frontiers | Frontiers in Energy Research

TYPE Original Research
PUBLISHED 11 November 2024
DOI 10.3389/fenrg.2024.1385170

OPEN ACCESS

EDITED BY
Mehmet Akif Destek,
University of Gaziantep, Türkiye

REVIEWED BY
Tunahan Degirmenci,
Sakarya University, Türkiye
Ahmed Ibrahim Osman,
Queen's University Belfast, United Kingdom

*CORRESPONDENCE
Muhammad Shakeel,
m.shakeel32@gmail.com,
muhammmad.shakeel@vu.edu.pk

RECEIVED 12 February 2024
ACCEPTED 21 October 2024
PUBLISHED 11 November 2024

CITATION
Shakeel M and Nobre C (2024) Do clean fuel and trade-openness reduce environmental degradation in China: evidence from asymmetric model.
Front. Energy Res. 12:1385170.
doi: 10.3389/fenrg.2024.1385170

Do clean fuel and trade-openness reduce environmental degradation in China: evidence from asymmetric model

Muhammad Shakeel[1]* and Catarina Nobre[2]

[1]Department of Economics, Virtual University of Pakistan, Lahore, Pakistan, [2]VALORIZA, Research Center for Endogenous Resource Valorization, Portalegre Polytechnic University, Campis Politécnico, Portalegre, Portugal

Introduction: This study investigates the relationship between economic growth, clean fuel utilization, trade, and environmental pollution. By focusing on the potential of clean fuels and trade in reducing pollution, this research aims to understand their role in promoting environmental sustainability in China from 1990 to 2020.

Methods: The study employs the Nonlinear Autoregressive Distributed Lags (NARDL) approach to analyze time series data. This method enables the decomposition of impacts from clean fuels and trade on pollution levels, facilitating an understanding of their distinct contributions to environmental outcomes.

Results: Findings indicate that economic growth is associated with an increase in pollution levels, while clean fuel usage exhibits a modest but significant reduction effect. Nonetheless, the relatively small coefficients highlight the need for a greater share of clean fuels in China's energy mix. Additionally, trade shows a significant negative relationship with pollution emissions, with data reflecting a gradual decline in pollution over time.

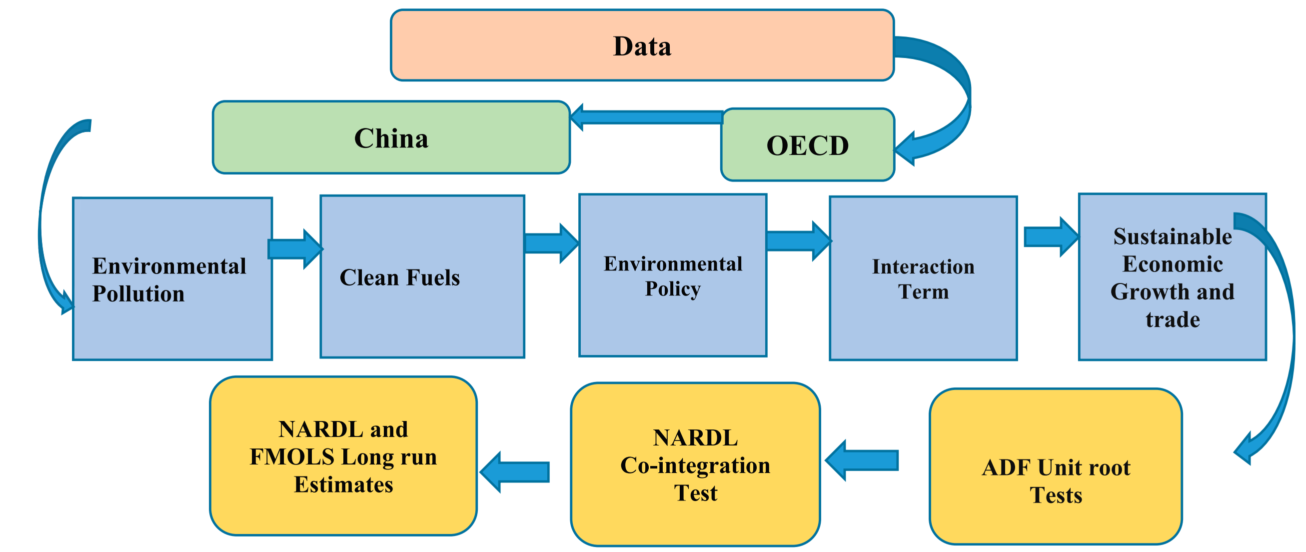
Discussion: These results underscore the benefits of clean fuel adoption and trade promotion as effective measures for mitigating pollution. However, they also highlight the necessity for stronger regulatory policies, public awareness initiatives, and investments in sustainable technologies to ensure China's long-term environmental sustainability.

KEYWORDS

clean fuels, trade openness, GDP, environmental degradation, nonlinear ARDL

1 Introduction

The Environmental Kuznets Curve (EKC) is a hypothetical idea that proposes that environmental degradation at the start rises with output growth; nonetheless, it will fall when a specific level of output has been reached. The EKC is similar to that of environmental degradation. The introduction of clean fuel is one of the ways to reduce environmental degradation and improve the air quality index. The use of clean fuels as an alternative



GRAPHICAL ABSTRACT

to traditional fuels has been suggested as a practical solution to reduce air pollution and greenhouse gas emissions.

Clean energy reduces environmental degradation and improves air quality by minimizing the harmful emissions produced by traditional fossil fuels. Sources like solar, wind, and hydropower generate electricity without releasing pollutants such as carbon dioxide (CO_2), sulfur dioxide (SO_2), and nitrogen oxides (NOx), which are major contributors to air pollution and climate change. Clean fuels, such as biofuels and hydrogen, offer alternatives to gasoline and diesel in transportation, cutting down on particulate matter and greenhouse gases.

By replacing fossil fuels with these cleaner alternatives, clean energy helps mitigate the health risks associated with poor air quality and slows the pace of global warming (Wang et al., 2018; Zhang et al., 2019). Renewable energy sources could decarbonize 90% of the electricity industry by 2050, drastically reducing carbon emissions, and contributing to climate change mitigation (Osman et al., 2023). Life cycle assessment revealed that 2.68 CO2e are embodied per ton of biochar. The Carbon removal quantification was calculated, and it showed that a total of 2.879 tCO2e is embodied per tonne of biochar which highlights the role of these renewable for carbon emissions (Fawzy et al., 2022; Lefebvr et al., 2023 among others).

Notwithstanding, China is the world's largest consumer of energy, and its dependence on fossil fuels such as coal, oil, and gas has led to significant environmental problems, including air pollution, water pollution, and greenhouse gas emissions (Rehman et al., 2021; Ahmad et al., 2021; Zeshan and Shakeel 2020). In recent years, China has taken steps to shift towards cleaner energy sources, but it still faces significant challenges in reducing its dependence on fossil fuels and curbing pollution. Clean fuels, such as renewable energy sources like wind, solar, hydroelectric, and biomass, can play a crucial role in reducing China's reliance on fossil fuels and decreasing pollution.

The Chinese government has decided to achieve optimal goals by increasing the clean energy resources in the country's energy mix, with a direction of reaching 20% by 2025 (Internation Energy Agency, 2021). China still relies heavily on fossil fuels, particularly coal, which accounts for more than 50% of the country's energy consumption. Coal-fired power plants are a significant source of air pollution in China, and the country's air quality is a major public health concern. The Chinese government has implemented measures to reduce coal consumption, such as implementing stricter environmental regulations and promoting the use of natural gas; however, progress has been slow (World Bank, 2022).

Globalization has had a significant impact on trade between developing countries, leading to various effects on pollution. The trade has three major effects on pollution: size, composition, and technology (Antweiler et al., 2001). This size impact suggests that expanding trade often causes an increase in energy use, which can contribute to environmental damage. The composition effect is based on the idea that a country's production composition, determined by its comparative advantages, can affect pollution levels, with capital-intensive industries being more polluting than labor-intensive sectors (Bekun et al., 2019). Finally, the technology impact highlights how trade facilitates the transfer of technology between trading partners, promoting the adoption of cleaner and more efficient practices (Rehman et al., 2021; Nadeem et al., 2023).

Aligned with the United Nations' sustainable development goals (SDGs), nations are actively pursuing strategies to achieve their carbon reduction objectives. Given the constraints on financial resources, it is imperative that carbon reduction policies optimize public fund utilization. However, existing research has largely overlooked a comprehensive examination of China's environmental situation, neglecting crucial aspects, like the uptake of renewable energy. This study addresses this gap by delving into the environmental landscape of China, considering both financial commitment to environmental protection and the adoption of renewable energy sources. Moreover, this research goes beyond conventional approaches by exploring the influence of clean energy consumption and trade dynamics on the overall environmental paradigm. Through these endeavors, this study makes a significant contribution to advancing the objectives outlined in SDG 7 (ensuring access to affordable and clean energy) and SDG 13 (taking urgent action to combat climate change and its impact) within the context of China.

The main aim of the existing work is to assess the long-run relationship between environmental pollution, GDP, fossil fuels, clean fuels, and trade openness in China. The novelty of this study lies in employing carbon dioxide equivalents (CO2e) instead of carbon dioxide (CO_2), as well as segregating energy into fossil fuels and clean fuels to measure their independent role in controlling pollution. The use of CO_2 equivalents will provide a better estimate of environmental degradation owing to the presence of other gases in the environment including CO_2. The independent role of clean fuels in total energy will lead to an assessment of the potential of clean energy in China's economy. Clean fuels include both renewable and nonrenewable clean energy use in the economy; therefore, they provide a broader estimate of clean energy (Nadeem et al., 2023).

Several studies have assessed the association between economic growth, environmental degradation, and renewable energy, and some have supported the EKC hypothesis. Therefore, we can conclude that the studies corroborate the evidence for many regions, as the pollution level reduces after a certain level of output. Clean fuel introduction can be one way to reduce environmental degradation and improve air quality, as shown in various studies (e.g., Degirmenci and Aydin 2024). There are relatively few studies which incorporate trade variable and employ nonlinear ARDL approach specifically for China. Also using CO_2 equivalents will cover other pollutants mentioned earlier (SO_2, NOx) to measure pollution level therein a broader measure of environmental quality with clean energy and other economic variables.

The untapped potential of clean fuel with trade and GDP could be insightful considering China's SDG targets. Existing studies on this topic ignore these dimensions. The model estimates are calculated using fully modified ordinary least squares (OLS) methods and nonlinear autoregressive distributed lag models (NARDL). Notwithstanding, the NARDL model is considered superior to the fully modified and ordinary OLS because it accounts for nonlinear relations and allows the capture of more complex patterns and dynamics that may be missed by linear models such as OLS. These findings of the study will underscore the need for and importance of clean fuels, GDP, and trade openness in controlling pollution-related policies in China.

The rest of the paper is being tracked as follows; 2nd section discusses the review of literature related to the topic, 3rd section discusses the analytical framework and data description, 4th section presents the methodology employed, 5th section contains the findings and discussion and last section have concluding remarks of the paper.

2 Review of literature

Several studies have explored the relationship between environmental degradation, income, and clean fuel. This review examines major studies that provide insights into the EKC theory and clean fuel. It is nevertheless clear that the present section will discuss the existing gap and help to guide the development of methods and models.

Barbier (2002) provides a comprehensive review of the literature on the EKC theory, including the evidence for and against it. The study highlighted different methodology used and different variables taken for many regions and countries. They concluded that further research with using robust methods could unleash the pathways to control pollution in the world.

Stern, (2004) examined the rise and fall of environmental Kuznets curve. This study examines the empirical evidence for the EKC theory and discusses the challenges in testing it. The authors discuss the need to introduce other variables like trade openness etc., in the understanding of pollution-related dynamics.

Bhattarai et al. (2012) uses panel data from 58 countries between 1990 and 2008 to test the EKC hypothesis for forestry sector CO_2 emissions and investigates the role of FDI in this relationship. The authors find that while the EKC hypothesis is supported for the forestry sector, FDI does not have a significant impact on CO_2 emissions. Additionally, the authors find that income, population, and forest area are important determinants of forestry sector CO_2 emissions. The study's findings suggest that economic development alone may not be enough to reduce environmental degradation, and that targeted policies and regulations may be necessary to address forestry sector CO_2 emissions. The study left the gap for employing trade variable and CO_2 equivalents.

Rahman and Shahari (2018) examines the EKC theory in Malaysia, focusing on the role of renewable energy consumption and trade. The EKC hypothesis suggests that environmental degradation increases with economic growth up to a certain point, after which it starts to decline as the economy becomes more developed and better able to afford and implement environmentally-friendly technologies and policies. The authors use a time-series analysis from 1971 to 2014 to examine the relationship between CO_2 emissions, renewable energy consumption, economic growth, and trade. However, employment of nonlinear ARDL approach may consider nonlinear patterns in the analysis.

Adom and Insaidoo (2016) examines the relationship between renewable energy consumption, trade, and greenhouse gas emissions in selected African countries. The study uses data from 13 African countries over the period 1990–2011. The authors employ panel data analysis techniques to estimate the relationship between renewable energy consumption, trade, and greenhouse gas emissions. They find that renewable energy consumption has a negative and statistically significant impact on greenhouse gas emissions in the selected African countries. The authors also find that trade has a significant positive effect on greenhouse gas emissions, which suggests that international trade may be contributing to an increase in emissions in these countries. It is nevertheless clear that country specific findings are much insightful for development of policy framework for clean energy.

Jiang et al. (2022) explores the relationship between economic growth, coal consumption, and environmental degradation in China. The study uses provincial panel data from 1995 to 2015 and applies the Environmental Kuznets Curve (EKC) framework to examine whether economic development leads to an improvement in environmental quality, as measured by air pollution. The authors find evidence of an inverted U-shaped relationship between economic growth and environmental degradation in China. However, the authors also find that coal consumption, which is a major contributor to air pollution in China, plays a significant role in the EKC relationship.

Creutzig et al. (2021) assessed the feasibility of achieving a rapid transition away from fossil fuels. The authors analyzed the current state of renewable energy technologies and discussed the policy changes needed to accelerate the transition.

Shafiee and Topal (2021) reviewed the use of hydrogen as a clean fuel in the transportation sector. The authors highlighted the advantages and disadvantages of using hydrogen and discussed the current state of the technology.

Shakeel (2021) noted that fossil fuels, non-fossil fuels, exports have a long run relationship with GDP in south Asia region. They employed structural break models with Hansen co-integration approach. The findings revealed that fossil fuels and exports are granger causing GDP in the long run while non fossil fuels and exports are not significant in the long run.

Menegaki and Tugcu (2018) notes that energy use proxies with renewable and non-renewable and GDP have a two-way causality with other variables using the data from 1990 to 2015. They corroborate that energy conservation will harm the sustainable economic GDP in Asia. The study contributes significantly but confines itself in the direction of not providing country specific results.

Shakeel and Ahmed (2021) notes that there exists a long run panel co-integration amid the GDP, energy, trade, in production function of South Asian economies. They used annual data of five countries in a panel approach. They find out a causal association two way affiliation betwixt energy and trade. Also, trade has been causing energy consumption implying that there is much need to understand the dynamics of energy with further studies. The study leaves the gap for clean energy in China and other regions.

Bhuiyan et al. (2022) noted that adopting renewable energy will lead to improve output of both developed and developing nations. They concluded the finding with systematic review of peer reviewed journal-based articles which were collected from SCI and SSCI indexing. They also noted that there is relatively less significance of using renewable energy with output at a specific threshold. They provided important results but leave the gap for other clean fuels which this study attempts to cover.

Awan et al. (2022) examined the association among renewable energy, urbanization and FDI for ten emerging economies over the years 1996–2015. They used the methods of moments quintile regression and found that renewable energy reduces the pollution at all levels of quintile, ceteris paribus. The study contributes significantly but leaves the gap between clean fuels and output for other regions.

Abbasi et al. (2022) examined the environmental factors with fossil fuel, renewable energy, and GDP among others. They used the method of dynamic ARDL simulation and frequency domain causality to find the potential relationships. They noted that fossil fuel sources increase CO_2 emission while renewable energy reveals *vice versa*. The authors contribute significantly but does not provide the dynamic association among clean fuels and GDP in China.

Abbasi et al. (2022) examined the asymmetric links of renewable, non-renewable energy and terrorism in Pakistan. They used nonlinear ARDL methods and found that there is positive and negative changes which affect the renewable energy and terrorism link in the country. They provided novel finding but lack in the direction of clean energy and GDP. Ahmad et al. (2020) explores the heterogeneous links among urbanization, the intensity of electric power consumption, water-based emissions, and economic progress in regional China. The empirical analysis provides valuable insights into the complex relationship between these factors and their implications for sustainable development in urban areas. The study employs robust methodology and utilizes a rich dataset to investigate the specific dynamics at play. The findings highlight the need for targeted policies and strategies to address the environmental challenges associated with urbanization while promoting economic growth.

Ahmad et al. (2020) focused on modeling the heterogeneous dynamic interactions among energy investment, SO_2 emissions, and economic performance in regional China. The study contributes to the understanding of the complex relationships between energy investments, environmental pollution, and economic development. The research methodology is rigorous, incorporating advanced modeling techniques to capture the dynamics over time. The findings shed light on the effectiveness of different energy investment strategies in reducing SO_2 emissions and their impact on economic performance.

Batool and Rehman (2023) examines the mediating role of green technology innovations in the relationship between environmental regulations and Chinese energy sustainability at the provincial level. The research contributes to the understanding of the mechanisms through which environmental regulations affect energy sustainability outcomes.

Sue et al. (2023) investigated the intricate interplay among renewable energy, economic freedom, and economic policy uncertainty across G7 and BRIC countries. Employing dynamic panel threshold analysis, their study enhances comprehension of these multifaceted interactions. Their findings offer valuable insights into the optimal conditions for effective renewable energy policies, fostering both economic growth and stability.

Işık et al., 2023 delved into the asymmetric repercussions of foreign direct investment inflows, financial development, and social globalization on environmental pollution. This study adds to the existing literature on the environmental consequences of globalization and foreign direct investment. Through empirical analysis, the research provides significant insights into the divergent effects of these factors on environmental pollution within distinct contexts. The research underscores the necessity of tailored environmental policies considering these heterogeneous impacts.

Deng et al. (2022) investigated the influence of social globalization, foreign direct investment inflows, and financial development on environmental pollution, utilizing a globally representative sample of 107 countries. Their empirical exploration sheds light on the intricate dynamics connecting CO_2 emissions, economic growth, and employment. The results hold implications for policymakers striving to shape sustainable development strategies on a regional scale.

Rehman et al. (2023) investigates the asymmetrical influence of foreign direct investment, remittances, reserves, and information and communication technology on Pakistan's economic development. The research contributes to the understanding of the multifaceted drivers of economic development in Pakistan.

Rehman et al. (2022) examined the intricate balance between renewable energy, urbanization, fossil fuel consumption, and economic growth in Romania, assessing short- and long-term implications. Their work advances our understanding of the trade-offs and synergies inherent in this context.

Cagler and Askin (2023) delved into two pivotal environmental quality metrics: CO_2 emissions and load capacity factor. While co-integration was not observed in the emissions model, it surfaced in the load capacity factor model. The outcomes suggest that economic growth and competitive industrial performance exert adverse effects on environmental quality. On the contrary, renewable energy consumption and human capital were identified as enhancers of the load capacity factor. This research advocates for human capital and renewable energy consumption as potent instruments for bolstering the load capacity factor.

Degirmenci and Aydin (2024) makes a significant contribution to the study of environmental sustainability, particularly by addressing the role of Annex II countries under the Kyoto Protocol. The authors present a compelling case for testing the load capacity curve (LCC) hypothesis, which relates economic growth to environmental degradation. Their focus on green innovation, green tax, green energy, and technological diffusion as key factors in driving sustainability adds an important dimension to existing environmental economics literature. The study's limitation to Annex II countries narrows the generalizability of its findings. While this focus is justifiable given the research context, expanding the analysis to include non-Annex countries could offer more comprehensive insights into the global effort to meet Kyoto Protocol targets.

Aydin and Degirmenci (2024) provides a significant contribution to the ongoing discourse on environmental sustainability by examining the effects of clean energy consumption, green innovation, and technological diffusion on sustainability across 10 European Union countries. The novelty of this research lies in its focus on the Load Capacity Curve (LCC) hypothesis, which has been underexplored in comparison to the more frequently studied Environmental Kuznets Curve (EKC) hypothesis. Their findings underscore the importance of technological diffusion and innovation in addressing environmental challenges, while also highlighting the need for country-specific strategies to achieve sustainability goals.

In summary, the EKC framework suggests that the relationship between economic development, energy use, trade, and environmental degradation is complex and nonlinear. While initial increases in energy use and trade may lead to increased environmental degradation, beyond a certain threshold of economic development, environmental degradation may begin to decrease even as energy use and trade continue to grow. The specific shape and functional form of this relationship may vary depending on the context and the specific environmental indicator of interest. Therefore employing nonlinear ARDL may guide us further in this regard.

Overall, these reviews and studies suggest that the EKC hypothesis is a complex and context-specific relationship that varies across countries, regions, and pollutants. While the relationship between economic development and environmental degradation may eventually turn positive, this turning point is influenced by many factors, including government policies, technological advancements, public awareness, and cultural norms. Further research is needed to better understand the EKC relationship and identify effective policies and interventions to achieve environmental sustainability. According to Jiang et al. (2022), China will be a major consumer of energy, including fossil fuels. However, the country has set a double carbon target to control pollution. Despite a reduction in domestic subsidies by 2020, China's local market structure has demonstrated resilience. China has increased its use of clean energy, including solar panels, by 15.7% compared with 2019 (Bhuiyan et al., 2022). To support its destination of limiting carbon dioxide release before 2,030 and accomplishing carbon neutrality by 2,060, China has set a target of reaching 1,200 gigawatts (GW) of installed wind and solar power capacity by 2,030, which is almost double the current 635 GW capacity. Thus, it will be interesting to assess the clean energy with trade and output for environmental degradation in China.

Therefore, the present work attempts to cover the literature gap for China using CO_2 equivalents, GDP, clean fuels, fossil fuel and trade.

3 Analytical framework and data description

Initially, as a country's energy use and trade activity increase with economic development, environmental degradation may also increase. However, beyond a certain threshold, as the country becomes more economically advanced, environmental degradation may begin to decrease even as energy use and trade continue to grow.

Mathematically, the EKC can be represented by the following equation:

$$E = f(Y) \tag{1}$$

where E represents environmental degradation (e.g., pollution), Y represents GDP or economic development, and f() represents some function of the relationship between the two variables. In the case of energy and trade, the equation could be extended to include additional variables such as energy consumption (EC) and trade openness (TO):

$$E = f(Y, EC, TO) \tag{2}$$

The specific functional form of f () is not well established and may vary depending on the context and the environmental indicator of interest. However, some studies have suggested that the EKC relationship may be characterized by a quadratic or cubic polynomial function, suggesting that the relationship between economic development, energy use, trade, and environmental degradation may not be linear.

$$E = \beta_0 + \beta_1 Y + \beta_2 Y_2 + \beta_3 EC + \beta_4 TO + \varepsilon \tag{3}$$

In this equation, E represents the dependent variable (pollution measure with CO_2 equivalents), while Y, EC, and TO represent the independent variables of GDP, energy (fossil and clean fuels) and trade openness. The β_0, β_1, β_2, β_3, β_4 are the coefficients that represent the effect of each predictor on the response variable. Finally, ε represents the random error term that accounts for the variability in the response variable that cannot be explained by the predictors. The squared terms capture the potential non-linear relationship between the independent variables and environmental degradation.

3.1 Theoretical connection with asymmetric effects

In the NARDL framework, by incorporating the concepts of asymmetric effects, we can examine how the relationship between trade, clean energy, and the outcome variable changes concerning positive and negative changes in these variables. For example:

3.1.1 Positive shock in trade

A positive shock in trade could lead to increased economic activity, which might benefit the outcome variable positively. However, it could also introduce challenges such as heightened competition or exposure to external market fluctuations, which might have a negative impact on the outcome variable.

3.1.2 Negative shock in trade

Conversely, a negative shock in trade could temporarily reduce economic activity, potentially affecting the outcome variable negatively. However, this might also lead to the implementation of policy measures or increased domestic focus, which could have positive effects in the long run.

3.1.3 Positive shock in clean energy

An increase in the use of clean energy might have positive impacts on the outcome variable, such as reduced environmental degradation or increased investments in sustainable technologies. However, the initial costs of clean energy adoption could temporarily affect the outcome variable negatively.

3.1.4 Negative shock in clean energy

A negative shock in clean energy might hinder progress in sustainability efforts and negatively affect the outcome variable. However, this could also prompt the exploration of alternative clean energy solutions or policy interventions to incentivize clean energy usage, leading to positive effects in the long term.

The study used annual time series of data of carbon dioxide equivalents to measure pollution, GDP at constant dollar prices to measure production, fossil fuel and clean fuels in kilotons of oil equivalents and merchandise trade to GDP ratio at constant US dollar prices to measure trade openness from the period 1990–2020 for China (Table 1). The data for these variables have been obtained from World Development Indicator (2023). We have selected this period considering the Kyoto Protocol of 1987 to reduce environmental degradation as well as the availability of all the variables for this time frame. The technical contribution of the present works rests in the adoption of EKC function with using CO_2 equivalents and clean energy with other variables employing NARDL model.

Clean energy refers to forms of energy that are not derived from carbohydrates and do not release carbon dioxide during their generation. This category encompasses various sources such as hydroelectric power, nuclear power, geothermal energy, and solar power, among others. The indicator used to assess the proportion of clean energy in relation to total energy consumption is termed "Alternative and nuclear energy (% of total energy use)" according to the World Bank as the data source.

TABLE 1 XXX.

Variables and unit of measurement	Source of the data
Total greenhouse gas emission in KT of CO_2 equivalent	World Bank (2022) World Development Indicators
Real economic GDP at constant 2015 US dollars to measure economic output	World Bank (2022) World Development Indicators
Capital formation/GDP at constant 2015 US dollars to measure capital stock	World Bank (2022) World Development Indicators
Trade as ration of exports and imports to GDP at constant dollars	World Bank (2022) World Development Indicators
Addition of renewable and non-renewable clean sources in KT of oil equivalents to measure clean energy	World Bank (2022) World Development Indicators
Fossil fuels energy in KT of oil equivalents to measure fossil fuel energy	World Bank (2022) World Development Indicators

4 Methodology

The present section discusses the econometric method employed in the paper. The steps of unit root, co-integration and NARDL have been used to find the dynamics relationship among the model. Equations 1–6 are applied to estimate the model in next section.

4.1 Unit root

As a first step, it is recommended to test the non-stationarity of the times series of the model. For series having deterministic elements in the shape of a constant or a linear trend; Elliott et al. (1992) a.k.a ERS formulated an asymptotically point optimum test to discover a unit root. The test is an asymptotically point-optimal test for the presence of a unit root in a time series. A unit root refers to a characteristic of a time series in which the mean and variance of the series are not constant over time, but instead grow at a rate that is proportional to the time index. The ERS test is based on the idea of testing a linear time trend against a stationary alternative hypothesis. So we used this ERS test reported in Table 2.

$$\Delta yt = \alpha + \beta yt - 1 + \gamma \Delta yt - 1 + \delta 1yt - 2 + \delta 2yt - 3 + . + \delta p - 1yt - p + \varepsilon t \quad (4)$$

In this equation, the variable yt represents the time series being analyzed, Δyt represents the first difference of yt (i.e., the difference between consecutive observations), α is the intercept term, β is the coefficient on the lagged level of yt, γ represents the coefficient on the lagged first difference of yt, δ1, δ2, δp-1 are the coefficients on the lagged levels of yt, and εt is the error term at time t.

TABLE 2 Descriptive statistics.

	COE	Y	CF	FF	TO
Mean	15.76174	29.15449	2.988554	4.42462	3.492014
Median	15.84349	29.17715	2.736349	4.4584	3.505064
Maximum	16.35751	30.39115	5.107017	4.487494	3.524038
Minimum	14.99117	27.65803	0.918712	4.315245	3.437961
Std. Dev.	0.490944	0.847209	1.357389	0.059629	0.026936
Skewness	−0.134264	−0.153931	0.105738	−0.498633	−0.512286
Kurtosis	1.391608	1.748494	1.652619	1.633174	1.745249
Jarque-Bera	3.545378	2.21473	2.480212	3.817001	3.498862
Probability	0.169876	0.330429	0.289354	0.148303	0.173873

observation = 31.

4.2 Co-integration test

The second place in the journey of examination is the potential estimation of the long run connection among the time series of the model presented in previous section. The study employs the test of Hansen (1995) parameter instability as well. The Hansen co-integration test is an extension of the standard Johansen co-integration test, which is a widely used method to test for co-integration. The Hansen test is considered more powerful than the Johansen test in certain cases, particularly when there is a small sample size. We have used the nonlinear ARDL bound test to test the potential long run relationship amid variable as well.

5 Fully modified OLS and non-linear ARDL

The equation for FMOLS is as follows:

$$y_t = \beta_0 + \beta_1 x_{1t} + \ldots + \beta_k x_{kt} + \varepsilon_t \quad (5)$$

where: y_t is the dependent variable at time t. x_{1t} +. + x_{kt} are k independent variables at time t. B's are the parameters to be estimated. ε_t is the error term at time t.

The FMOLS estimator modifies the OLS estimator by including lagged values of the dependent variable and the independent variables as regressors. The equation for the FMOLS estimator is as follows:

$$\ln y_t = \beta_0 + \beta_1 \ln x_{1t} + \ldots + \beta_{k\ln} x_{kt} + \alpha y_{t-1} + \sum\nolimits_i^k \gamma_i \ln x_{it-1} + \varepsilon_t \quad (6)$$

where: α is the coefficient on the lagged dependent variable in natural log, $\ln yt_{-1}$. γ is the coefficient on the lagged independent variable in natural log, $\ln x_{it-1}$.

The FMOLS estimator uses instrumental variables to address endogeneity and adjusts the error term for autocorrelation. It is commonly used in time series analysis to estimate the long-run relationships between variables.

Equation 7 is a Nonlinear Auto-regressive Distributed Lag (NARDL) model. It relates the natural logarithm of CO_2 equivalent emissions [ln(CO_2eqv)] to various explanatory variables, such as the natural logarithm of energy consumption [ln(CE)], the natural logarithm of GDP [ln(GDP)], and the natural logarithm of trade [ln(t)]. The equation includes several interaction terms and squared terms to capture potential nonlinear relationships between the variables. The coefficients (b1, b2, …, b9) represent the estimated effects of the corresponding variables on ln (CO_2e), while "a" represents the intercept term. The error term "e" captures the unexplained variability in the model.

Overall, the equation aims to quantify the relationship between ln(CO2e) and the explanatory variables, accounting for potential nonlinear effects and the dynamics of the relationship over time. The NARDL model allows for asymmetry, meaning it can capture different effects of the explanatory variables during periods of increasing or decreasing CO2e emissions.

$$\ln(\mathrm{CO2e}) = a + b_1 \ln(\mathrm{CE}) + b_2 \ln(\mathrm{GDP}) + b_3 \ln(t) + b_4 (\ln(\mathrm{CE}))^2 + b_5 * (\ln(\mathrm{GDP}))^2 + b_6 * (\ln(t))^2 + e \quad (7)$$

The terms with squared logarithms (powers of 2). These terms allow for non-linearity and potential interactions among the variables in the model. Equation 7 allows for capturing potential nonlinear effects through the squared terms and interactions, and the dynamics of the relationship over time due to the inclusion of lagged variables.

The NARDL model is valuable because it allows for the exploration of asymmetry, meaning it can capture different effects of the explanatory variables during periods of increasing or decreasing CO2e emissions. This feature is particularly important when studying environmental phenomena, as the relationships between variables may not always be symmetric over time. NARDL allows for separate estimation of positive and negative changes in explanatory variables, offering insights into how upward and downward movements in environmental factors (e.g., trade) differently impact environmental degradation, which the linear

10.3389/fenrg.2024.1385170

TABLE 3 ERS/ADF-GLS unit root test.

Variables	Level	Critical	Difference	critical
GDP	−0.19**	−1.95	−2.18	−1.95
COE	−1.14*	−1.95	−2.24	−1.95
F.F	−1.18*	−1.95	−2.40	−1.95
C.F	0.24**	−1.95	−5.29	−1.95
T.O	0.04**	−1.95	−3.31	−1.95

*and**denotes level of significance at 10% and 5%.

TABLE 4 Results of BDS test.

Variable/dimension	m = 2	m = 3	m = 4
COE	0.15*	0.251*	0.331*
CE	0.191*	0.33*	0.411*
t	0.181*	0.322*	0.401*
GDP	0.174*	0.196*	0.365*

m denotes the dimensions and*denotes the level of significance at 5%.

TABLE 5 Results of hansen co-integration test and NARDL bound test.

	Stochastic	Determinis	Excluded	
Lc statistic	Trends (m)	Trends (k)	Trends (p2)	Prob.*
0.955449	5	2	1	0.088

Asym. test		Statistic	L-B	U-B	Co-integration
			5%	5%	
Fpss	Nonlinear	12.257	2.45	3.61	Yes
tBDM	Nonlinear	−6.34	−2.86	−4.38	yes

ARDL cannot capture. This provides a more realistic and nuanced understanding of the EKC dynamics.

The estimated coefficients and their significance provide insights into the strength and direction of the relationships between the variables in the model.

8 Results and discussion

The present section discusses the findings of the estimated model. The steps involved has been followed as per methodology section. Firstly Table 2 discusses the descriptive statistics of the selected variables. It is clear that mean value of each series are closely associated. Also, it is evident that there is no issue of outlier in the data as per median, minimum and maximum values of the variables.

The value of Jarque-Bera test of normality accepts the null hypothesis that CO equivalents, GDP(Y), clean fuel (CF), fossil fuel (FF) and trade openness (To) are normally distributed. This means that sample of these variables comes from a normal distributed data of the population.

In the next step, a unit test has been applied to calculate the order of integration of the variables. The results of the ERS test are present in Table 3. The results reveal that COE, GDP, fossil fuel, clean fuel and trade openness are non-stationary at levels at 5% or 10% level of significance. It is however clear that at first difference, these variables are found stationary or integrated of order zero. Thus, it is found that these variables are integrated of order one or I (1) process.

Before applying regression models, it is essential to assess whether the data series exhibits linearity or non-linearity. To ascertain the non-linear patterns within the variables under consideration, we employ the BDS (Brock, Dechert, and Scheinman) test for independence, as proposed in the work by Brock et al. (1996). The three dimensions in the BDS test refer to time-series data: (1) m2 the embedding dimension, representing the number of past observations used to predict future values, (2) m3 the distance metric, which measures the closeness between points in phase space, and (3) m4 the length of the series, which affects the accuracy of the test. These dimensions help detect non-linear dependencies in the data. The results, which are presented in Table 4, demonstrate that all the underlying variables exhibit non-linear dependence across all embedding dimensions.

Likely, in the next step, we estimated the Hansen co-integration test for the potential long run equilibrium relationship among the selected variables in Table 4.

We employ a methodology of moving from a broader-to-narrower approach when choosing the appropriate Nonlinear Autoregressive Distributed Lag (NARDL) model. Our initial exploration involves setting the maximum lag lengths as $p = q = 4$. This procedure allows us to systematically investigate potential asymmetric long-term co-integration connections within the series. To accomplish this, we utilize the Fpss test introduced by Banerjee et al. (1998), as well as the tBDM test developed by Pesaran et al. (2001), as recommended by Shin et al. (2014).

The outcome outlined in Table 5 demonstrates that there is indication of co-integration among the selected series of the model at 5% level of significance. Therefore, we conclude the existence of a valid asymmetric long-run relationship between pollution, trade, clean energy, and GDP.

In Table 6, clean energy (CE) variable represents the first difference of the logarithm of CE (clean energy). It has a coefficient of 0.0250, indicating that a one-percent increase in CE is associated with a 0.0102 percent decrease in the dependent variable environmental degradation. This is also evident that one percent decrease of clean energy will lead to increase the pollution by 0.015 percent. Therefore, positive and negative values have different effects on pollution in the model. It is however interesting that taking the CE square will lead to reduce the environmental degradation at latter stages when economy adapts and indigenize the clean energy into the economy. This also means there is nonlinear relationship among the clean energy and environmental degradation. The affiliation

TABLE 6 Results of NARDL model.

	Estimated Coefficient	Std. Errors	t-value	Pr(>|t|)
(Intercept)	−0.0102	0.0525	−0.19	8.466e-01
diff_log_CE(+)	−0.0150	0.0071	2.14	1.322e-0
diff_log_CE(−)	0.0330	0.0096	3.33	1.712e-0
diff_log_GDP	0.2259	0.07318	3.08	3.853e-03
diff_log_t (+)	−0.312	0.014	−2.21	1.13e-02
diff_log_t (−)	0. 124	0.059	2.40	1.3e-02
log_CE_squared	−0.3356	0.23114	−1.85	1.569e-01
log_GDP_squared	−0.1580	0.1738	−0.90	3.688e-01
log_t_squared	0.3860	0.2302	1.67	1.035e-01
ECT-1	**−0.51**	**0.0731**	**−7.28**	

between a positive/negative shock to the environmental condition and CE corroborates a negative/positive, less elastic, and significant link at the 1% significance level. It is inferred that more clean energy will reduce the pollution in China. Consequently, any strategy in China intending to grow the level of clean energy will contribute to control pollution. This is because at lower level of clean energy share, pollution cannot be reduced significantly and therefore, country should increase the energy share of these clean fuels, ceteris paribus.

GDP variable represents the first difference of the logarithm of GDP. It has a coefficient of 0.2259, suggesting that a one-percent increase in GDP is associated with a 0.2259 percent increase in the dependent variable. The value of GDP square is −0.15 but insignificant indicating the at higher level of economic prosperity, the country needs to adopt clean technologies to reduce pollution, ceteris paribus.

diff_log_t: This variable represents the first difference of the logarithm of t (trade openness). It has a coefficient of −0.312 when positive values considered, indicating that a one-unit increase in t is associated with a −0.31 percent decrease in the dependent variable (pollution). This implies that as trade increases, it could reduce environmental pollution. This is because of the composition effect of trade which suggests that labor intensive economies will emit less pollution, ceteris paribus (Shakeel and Ahmed, 2021). However, the negative value of trade shows that a one percent decrease in trade will increase the pollution by 0.124 percent. Therefore, positive and negative values of trade have asymmetric effect on pollution with a different magnitude. These estimates are helpful in policy guidelines for environmental degradation.

The affiliation between a positive/negative shock to the pollution and trade indicates a negative/positive, elastic, and significant link at the 1% significance level. It can be inferred that any rise in trade will reduce the pollution in China. Thus, any policy in China targeting at growing the level of trade will contribute to control pollution. This is because trade could impact the environmental condition by scale effect, composition effect and technique effect. The existing estimate supports the technique effect as using clean technology is indicative of improving environmental degradation.

log_CE_squared, log_GDP_squared, log_t_squared: These variables represent the squared terms of CE, GDP, and t, respectively. Their coefficients are −0.3356, −0.1580, and 0.3860, respectively. These coefficients indicate the relationship between the squared terms and the dependent variable, considering potential non-linearities.

The coefficient (−0.51) represents the error correction term. It indicates the speed at which the dependent variable adjusts towards its long-run equilibrium relationship with the independent variables. In this case, a value of −0.51 suggests that environmental pollution corrects about 51% of the disequilibrium in each period. This means that in the long run, all the variables are significant to contribute towards the equilibrium level of pollution, ceteris paribus.

Clean energy and trade openness are also significant to improve the environmental degradation. Thus, it is clear the clean energy which is among the SDG 7 and climate which is SDG 13 targets can be achieved using clean energy and promoting trade of the economy. Also, there are forward and backward linkages of trade through which a country can enhance economic activity and environment through technology spillover (Cagler, 2023; Rehman et al., 2023).

The use of cleaner fuel sources is associated with reduced pollution, while international trade are also associated with better environmental quality as per NARDL estimates. The magnitude of clean fuel is not as per expectation as country is cultivating the culture of clean fuel recently while share of fossil fuels is huge.

In the last step, we estimated that long run estimates using the fully modified OLS methods as per methodology section (Table 7). The dependent variable in this model is likely to be a measure of environmental quality (carbon emissions), while the independent variables are GDP, Clean fuel, Fossil fuel, Trade, and a time trend (@TREND).

The coefficient estimates of the independent variables suggest the following: GDP has a negative coefficient (−8.211914), implying

TABLE 7 Results of Fully modified OLS.

Variabl	Coefficient	Std. Error	t-Statistic	P Value
CO_2E				
GDP	−8.211914	0.479318	−17.13251	0.00
GDP^2	0.157951	0.00853	18.51632	0.00
Clean fuel	0.040428	0.014561	2.776409	0.01
Fossil fuel	3.174775	0.556406	5.705859	0.00
Trade	3.880556	1.103343	3.517091	0.00
constant	94.21929	6.698053	14.06667	0.00
@TREND	−0.072674	0.007877	−9.225591	0.00

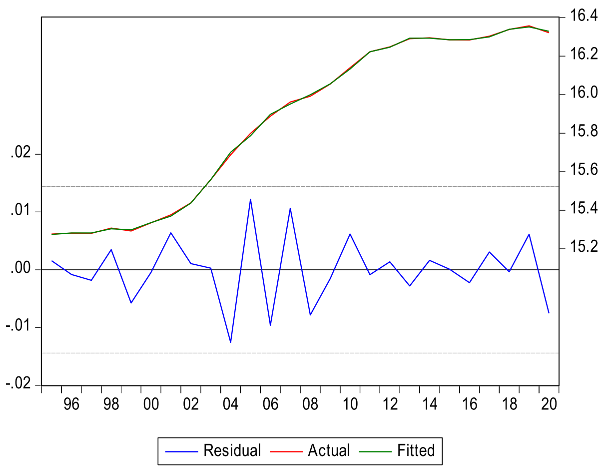


FIGURE 1
Estimated residual.

that environmental quality decreases with economic growth initially. GDP^2 has a positive coefficient (0.157951), indicating that there is an inverted U-shaped relationship between economic growth and environmental quality, consistent with the EKC hypothesis. The coefficient estimate suggests that environmental quality improves after a certain level of economic development is reached. Clean fuel has a positive coefficient (0.040428), implying that the use of cleaner fuel sources is associated with increased Coe emission. This could be due to the higher initial cost of clean fuel and use of pollution related process in the development of clean fuels (see Shakeel and Iqbal, 2014; Shakeel, 2021a; Shakeel, 2021b). The value of the clean fuel is smaller implying for the smaller share in the economy of China relative to fossil fuels. Likely, Fossil fuel has a positive coefficient (3.174775), suggesting that the use of fossil fuels is associated with worse environmental quality. Trade has a positive coefficient (3.880556), indicating that international trade is associated with worse environmental quality. The time trend variable (@TREND) has a negative coefficient (−0.072674), implying that environmental quality has been improving over time. The standard errors, t-statistics, and p-values provide information on the statistical significance of the coefficient estimates. All the independent variables have statistically significant coefficients at the 5% level of significance.

The co-integration-based graph of residuals from the estimated NARDL model also confirms the existence of long run relationship as there is a stationary pattern of the residuals (see Figures 1, 2). We have employed both the cumulative sum (CUSUM) and cumulative sum of squares (CUSUMSQ) tests to assess the consistency of the regression. The outcomes presented in Figure 2, indicate that the blue line remains within the 5% critical threshold. This implies that the estimated NARDL model demonstrates stability.

9 Conclusion and implications

This research investigates the effects of various factors, including GDP, clean and fossil fuels, and trade, on CO2e emissions in China. Specifically, it explores the potential for clean fuel to mitigate pollution and promote sustainability. The study utilizes time series data from 1990 to 2020 and employs NARDL AND FMOLS methods. Based on the NARDL regression results, we can conclude that GDP have a significant postive impact on CO2e emissions. This suggests that economic growth and development are associated with higher levels of pollution. Additionally, the use of clean fuels has a small but significant negative effect on CO2e emissions, while the negative values of clean fuels haave a significant positive impact on emissions. The variable for trade also corroborated the same patterns on CO2e emissions, indicating that countries that engage in more trade may have lower levels of pollution in the long run. Finally, the trend variable indicates a decreasing trend in CO2e emissions over time.

Clean fuel is a type of fuel that produces fewer harmful emissions when burned compared to traditional fossil fuels like coal, oil, and natural gas. The use of clean fuels can potentially contribute to reducing environmental degradation and pollution. However, the effectiveness of clean fuels in reducing pollution levels largely depends on the type of fuel used and the way it is produced and transported. For example, biodiesel can reduce emissions of carbon monoxide and particulate matter, but it can also lead to increased emissions of nitrogen oxides and other harmful substances. Thus, the smaller value of coefficients implies that country still need to increase the share of these clean fuels in China.

When it comes to the EKC hypothesis, the use of clean fuels could potentially accelerate the process of reaching the turning point where environmental degradation begins to decline. However, it is important to note that clean fuels alone are unlikely to be sufficient to address the underlying causes of environmental degradation. Other measures, such as regulatory policies, public awareness campaigns, and investments in sustainable technologies, will also be necessary to achieve long-term environmental sustainability.

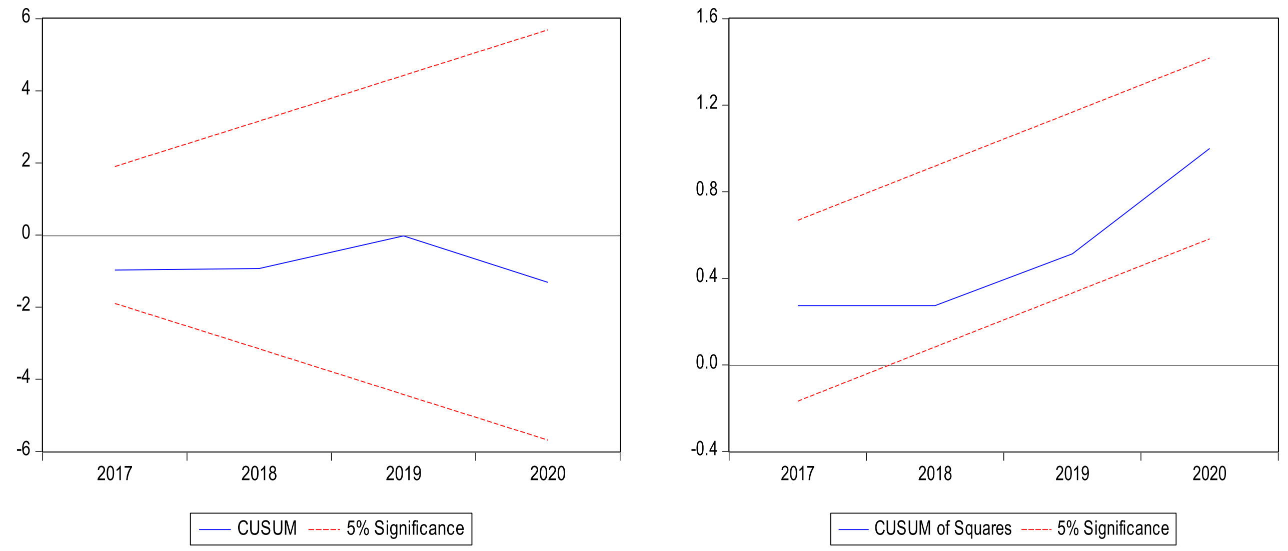


FIGURE 2
CUSUM and CUSUMQ PLOT of estimated residuals.

The findings highlight the importance of considering the interplay between economic growth, clean energy, trade openness, and environmental degradation. By adopting targeted policies and sustainable practices, countries can achieve the Sustainable Development Goals related to clean energy (SDG 7) and climate action (SDG 13), while promoting economic growth and environmental sustainability.

The policy implications of this analysis are as follows:

- Promoting clean energy adoption: Governments should prioritize policies that encourage the use of clean energy sources. This can include subsidies, tax incentives, and research and development funding for renewable energy technologies. By indigenizing clean energy into the economy, countries can reduce environmental degradation and move towards sustainable development.
- Implementing sustainable economic policies: As countries strive for economic growth, it is crucial to adopt sustainable economic policies that consider environmental implications. This can involve promoting resource efficiency, circular economy practices, and sustainable consumption and production patterns. Balancing economic growth with environmental sustainability is essential for achieving long-term environmental quality.
- Enhancing trade policies: Governments should aim to create trade policies that promote environmentally friendly practices. This can involve integrating environmental standards and regulations into trade agreements, encouraging eco-friendly industries, and supporting sustainable supply chains. By leveraging trade openness, countries can benefit from technology spillovers and improve environmental quality.
- Continued monitoring and research: Environmental policies should be based on robust monitoring and research. Regular assessment of environmental indicators and their relationship with economic variables is crucial for informed policy decision-making. Ongoing research should focus on understanding the non-linear dynamics between economic growth, clean energy adoption, trade openness, and environmental degradation.

The present study is limited in the context of not using other economic and environmental variables like biodiversity, water quality etc. These variables could be of much help in understanding the complex nature of economic-environmental dynamics in China and other regions of the world. Additionally, considering sector-specific analyses could provide more granular insights into how different industries contribute to or detract from environmental sustainability. Notwithstanding, this is a future direction of the present work.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

MS: Writing–original draft. CN: Writing–original draft.

Funding

The author(s) declare that financial support was received for the research, authorship, and/or publication of this article. This work was supported by Fundação para a Ciência e a Tecnologia, I.P. (Portuguese Foundation for Science and Technology) under project

UIDB/05064/2020 (VALORIZA - Research Centre for Endogenous Resource Valorization).

Acknowledgments

We are thankful for the handling editor and reviewers their useful comments to improve the work.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

Author disclaimer

The views expressed in the article are of the authors and not of the institutions of the authors.

References

Abbasi, K. R., Shahbaz, M., Zhang, J., Irfan, M., and Alvarado, R. (2022). Analyze the environmental sustainability factors of China: the role of fossil fuel energy and renewable energy. *Renew. Energy* 187, 390–402. doi:10.1016/j.renene.2022.01.066

Adom, P. K., Insaidoo, M., Minlah, M. K., and Abdallah, A. M. (2017). Does renewable energy concentration increase the variance/uncertainty in electricity prices in Africa?. *Renew. Energy.* 107, 81–100.

Ahmad, M., Chandio, A. A., Solangi, Y. A., Shah, S. A. A., Shahzad, F., Rehman, A., et al. (2021). Dynamic interactive links among sustainable energy investment, air pollution, and sustainable development in regional China. *Environ. Sci. Pollut. Res.* 28, 1502–1518. doi:10.1007/s11356-020-10239-8

Ahmad, M., Zhao, Z. Y., Irfan, M., Mukeshimana, M. C., Rehman, A., Jabeen, G., et al. (2020). Modeling heterogeneous dynamic interactions among energy investment, SO2 emissions and economic performance in regional China. *Environ. Sci. Pollut. Res.* 27, 2730–2744. doi:10.1007/s11356-019-07044-3

Antweiler, W., Copeland, B. R., and Taylor, M. S. (2001). Is Free Trade Good for the Environment?. *Am. Econ. Rev.* 91 (4), 877–908. doi:10.1257/aer.91.4.877

Awan, A., Abbasi, K. R., Rej, S., Bandyopadhyay, A., and Lv, K. (2022). The impact of renewable energy, internet use and foreign direct investment on carbon dioxide emissions: a method of moments quantile analysis. *Renew. Energy* 189, 454–466. doi:10.1016/j.renene.2022.03.017

Aydin, M., and Degirmenci, T. (2024). The impact of clean energy consumption, green innovation, and technological diffusion on environmental sustainability: new evidence from load capacity curve hypothesis for 10 European Union countries. *Sustain. Dev.* 32 (3), 2358–2370. doi:10.1002/sd.2794

Banerjee, A., Dolado, J., and Mestre, R. (1998). Error-correction mechanism tests for cointegration in a single-equation framework. *J. Time Ser. Anal.* 19 (3), 267–283.

Batool, Z., and Rehman, A. (2023). Exploring the effects of farm mechanization, financial development, and renewable energy on China's food production. *Environ. Dev. Sustain.*, 1–20.

Bekun, F. V., Alola, A. A., and Sarkodie, S. A. (2019). Toward a sustainable environment: Nexus between CO2 emissions, resource rent, renewable and nonrenewable energy in 16-EU countries. *Sci. Total Environ.* 657, 1023–1029.

Bhattarai, M., Hammig, M., and Kauffman, K. (2012). Forestry sector CO_2 emissions and the environmental Kuznets curve: the role of FDI and trade openness. *Ecol. Econ.* 77, 183–187.

Bhuiyan, M. A., Zhang, Q., Khare, V., Mikhaylov, A., Pinter, G., and Huang, X. (2022). Renewable energy consumption and economic growth nexus—a systematic literature review. *Front. Environ. Sci.* 412. doi:10.3389/fenvs.2022.878394

Brock, I. C., Engler, A., Ferguson, T., Filthaut, F., Kraemer, R. W., Merk, M., et al. (1996). Luminosity measurement in the L3 detector at LEP. *Nucl. Instrum. Methods Phys. Res. A. Accelerators, Spectrometers, Detectors and Associated Equipment.* 381 (2–3), 236–266.

Caglar, A. E. (2023). Can nuclear energy technology budgets pave the way for a transition toward low carbon economy: insights from the United Kingdom. *Sustain. Dev.* 31 (1), 198–210. doi:10.1002/sd.2383

Caglar, A. E., and Askin, B. E. (2023). A path towards green revolution: how do competitive industrial performance and renewable energy consumption influence environmental quality indicators? *Renew. Energy* 205, 273–280. doi:10.1016/j.renene.2023.01.080

Creutzig, F., Goldschmidt, J. C., Lehmann, P., Schmid, E., and von Blücher, F. (2021). Accelerating the global transition away from fossil fuels: a roadmap for rapid and inclusive decarbonization. *Energy Res. and Soc. Sci.* 74, 101998.

Degirmenci, T., and Aydin, M. (2024). Testing the load capacity curve hypothesis with green innovation, green tax, green energy, and technological diffusion: a novel approach to Kyoto protocol. *Sustain. Dev.* 32, 4931–4945. doi:10.1002/sd.2946

Deng, Q. S., Alvarado, R., Cuesta, L., Tillaguango, B., Murshed, M., Rehman, A., et al. (2022). Asymmetric impacts of foreign direct investment inflows, financial development, and social globalization on environmental pollution. *Econ. Analysis Policy* 76, 236–251. doi:10.1016/j.eap.2022.08.008

Elliott, G., Rothenberg, T. J., and Stock, J. H. (1992). Efficient tests for an autoregressive unit root. *Econometrica* 64, 813–836.

Fawzy, S., Osman, A. I., Mehta, N., Moran, D., Ala'a, H., and Rooney, D. W. (2022). Atmospheric carbon removal via industrial biochar systems: a techno-economic-environmental study. *J. Clean. Prod.* 371, 133660. doi:10.1016/j.jclepro.2022.133660

Internation Energy Agency (2021). China has a clear pathway to build a more sustainable, secure and inclusive energy future. Press. Available at: https://www.iea.org/news/china-has-a-clear-pathway-to-build-a-more-sustainable-secure-and-inclusive-energy-future.

Işık, C., Simionescu, M., Ongan, S., Radulescu, M., Yousaf, Z., Rehman, A., et al. (2023). Renewable energy, economic freedom and economic policy uncertainty: new evidence from a dynamic panel threshold analysis for the G-7 and BRIC countries. *Stoch. Environ. Res. Risk Assess.* 37, 3367–3382. doi:10.1007/s00477-023-02452-x

Jiang, T., Yu, Y., Jahanger, A., and Balsalobre-Lorente, D. (2022). Structural emissions reduction of China's power and heating industry under the goal of double carbon: a perspective from input-output analysis. *Sustain. Prod. Consum.* 31, 346–356. doi:10.1016/j.spc.2022.03.003

Lefebvre, D., Fawzy, S., Aquije, C. A., Osman, A. I., Draper, K. T., and Trabold, T. A. (2023). Biomass residue to carbon dioxide removal: quantifying the global impact of biochar. *Biochar* 5 (1), 65. doi:10.1007/s42773-023-00258-2

Menegaki, A. N., and Tugcu, C. T. (2018). Two versions of the Index of Sustainable Economic Welfare (ISEW) in the energy-growth nexus for selected Asian countries. *Sustain. Prod. Consump.* 14, 21–35.

Nadeem, M., Wang, Z., and Shakeel, M. (2023). Real output, fossil fuels, clean fuels and trade dynamics: new insights from structural break models in China. *Appl. Energy* 350, 121746. doi:10.1016/j.apenergy.2023.121746

Osman, A. I., Chen, L., Yang, M., Msigwa, G., Farghali, M., Fawzy, S., et al. (2023). Cost, environmental impact, and resilience of renewable energy under a changing climate: a review. *Environ. Chem. Lett.* 21 (2), 741–764. doi:10.1007/s10311-022-01532-8

Pesaran, M. H., Shin, Y., and Smith, R. J. (2001). Bounds testing approaches to the analysis of level relationships. *J. Appl. Econometrics.* 16 (3), 289–326.

Rahman, M. S., and Shahari, F. (2019). Does the financial integration in ASEAN+; 3 respond to financial cooperation agreement and influence the real sectors?. *Rev. Pac. Basin Financ.* 22 (01), 1950002.

Rehman, A., Ma, H., Chishti, M. Z., Ozturk, I., Irfan, M., and Ahmad, M. (2021). Asymmetric investigation to track the effect of urbanization, energy utilization, fossil fuel energy and CO_2 emission on economic efficiency in China: another outlook. *Environ. Sci. Pollut. Res.* 28, 17319–17330. doi:10.1007/s11356-020-12186-w

Rehman, A., Radulescu, M., Ahmad, F., Kamran Khan, M., Iacob, S. E., and Cismas, L. M. (2023). Investigating the asymmetrical influence of foreign direct investment, remittances, reserves, and information and communication technology on Pakistan's economic development. *Econ. Research-Ekonomska Istraživanja* 36 (2), 2131591. doi:10.1080/1331677x.2022.2131591

Rehman, A., Radulescu, M., Cismaş, L. M., Cismaş, C. M., Chandio, A. A., and Simoni, S. (2022). Renewable energy, urbanization, fossil fuel consumption, and economic growth dilemma in Romania: examining the short-and long-term impact. *Energies* 15 (19), 7180. doi:10.3390/en15197180

Shafiee, S., and Topal, E. (2021). A review of hydrogen as a clean fuel in transportation. *Renew. Sustain. Energy Rev.* 135, 110100.

Shakeel, M. (2021). Economic output, export, fossil fuels, non-fossil fuels and energy conservation: evidence from structural break models with VECMs in South Asia. *Environ. Sci. Pollut. Res.* 28 (3), 3162–3171. doi:10.1007/s11356-020-10729-9

Shakeel, M. (2021a). Economic output, export, fossil fuels, non-fossil fuels and energy conservation: evidence from structural break models with VECMs in South Asia. *Environ. Sci. Pollut. Res.* 28 (3), 3162–3171. doi:10.1007/s11356-020-10729-9

Shakeel, M. (2021b). Analyses of energy-GDP-export nexus: the way-forward. *Energy* 216, 119280. doi:10.1016/j.energy.2020.119280

Shakeel, M., and Ahmed, A. (2021). Economic growth, exports, and role of energy conservation: evidence from panel co-integration-based causality models in South Asia. *Energy and Environ.* 32 (1), 3–24. doi:10.1177/0958305x19899372

Shakeel, M., and Iqbal, M. M. (2014). Energy consumption and GDP with the role of trade in South Asia, in 2014 International Conference on Energy Systems and Policies (ICESP), Islamabad, Pakistan, 24–26 Nov. 2014, 1–5. doi:10.1109/ICESP.2014.7346987

Shin, Y., Yu, B., and Greenwood-Nimmo, M. (2014). Modelling asymmetric cointegration and dynamic multipliers in a nonlinear ARDL framework. *Festschrift in honor of Peter Schmidt: Econometric methods and applications*, 281–314.

Stern, D. I. (2004). The rise and fall of the environmental Kuznets curve. *World Dev.* 32 (8), 1419–1439. doi:10.1016/j.worlddev.2004.03.004

Su, L., Zheng, Y., Ahmad, F., Ozturk, I., Wang, Y., Tian, T., et al. (2023). Environmental regulations and Chinese energy sustainability: mediating role of green technology innovations in Chinese provinces. *Sustainability* 15 (11), 8950. doi:10.3390/su15118950

Wang, Y., Wang, X., Xie, S., Xie, J., and Yao, L. (2018). Characteristics and formation mechanisms of severe haze pollution in China. *Environ. Pollut.* 243, 215–226.

World Bank (2022). World development indicators. Available at: https://data.worldbank.org/onlinedatabase.

Yandle, B., Vijayaraghavan, M., and Bhattarai, M. (2002). *The environmental Kuznets curve*. A Primer, PERC Research Study 2 (1), 1–38.

Zeshan, M., and Shakeel, M. (2020). Adaptation and mitigation policies to climate change: a dynamic cge-we model. *Singap. Econ. Rev.* 68, 2169–2193. doi:10.1142/s0217590820500654

Zhang, Y., Li, J. S., Wu, Y., and Chen, Y. (2019). The environmental Kuznets curve in China: a comprehensive review of the literature. *J. Clean. Prod.* 208, 1032–1042.