{t-j}^{+} + \cdots$$
$$+ \sum_{j=0}^{p_9} \varphi_{9j}\, \Delta TR_{t-j}^{-} + \varsigma_0 CE_{t-1} + \varsigma_1 RE_{t-1}^{+} + \varsigma_2 RE_{t-1}^{-} + \varsigma_3 TI_{t-1}^{+} + \varsigma_4 TI_{t-1}^{-} + \cdots$$
$$+\varsigma_5 UR_{t-1}^{+} + \varsigma_6 UR_{t-1}^{-} + \varsigma_7 TR_{t-1}^{+} + \varsigma_8 TR_{t-1}^{-} + \varepsilon_t. \quad (8)$$

In order to illustrate the process of error-correction term (ECT) exploration, one can utilise the following assumptions:

$$\Delta CE_t = \varphi_0 + \sum_{j=1}^{p_1} \varphi_{1j}\, \Delta CE_{t-j} + \sum_{j=0}^{p_2} \varphi_{2j}\, \Delta RE_{t-j}^{+} + \sum_{j=0}^{p_3} \varphi_{3j}\, \Delta RE_{t-j}^{-} + \sum_{j=0}^{p_4} \varphi_{4j}\, \Delta TI_{t-j}^{+} + \cdots$$
$$+ \sum_{j=0}^{p_5} \varphi_{5j}\, \Delta TI_{t-j}^{-} + \sum_{j=0}^{p_6} \varphi_{6j}\, \Delta UR_{t-j}^{+} + \sum_{j=0}^{p_7} \varphi_{7j}\, \Delta UR_{t-j}^{-} + \sum_{j=0}^{p_8} \varphi_{8j}\, \Delta TR_{t-j}^{+} + \cdots$$
$$+ \sum_{j=0}^{p_9} \varphi_{9j}\, \Delta TR_{t-j}^{-} + \gamma_0 ECT_{t-1} + \varepsilon_t. \quad (9)$$

Equation (9) is an error correction representation for the corresponding variables included in the investigation.

3.3. GMM technique

In addition, the GMM method was used to investigate the interaction that exists between components such as CO_2 emissions and other independent variables. Considerations regarding endogeneity and correlation in the model could be addressed by the use of the GMM technique, which ultimately results in the following formulation for the estimated model:

$$LCE_t = \delta_0 LCE_{t-1} + \delta_1 LRE_t + \delta_2 LTI_t + \delta_3 LUR_t + \delta_4 LTR_t + \varepsilon_t. \quad (10)$$

Equation (10) is the demonstration of the GMM model with the interaction of variables.

4. Results and discussion

First, the authors performed an analysis of the descriptive characteristics of the dataset before beginning the formal empirical investigation. The descriptive statistics and the correlation analysis are shown below in Tables 2 and 3, respectively. An example of a statistical measure that may be used to illustrate the central tendency of a dataset is the mean value. The standard deviation is a calculation that determines how far off the data are from the mean value. It is possible to determine the degree to which the data is spread by looking at the range of values. According to the research findings regarding the average and variability of the data, the dataset did not include any values considered to be extraordinary. There are two statistical metrics known as skewness and kurtosis utilised to estimate the degree to which a dataset deviates from a normal distribution. The values of skewness and kurtosis for data that is distributed properly are 0 and 3, respectively. As an additional point of interest, the Jarque-Bera test is a formal approach used to evaluate the normality of a distribution. The JB test is used to assess the null hypothesis to ascertain whether a series adheres to a normal distribution. All the variables in the JB statistics had probability values greater than 0.05, resulting in the acceptance of the null hypothesis.

Table 2. Descriptive analysis

	CE	*RE*	*TI*	*UR*	*TR*
Mean	11.664	3.894	6.863	1.051	3.414
Median	11.708	3.870	6.839	1.034	3.444
Max	12.199	4.061	7.460	1.414	3.650
Mini	10.985	3.740	6.261	0.576	3.066
SD	0.350	0.081	0.307	0.248	0.164
Skew	-0.304	0.269	-0.160	-0.319	-0.416
Kurt.	2.044	2.386	2.405	1.984	2.085
J-Bera	1.657	0.863	0.588	1.859	1.974
Prob	0.436	0.649	0.744	0.394	0.372

Source: authors' own work.

Furthermore, the findings presented in Table 3 provide evidence of an association among the variables (*CE*, *RE*, *TI*, *UR*, and *TR*) under consideration, indicating that each variable was correlated with the others.

Table 3. Variables correlation

	CE	*RE*	*TI*	*UR*	*TR*
CE	1.000	-0.971	0.399	-0.897	-0.482
RE	-0.971	1.000	-0.452	0.862	0.453
TI	0.399	-0.452	1.000	-0.142	-0.287
UR	-0.897	0.862	-0.142	1.000	0.433
TR	-0.482	0.453	-0.287	0.433	1.000

Source: authors' own work.

4.1. Unit root testing

The study looked at the possibility of both the long and short-term interactions between the pertinent factors by first examining the sequence in which they were integrated. Table 4 presents and interprets the findings of the unit root investigation. Several tests were carried out both at the level and the first difference to determine whether stationarity was present. For the ADF (Dickey & Fuller, 1979), DF-GLS (Elliott et al., 1996), and PP (Phillips & Perron, 1988) tests, under the null hypothesis, it was presumed that the series did not exhibit stationary characteristics. None of the variables exhibited stationarity, rendering the outcomes of the unit root tests inconclusive, even after undergoing two differentiations. Various orders of integration could be allocated to the variables, signifying that certain variables exhibit stability upon a single differentiation, while others remain stationary at their original level of specification.

Table 4. Unit root testing

Variables	ADF Test		DF-GLS Test		PP Test	
	I(0)	I(1)	I(0)	I(1)	I(0)	I(1)
CE (T-stat & Prob.)	-1.952 (0.305)	-4.563*** (0.000)	-1.952 (0.856)	-4.527*** (0.000)	-1.931 (0.313)	-4.563*** (0.001)
RE (T-stat & Prob.)	-1.905 (0.325)	-4.192*** (0.000)	-0.917 (0.366)	-4.021*** (0.000)	-1.972 (0.296)	-4.192*** (0.000)
TI (T-stat & Prob.)	-1.960 (0.301)	-4.405*** (0.001)	-1.318 (0.197)	-4.411*** (0.000)	-1.988 (0.290)	-4.405*** (0.000)
UR (T-stat & Prob.)	-1.698 (0.421)	-4.527*** (0.001)	-1.424 (0.167)	-2.511** (0.019)	-1.398 (0.569)	-3.163*** (0.003)
TR (T-stat & Prob.)	-1.755 (0.394)	-5.198*** (0.000)	-1.644 (0.110)	-5.295*** (0.000)	-1.880 (0.336)	-5.198*** (0.000)

Note: *** *p<1%*, ** *p<5%.*

Source: authors' own work.

4.2. Bounds testing to validate the cointegration

The findings of the bounds testing approach used to determine whether a cointegration link exists are shown in Table 5. According to the F-test result of 21.342, the significant thresholds of 1%, 2.5%, 5%, and 10% were exceeded, which indicates that the thresholds were surpassed. In this instance, one may conclude that the model's variables were interdependent over the long run and thus reject the null hypothesis claiming no cointegration. In the process of bounds testing, the asymmetric approach was used to check for cointegration. The component and equilibrium indicator were considered to be markers of a long-term connection.

Table 5. Findings of bounds test to cointegration

F-stat. value (21.342) K (4)	Signif.	I(0)	I(1)
	10%	2.2	3.09
	5%	2.56	3.49
	2.5%	2.88	3.87
	1%	3.29	4.37

Source: authors' own work.

Upon confirming the integrating series within the evaluation criteria, the interaction between the variables in this investigation was deemed to be of utmost importance. Through the use of a beginning immediate strategy, the key motive of this analysis was to demonstrate the link that exists between the subject variables under investigation. To suggest integration test variables, this strategy may be used in situations when the anticipated statistical significance is greater than the basic values shown below and above. Table 6 provides a comprehensive breakdown of the results obtained using Johansen's cointegration technique (Johansen & Juselius, 1990), which makes use of interference to ascertain the dependability of components.

Table 6. Cointegration technique

N-hyp.	Trace-stat.	C-values (0.05)	Prob. **	N-hyp.	M-Eigen stat.	C-values (0.05)	Prob. **
At r ≤ 0*	67.589	69.818	0.074	At r ≤ 0*	27.551	33.876	0.235
At r ≤ 1	40.037	47.856	0.221	At r ≤ 1	24.511	27.584	0.117
At r ≤ 2	15.5262	29.797	0.745	At r ≤ 2	11.179	21.131	0.629
At r ≤ 3	4.347	15.494	0.873	At r ≤ 3	3.913	14.264	0.868
At r ≤ 4	0.434	3.841	0.509	At r ≤ 4	0.434	3.841	0.509

Note: ** asterisks show the probability values of MacKinnon-Haug-Michelis (1999).

Source: authors' own work.

4.3. Outcomes of asymmetric technique

This study used the asymmetric approach to discover the nexus between variables, and the outcomes are presented in Table 7. According to the short-run analysis, there was a negative association between renewable energy consumption and environmental quality in Pakistan. The probability values for this correlation were (0.017) and (0.000), respectively, due to positive and negative shocks. Environmental quality was also negatively affected by fluctuating urbanisation, with probability values of (0.874) and (0.082) due to positive and negative shocks. Technological innovation had positive coefficients that revealed a positive correlation with environmental quality, with probability values of (0.040) and (0.617). Furthermore, the variable trade had both positive and negative coefficients, indicating a positive and negative relationship to environmental quality in Pakistan.

Table 7. Non-linear ARDL results

Short-run analysis				
Variable	Coefficient	Std. Error	t-Statistic	Prob.
C	9.284	1.486	6.244	0.000***
CE(-1)	-0.840	0.135	-6.220	0.000***
RE^+	-0.993	0.382	-2.598	0.017**
RE^-	-1.874	0.301	-6.209	0.000***
TI^+	0.082	0.037	2.189	0.040**
TI^-	0.026	0.051	0.508	0.617
UR^+	-0.022	0.143	-0.160	0.874
UR^-	-0.114	0.062	-1.831	0.082*
TR^+	0.025	0.068	0.373	0.712
TR^-	-0.037	0.042	-0.878	0.390
CointEq(-1)	-0.362	0.029	-12.439	0.000***
Long-run analysis				
RE^+	-1.181	0.424	-2.781	0.011**
RE^-	-2.229	0.303	-7.338	0.000***
TI^+	0.098	0.040	2.447	0.023**
TI^-	0.031	0.062	0.497	0.624
UR^+	-0.027	0.172	-0.158	0.875
UR^-	-0.136	0.081	-1.669	0.110
TR^+	0.030	0.079	0.382	0.706
TR^-	-0.044	0.049	-0.906	0.375
C	11.045	0.015	692.086	0.000***
R^2 (0.997)	Akaike IC (-4.622)			
Adj-R^2 (0.995)	SC (-4.155)			
F-stat. (801.665)*	DW stat. (1.938)			
Prob (F-statistic) (0.000)	HQC (-4.472)			

Note: *** *p*<1%, ** *p*<5%, * *p*<10%.

Source: authors' own work.

In contrast, long-run estimation outcomes demonstrated that renewable energy usage and the process of urbanisation had detrimental impacts on the environment. This impact was caused by both positive and negative shocks, with probability values of (0.011), (0.000), (0.875), and (0.110), respectively. Technological innovation had a significant impact on the environmental quality in Pakistan, as shown by probability values of (0.023) and (0.624) via both positive and negative shocks. Moreover, the variable trade had both beneficial and detrimental effects on environmental quality as a result of positive and negative disruptions. Urbanisation’s rapid progress has not only enhanced people’s quality of life but also sparked worldwide apprehension over environmental sustainability. The challenge of urban overconcentration or the excessive aggregation of metropolitan areas has become a primary focus in modern urban planning and the advancement of energy-efficient and environmentally sustainable infrastructure. Due to socioeconomic advancement and heightened productivity, along with rural labour transitions from agriculture to the industrial and service sectors in urban areas, a phenomenon is referred to as urbanisation. Moreover, this involves transforming underdeveloped urban areas into more developed areas. Urbanisation promotes the development of infrastructure, encourages industrial growth, improves transportation systems, and increases energy consumption in urban regions (Hashmi et al., 2021; Ouyang & Lin, 2017; Liang et al., 2019).

The constructed environment, encompassing the infrastructure and services essential for daily human activities, directly influences a country’s economic and social development. The construction industry has experienced a significant increase in CO_2 emissions due to urbanisation. By adopting and promoting environmentally sustainable technology, technological innovation elevates energy consumption and carbon emissions. Emerging technologies possess the capacity to enhance environmental standards, while reducing carbon dioxide emissions. Reduced pollution levels and enhanced environmental sustainability are further results of technological progress and the implementation of environmental regulations in countries accommodating businesses (Jin et al., 2017; Zheng et al., 2023). Enhancing green total factor productivity is a crucial factor in fostering high-quality economic growth. Technological innovation is necessary to tackle the impacts of climate change, and serves as the primary catalyst for reducing carbon emissions, offering a significant opportunity for governments worldwide to make substantial progress in carbon emission reduction. Green development, driven by innovation, has emerged as a vital factor in accomplishing industrial transformation and upgrading, as well as enhancing quality and efficiency in the modern day. Green technology innovation, which focuses on the environment, is a highly effective kind of technology that has a greater beneficial influence on the environment compared to regular technology innovation. Reducing the consequences of global warming is a vital function it performs, since it not only promotes sustainable economic development but also significantly decreases carbon dioxide emissions (Jin et al., 2017; Wang et al., 2021; Zhao et al., 2022).

The statistical values for R^2, Adj-R^2, Akaike IC, and DW statistics are (0.997), (0.995), (-4.622), and (1.938), respectively. The stability test outcomes are presented in Table 8, showing that the F-statistical value of the Breusch-Godfrey serial correlation LM test was (0.084), with a p-value of (0.918). The Harvey's heteroskedasticity test yielded an F-Stat value of (1.136), with a corresponding probability value of (0.383).

Table 8. Outcomes of the stability test

Techniques	F-stat.	Prob.
(BG serial correlation LM test)	0.084	0.918
(H-test: Harvey)	1.136	0.383

Source: authors' own work.

Figure 3 shows the multipliers of positive and negative shocks to renewable energy consumption, urbanisation, technical innovation, and trade by narrowing and extending the trend bars, whereas Figure 4 shows the stability testing of CUSUM and its squares at the five-percent threshold of significance.

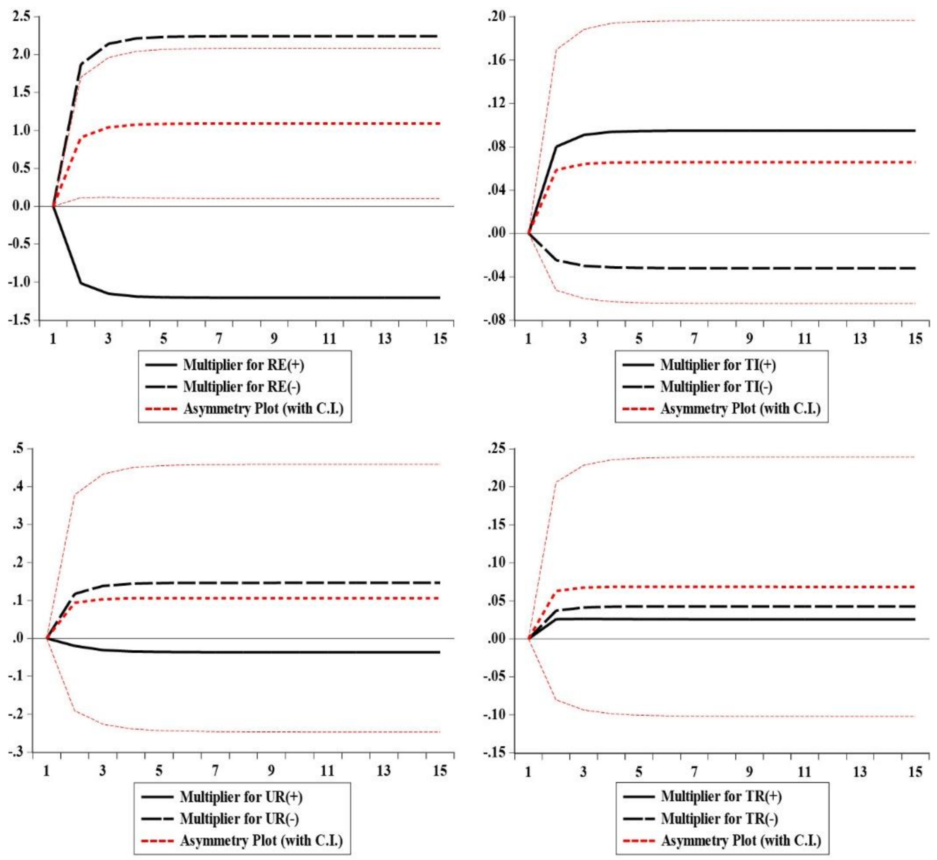

Fig. 3. Multiplier positive and negative shocks of RE, TI, UR and TR

Source: authors' own work.

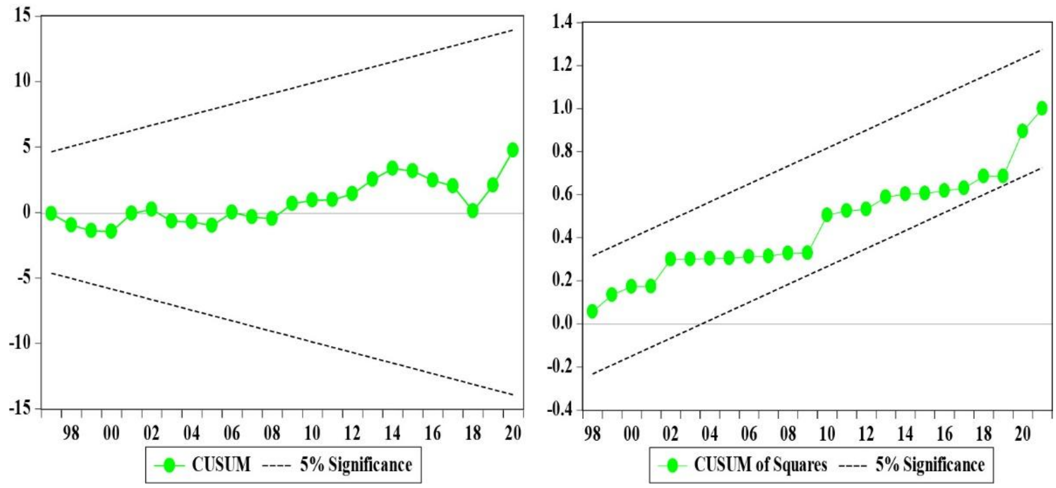

Fig. 4. Stability illustration at 5% significance

Source: authors' own work.

4.4. Robust least square and GMM techniques

This investigation used two robust procedures, namely RLS and GMM, to assess the robustness of the series. Tables 9 and 10 show the outcomes of this analysis. The results of the RLS indicate that renewable energy use, urbanisation, and trade had a detrimental impact on environmental quality, as shown by the coefficients of (-2.969), (-0.360), and (-0.042), and the corresponding probability values of (0.000), (0.001), and (0.585), respectively. Technological innovation during the analysis positively impacted environmental quality, as shown by a coefficient of (0.059) and a probability value of (0.234). The statistical values of R^2, A-R^2, Rw^2, and A-Rw^2 were (0.835), (0.810), (0.979), and (0.979), respectively.

Table 9. Robust Least Squares

Variable	Coeff.	SE	z-Stat.	Prob.
RE	-2.969	0.361	-8.205	0.000***
TI	0.059	0.050	1.188	0.234
UR	-0.360	0.109	-3.293	0.001***
TR	-0.042	0.078	-0.545	0.585
C	23.335	1.579	14.772	0.000***
R^2	0.835	*A-R²*		0.810
Rw^2	0.979	*A-Rw²*		0.979
AIC	38.744	*SC*		48.975

Note: RE, TI, UR and TR are log-transformed variables; *** $p<1\%$.

Source: authors' own work.

Table 10. Generalised Method of Moments

Variables	Coeff.	SE	t-Stat.	Prob.
RE	-3.130	0.361	-8.657	0.000***
TI	0.039	0.061	0.640	0.527
UR	-0.329	0.077	-4.255	0.000***
TR	-0.057	0.073	-0.781	0.441
C	24.118	1.830	13.176	0.000***
R^2	0.958	M-dep var		11.664
Adj-R²	0.951	SD-dep var		0.350
D-Watson stat.	0.610	J-stat		3.187

Note: *RE*, *TI*, *UR* and *TR* are log-transformed variables; *** $p<1\%$.

Source: authors' own work.

The GMM approach revealed that renewable energy, urbanisation, and trade had a negative influence on carbon emissions in Pakistan. The coefficients for renewable energy consumption, urbanisation, and trade were (-3.130), (-0.329), and (-0.057), respectively. The probability values for these coefficients were (0.000), (0.000), and (0.441). However, technological innovation in Pakistan showed a positive association with environmental quality, as indicated by the coefficient of (0.039) and a probability value of (0.527). The statistical values of R^2, Adj-R^2, M-dep var, SD-dep var, D-Watson stat, and J-stat were (0.958), (0.951), (11.664), (0.350), (0.610), and (3.187) respectively.

5. Conclusion and policy suggestions

The major objective of this analysis was to examine the interaction between utilisation of renewable energy, technological innovation, urbanisation, and trade on environmental quality in Pakistan using an Asymmetric (NARDL) technique. Additionally, two robust tests, RLS and GMM, were also employed to evaluate the resilience of the series. The outcomes indicated that the use of renewable energy and the stages of urbanization negatively affected environmental quality, as assessed by both short-term and long-term estimations using positive and negative shocks. During the analysis, technological innovation was found to positively impact environmental quality in Pakistan via positive and negative disruptions. The trade variable exhibited both significant and non-significant coefficients in relation to positive and negative disruptions, demonstrating a positive and negative impact on environmental quality. Moreover, the outcomes of the RLS and GMM analyses demonstrated that renewable energy consumption, urbanisation, and trade had a detrimental influence on environmental quality. In contrast, technological innovation had a positive effect on environmental quality. According to the results of the study, the renewable energy industry needs more supportive regulations as well as additional funds for research and development to meet environmental objectives.

The usual dependence on fossil fuels and resource exploitation complicates environmental conservation efforts. Pakistan and other developing countries can do more to protect the environment by enacting new legislation and encouraging renewable energy breakthroughs. Promoting economic diversification by investing in non-resource sectors may assist in minimising the economy's reliance on consumption. To promote the use of clean energy sources and lessen their reliance on fossil fuels, developing economies should concentrate on or gradually reduce subsidies for the fossil fuel industry in favour of sustainable development and green energy programs. Moreover, to prevent the environment from deteriorating further, investment must be made in technological advancements that aid in conservation and energy efficiency. To ensure trade agreements, the growing economy should aggressively seek sustainability and environmental quality requirements.

Implementation of legislation that makes it easier to build solid monetary structures and systems is critical for promoting the use of renewable energy sources. Governments must give priority to enhancing financial access, establishing specialised finance institutions, and providing supporting legal frameworks to encourage investments in renewable energy. In order to promote technological innovation, it is essential to incentivise the usage of energy-efficient equipment and practices which would effectively reduce energy consumption and hence decrease carbon emissions. The adverse effect of interaction terms on CO_2 emissions highlights the need for more financing and assistance toward research and development in clean energy technology. Green energy sources may be made more cost-effective and efficient by the allocation of funds towards innovation, thus enhancing their attractiveness and accessibility for widespread use.

5.1. Limitations and future directions

In the context of a developing economy, this study explored how variables such as green energy, urbanisation, technological innovation, and trade affect carbon emissions. This suggests that an analysis including areas or countries with different levels of development and institutional frameworks can provide insightful findings. Furthermore, additional research on the equitable distribution of the benefits of environmentally friendly energy is necessary, with a focus on protecting the most vulnerable communities. Promoting a fair and sustainable energy transition requires recognising and addressing the social and economic factors that limit affordability and accessibility.

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