China’s 2060 carbon-neutrality agenda: the nexus between energy consumption and environmental quality

Kaodui Li1,2,3 · Hongxin Ying1 · Yi Ning1 · Xiangmiao Wang1 · Mohammed Musah4 · Muntasir Murshed5,6 · Morrison Alfred7 · Yanhong Chu1 · Han Xu1 · Xinyi Yu1 · Xiaxin Ye1 · Qian Jiang1 · Qihe Han1

Received: 2 January 2022 / Accepted: 23 February 2022 / Published online: 23 March 2022 © The Author(s), under exclusive licence to Springer-Verlag GmbH Germany, part of Springer Nature 2022

Abstract
This study examined the nexus between energy consumption and environmental quality in light of China’s 2060 carbon-neutrality agenda utilizing annual frequency data from 1971 to 2018. In order to obtain valid and reliable outcomes, more robust econometric techniques were employed for the analysis. From the results, all the variables were first differenced stationary and cointegrated in the long-run. The elastic effects of the predictors on the explained variable were explored through the ARDL, FMOLS, and the DOLS techniques, and from the discoveries, energy utilization worsened environmental quality in the country via more CO2 emissions. Also, industrialization and urbanization deteriorated the country’s environmental quality; however, technological innovations improved ecological quality in the nation. On the causal connections between the variables, a unidirectional causality from energy consumption to CO2 effluents was discovered. Also, feedback causalities between industrialization and CO2 secretions, and between urbanization and CO2 exudates were disclosed. However, there was no causality between technological innovations and CO2 emanations. Based on the findings, the study recommended among others that, since energy consumption pollutes the environment, the country should transition to the utilization of renewable energies. Also, the government should allocate more resources to the renewable energy sector. This will help increase the portion of clean energy in the country’s total energy mix. Furthermore, research and development that are linked to the utilization of green energies should be supported by the government. Data constraints were the main limitation of this exploration. Therefore, in the future, if more data become available, similar explorations could be conducted to check the robustness of our study’s outcomes.

Keywords Energy consumption · Environmental quality · Industrialization · Technological innovations · Urbanization · China

Abbreviations

| EC | Energy consumption |
|----|-------------------|
| IND | Industrialization |
| URB | Technological innovations |
| EQ | Environmental quality |
| CO2 emissions | Carbon dioxide emissions |
| DARDL | Dynamic autoregressive distributed lag |
| ARDL | Autoregressive distributed lag |
| VECM | Vector error correction model |
| GMM | Generalized method of moments |
| AMG | Augmented mean group |

1 School of Finance and Economics, Jiangsu University, Zhenjiang, People’s Republic of China
2 College of Economics and Management, Nanjing University of Aeronautics and Astronautics, Nanjing, People’s Republic of China
3 Division of State-Owned Enterprise Reform and Innovation, Institute of Industrial Economics, Jiangsu University, Zhenjiang, People’s Republic of China
4 Department of Accounting, Banking and Finance, School of Business, Ghana Communication Technology University, Accra, Ghana
5 School of Business and Economics, North South University, Dhaka-1229, Bangladesh
6 Department of Journalism, Media and Communications, Daffodil International University, Dhaka, Bangladesh
7 Department of Accounting Studies Education, Akenpet Appiah-Menka University of Skills Training and Entrepreneurial Development, Kumasi, Ghana

Responsible Editor: Roula Inglesi-Lotz

Mohammed Musah
mmusah@gtcu.edu.gh

Springer
Introduction

The main ambition of most nations in recent times is to reduce the environmental implications of greenhouse gas (GHG) emissions which have resulted in global warming and climate change (Musa et al. 2021; Li et al. 2021). As a result, it has become imperative for the world economies to adopt policies that can enable them to decouple economic growth and environmental pollution (Qin et al. 2021). China as the leading emitter of carbon is under severe pressure to mitigate its CO₂ emissions (Ma et al. 2021; Yao and Zhang 2021; Liu et al. 2021; Xiaosan et al. 2021). As a signatory to the Paris Agreement (2015), Kyoto Protocol. (2005), Copenhagen Accord. (2009), and other international treaties, the country has initiated various environmental regulations and energy utilization strategies to help minimize the consumption of fossil fuels and other conventional energies that deteriorate its ecological quality (Yuelan et al. 2019; Li et al. 2021). By the year 2030, China aims to curtail its CO₂ emissions by 65% from the 2005 figure and promote the utilization of clean energies by about 25% (Yao and Zhang 2021; Li et al. 2021). Also, the government of China has the 2060 carbon-neutrality agenda which is one of its emission reduction strategies to help the nation attain become carbon neutral (Ahmad et al. 2019, 2018; Zeraibi et al. 2021; Rehman et al. 2021b). If China is able to meet its emission reduction targets, then, the world’s ambition of minimizing global warming and climate change would receive a major boost, because of the country’s dominance in global CO₂ effluents.

According to Lauri (2021), China’s CO₂ effusions increased by approximately 1.7% per year on average from 2015 to 2020. Irrespective of the economic consequences of the COVID-19 pandemic, the country’s CO₂ exudates continued to surge by about 1.5% in 2020. Overall, power generation by fossil fuels rose by 2.5% in 2020 compared to 2019 (China Electricity Council 2020). Moreover, production by industries accounted for 66% of the country’s total energy utilization and around 50% of its total emissions (China National Bureau of Statistics 2020). In 2019, steel and cement production surged by 7%, while noncombustion process-related emanations rose by 5.6%. Thus, industrial emissions are currently moving upwards, with productions from steel and cement being the dominant factors (Mikhail and Kate 2020). Though China has improved on its green energy generation, the share of solar, wind, and other clean sources of energies represent less than 10% of its total energy mix (China National Bureau of Statistics 2020). Besides, the nation’s economic recovery policies have been carbon-intensive, leading to the rise in fossil fuel power generation, coal mining output, and industrial coal utilization, resulting in more pollution (Lauri 2020). Therefore, shifting from this current energy profile to one focused on emission mitigations warrants a lot of efforts from the Chinese government.

Numerous explorations have focused on the linkage between energy consumption (EC) and environmental quality (EQ) in China. For example, Xiangmei et al. (2018) study on China affirmed EC as detrimental to EQ in the country. Also, Marques et al.’s (2021) investigation discovered CO₂ effusions as a driver of EC in the nation. Moreover, Yiping’s (2021) exploration confirmed electricity from renewable sources as beneficial to ecological quality in the country. According to Ma et al. (2019), industrial energy utilization
was the main determinant of environmental pollution in the country. Wang et al.'s (2021) study discovered energy from dirty sources as a trivial predictor of EQ in the nation. Also, Dong et al.'s (2018) analysis revealed green energy as harmless to EQ in the country. To Rong et al. (2020), electricity consumption explained more than 75% of CO2 effusions in the country. Moreover, Jian et al.'s (2019) study found EC as damaging to EQ in China. All the above explorations were conducted on China, but their findings are conflicting. The contrasting discoveries might be as a result of the methodologies employed, the time dimension or the studied variables among others. This suggests that the EC and EQ debate is far from over and demands more interrogations. Therefore, undertaken this research to come out with policy options to help China attain its sustainable development goals (SDGs) was deemed fitting. The main motivation of this study was to help China become carbon-neutral. According to a 2018 report of the Intergovernmental Panel on Climate Change, attaining global warming of 1.5 °C in 2030 will demand that global CO2 emanations reduce by 45% from 2010, reaching a net zero around 2050, while attaining global warming of 2 °C in 2030 will demand that global CO2 effluents reduce by 25% from 2030, reaching a net zero around 2070. Therefore, if China should wait until 2030 before they take carbon-neutrality actions, their global emission ambitions cannot be accomplished. Hence, a study to help the Chinese government to improve its CO2 effusions mitigation strategies was deemed appropriate.

The contributions of this exploration are in threefold. First, the study contributed methodologically by following a well-outlined analytical process. At the initial stage, stationarity tests were undertaken to examine the variables’ integration order. Afterwards, tests to check the cointegration attributes of the series were conducted. At the third phase, the elastic effects of the covariates on the response variable were explored. Finally, a causality test was undertaken to determine the path of causations amidst the series. Most prior explorations on the EC and EQ connection failed to follow a well-outlined econometric strategy. Secondly, the issue of omitted variable bias (OVB) is not been recognized by most studies on the connection between EC and EQ. This is disadvantageous because OVB could yield prejudiced and unreliable coefficient values, which could lead to erroneous inferences (Musah et al. 2021a, b, c; Li et al. 2020a, b). This study therefore controlled for industrialization (IND), technological innovations (TI), and urbanization (URB) to help minimize OVB issues. Finally, our exploration adopted the time series approach, which completely varies from other prior investigations on the topic of concern. This approach was used because it helps to improve the power of statistical tests leading to more robust outcomes. Most prior investigations on the studied topic adopted different approaches and might have failed to capture the true relationship amidst the series.

The significance of this exploration cannot be underrated. First, the recommendations of this study will help the Chinese government to adopt renewable and other energy utilization alternatives that will help boost ecological quality in the country. The study is also essential because it will help policymakers to implement other effective policy interventions that are required to minimize climate change and its repercussions. The study is finally vital in that, it adds to the existing literature on the linkage between EC and EQ. This will serve as a reference material for future studies on the topic of concern. This paper is original because, its goal is clearly stated; the methodologies used are extensive; the findings are well reported, evaluated, and debated; and the policy suggestions are well-thought-out. This paper is grouped into five sections. The “Introduction” section is the introduction of the study, while the “Literature review” section outlines literature that supports the issue at hand. The “Materials and methods” section is on the methodology, while the “Results of the study” section displays the study’s results and discussions. Finally, the “Conclusions and policy recommendations” section presents the conclusions, recommendations, and study limitations.

### Literature review

In this section, literature that are related to the topic are reviewed. The reviews are categorized into two. The first part reviews literature on the nexus between EC and EQ in China, while the second part presents reviews on the connection between EC and EQ in other parts of the world. On the linkage between EC and EQ in China, Rahman and Vu’s (2021) research discovered a positive association between EC and ecological pollution in the country. Also, the VECM Granger causality found a one-way causality from CO2 secretions to EC in the nation. Yao and Zhang (2021) also studied the connection between EC and EQ in China by employing the ARDL estimator. From the revelations, clean energy enhanced EQ in the country. Zheng et al. (2020) researched on China from the period 1978. From the results, the influence of energy intensity slowed the growth of CO2 effusions in the country. Shum et al. (2021) analyzed the determinants of EQ in China by employing the LASSO model. From the results, EC was a main driver of CO2 exudates. Xiangmei et al. (2018) undertook a study on China from 1953 to 2016. From the results, EC surged CO2 effusions in the country. Khan et al. (2021a, b, c, d) explored the beta decoupling relationship between EC and
From the results, CO2 effusions drove energy consumption from EC to CO2 effluents in China was found. Li et al. (2021) investigated the drivers of ecological footprint (EFP) in China over a 36-year period. The ARDL approach was engaged to determine the coefficients of the predictors. From the discoveries, energy from dirty sources was not a material predictor of EQ in the country. Alola et al. (2021) researched on China from 1971 to 2016. Based on the QQR estimates, fossil fuel and primary energy utilization impacted positively on EFP in all quantiles. Amazingly, clean energy utilization also exerted a positive influence on EFP in the country. Finally, the spectral Granger causality (SGC) discovered a causation from primary energy use to EFP and from clean energy to EFP. Zou and Zhang (2020) examined the connection between EC and EQ in China from 2000 to 2017. From the results, EC and EQ were interrelated as a feedback causality between the two series was observed. Tong et al. (2020) conducted a study on E7 countries by employing the ARDL technique. From the revelations, a short-run causality from EC to CO2 effluents in China was found. Li et al. (2021), Li et al. (2021), Li et al. (2021), Li et al. (2021), Li et al. (2021) investigated the linkage between energy structure and EQ in 30 Chinese provinces from 2011 to 2017. From the discoveries, energy structure based on coal had a substantial effect on emissions in the country. Jian et al. (2019) undertook a study on China from 1982 to 2017. From the results, EC surged ecological pollution in the country.

Numerous explorations on EC and EQ in other parts of the world have also been conducted with contrasting discoveries. For example, Agbede et al. (2021) investigated MINT countries over the period 1971 to 2017. The ARDL-PMG results of the study revealed a positive association between EC and environmental pollution. Also, a causality from EC to ecological pollution was unfolded. Ahmad et al. (2021a, b) investigated 11 developing economies from 1992 to 2014. From the discoveries, a surge in electricity consumption minimized environmental pollution in the economies. The finding implies country-specific policies should be undertaken to help stimulate EQ in the economies. Qayyum et al. (2021) analyzed the nexus between EC and EQ in India from 1990Q1 to 2015Q4. From the results, REC was beneficial to EQ in the country. Also, REC caused consumption-based CO2 effusions at different frequency levels. Chien et al. (2021) researched on top Asian economies from 1990 to 2017. Based on the CS-ARDL estimates, REC improved EQ in the economies; however, NREC spurred environmental pollution in the economies. Khan et al. (2021a, b, c, d) analyzed the linkage between EC and EQ in 21 developing economies from 1970 to 2018. The study employed the OLS, FE, and the GMM regression techniques in its analysis. From the discoveries, REC improved EQ in the economies; however, NREC was not friendly to the ecologies of the nations.

Khan et al. (2021a) assessed the connexion amidst EC and ecological pollution in 188 countries from 2002 to 2018. From the OLS, FE, GMM and the system GMM estimates, NREC escalated environmental pollution in the nations; however, REC was friendly to the countries’ environment. Xue et al. (2021) examined the linkage between EC and EQ in South Asian economies by employing recently developed econometric techniques. From the discoveries, REC improved EQ in the economies; however, NREC deteriorated ecological quality in the economies. Khan et al. (2021b) investigated the association between EC and environmental pollution in 180 economies from 2002 to 2019. From the OLS, FE and system GMM discoveries, REC reduced ecological pollution in the economies. Khan et al. (2021c) used a global panel to investigate the determinants of EQ from 2002 to 2019. From the two-step system GMM results of the study, REC enhanced EQ in the countries. Bekun et al. (2021) researched on SSA and discovered from the PMG econometric technique that conventional energy harmed EQ in the countries; however, clean energy improved the countries’ EQ. Bibi et al. (2021) investigated the linkage between biomass EC and EQ in the US from 1981M01 to 2019M12. From the revelations, a causation from BEC to CO2 effluents was discovered. Ali et al. (2021) undertook a study on Nigeria from 1981 to 2014. Based on the DARDL results, EC spurred CO2 excretions in the nation. Iqbal et al. (2021) explored the asymmetric effects of clean energy on CO2 effusions in Pakistan. The NARDL technique was used to determine the parameters of the covariates. From the results, positive changes in clean energy generation promoted CO2 exudates in the country; however, negative changes in clean energy generation mitigated CO2 secretions in the nation. Ahmad et al. (2021a, b) investigated 11 developing economies from 1992 to 2014. The FMOLS
and the PMG techniques were employed for the parameter estimations, and from the findings, electricity consumption mitigated environmental pollution in the economies. Also, a feedback causation amidst electricity consumption and CO₂ exudates was established.

Baydoun and Aga (2021) studied the linkage between EC and EQ in GCC economies from 1995 to 2018. From the CS-ARDL estimates, EC worsened EQ in the countries via high CO₂ excretion. Also, a causality from EC to CO₂ effluents was disclosed. Nawaz et al. (2021) analyzed the impasse of EC on EQ in South Asian economies from 1990 to 2017. Based on the FMOLS estimates, EC minimized EQ in the countries. Khurshid et al. (2021) investigated the association between EC and EQ in Western and Southern Europe from 2000 to 2018. The NARDL and the OLS approaches were engaged for the parameter estimations. From the discoveries, EC was a key polluter in the economies. Chunyu et al. (2021) researched on 18 countries from 2010 to 2019 and disclosed that energy from dirty sources mitigated EQ in the countries; however, energy from clean sources improved EQ in the nations. Musa et al. (2021) investigated the EC and EQ connection in EU-28 countries from 2002 to 2014. From the two-step GMM discoveries of the study, REC was positively related to environmental performance in the nations. Balli et al. (2020) researched on Turkey from 1960 to 2014. Based on the VECM output, a causation from EC to CO₂ exudates was confirmed. Osobajo et al. (2020) analyzed the association between EC and EQ in 70 economies from 1994 to 2013. Findings of the study confirmed EC as detrimental to EQ in the countries. Also, a one-directional causality from EC to CO₂ excretions was unfolded. Alharthi et al. (2021) investigated the link between EC and EQ in MENA countries from 1990 to 2015. From the discoveries, REC mitigated ecological pollution in the countries, but NREC worsened environmental pollution in the economies. Chontanawat (2020) explored the linkage between EC and CO₂ emanations in ASEAN region from 1971 to 2015. From the results, EC was materially related to environmental pollution in the region. All the aforesaid studies are on the connection between EC and EQ; however, their findings are contradictory. The conflicting outcomes might be as a result of the methodologies employed, the time dimension or the studied variables among others. This suggests that the EC and EQ argument is unceasing and warranted further investigations. Therefore, a study on the linkage between EC and EQ in China was worthwhile.

Materials and methods

Data source and descriptive statistics

A time series data on China for the period 1971 to 2018 was used for the study. The study period was chosen based on data availability. For instance, there was no data available for the proxy of environment quality (CO₂ emissions) after 2018. Also, data for energy consumption was not available from 1960 to 1970 and after 2014. Therefore, using the explained variable as the determining factor, the period 1971 to 2018 was deemed appropriate. This implies the data used for the analysis was not balanced. Further details on the series are outlined in Table 1. The descriptive statistics of the series are displayed in Tables 2 and 3. From the table, IND was the highest in terms of average values, while TI was the lowest. Also, TI was the most volatile based on the SD values, while URB was the least volatile. From the skewness results, the distribution of TI was negatively skewed, while that of the rest was positively skewed. The kurtosis outcomes also confirmed the distribution of TI to be leptokurtic in shape, while that of the rest was platykurtic in shape. Additionally, the covariates were not highly collinear based on the multi-collinearity test results. Finally from the PCA results indicated in Table 4, the predictors had higher

| Table 1 Variable description and measurement units |
|---------------------------------------------------|
| Variable                                      | Measurement unit                        | Source   |
| Environmental quality (CO₂ emissions)          | Metric tons per capita                  | WDI (2021) |
| Energy consumption (EC)                        | Kg of oil equivalent per capita          | WDI (2021) |
| Industrialization (IND)                        | Industry (including construction), value added (constant 2010 US$) | WDI (2021) |
| Technological innovation                       | Resident and nonresident patent applications | WDI (2021) |
| Urbanization (URB)                             | Urban population (% of total population)  | WDI (2021) |
**Table 2** Descriptive statistics and correlative matrix

| Statistic | lnCO2 | lnEC | lnIND | lnTI | lnURB |
|-----------|-------|------|-------|------|-------|
| Mean      | 0.955 | 6.764| 26.706| 0.254| 3.378 |
| Median    | 0.893 | 6.642| 26.634| 0.939| 3.371 |
| Maximum   | 2.023 | 7.713| 28.999| 1.822| 4.016 |
| Minimum   | 0.041 | 6.142| 24.659| −10.012| 2.844 |
| Std. dev  | 0.603 | 0.472| 1.398 | 1.921| 0.388 |
| Skewness  | 0.393 | 0.703| 0.081 | −3.644| 0.079 |
| Kurtosis  | 2.098 | 2.369| 1.674 | 19.435| 1.685 |
| Jarque–Bera| 0.781| 0.459| 0.698 | 0.385| 1.000 |
| Probability| 0.262| 0.108| 0.188 | 0.231| 0.193 |

**Table 3** Multi-collinearity tests results

| Variable | VIF | Tolerance | Farrar and Glauber test |
|----------|-----|-----------|-------------------------|
| lnEC     | 2.39 | 0.418     | 4.022 | 0.008*** |
| lnIND    | 2.93 | 0.341     | 5.774 | 0.037**  |
| lnTI     | 2.02 | 0.495     | 3.098 | 0.072*   |
| lnURB    | 2.52 | 0.397     | 2.979 | 0.005*** |
| Mean VIF | 2.47 | -         | -     | -        |

VIF variance inflation factor while ***, **, * denote significance at the 1%, 5%, and the 10% levels respectively.

**Table 4** Principal component analysis

| Component | Eigenvalue | Difference | Proportion | Cumulative |
|-----------|------------|------------|------------|------------|
| Comp 1    | 2.382      | 1.314      | 0.596      | 0.596      |
| Comp 2    | 1.068      | 0.719      | 0.267      | 0.863      |
| Comp 3    | 0.349      | 0.148      | 0.087      | 0.950      |
| Comp 4    | 0.201      | -          | 0.050      | 1.000      |

| Principal components (eigenvectors) | variable | Comp 1 | Comp 2 |
|-------------------------------------|----------|--------|--------|
| lnEC                                | 0.514    | -0.322 |
| lnIND                               | 0.529    | -0.198 |
| lnTI                                | 0.422    | 0.902a |
| lnURB                               | 0.528    | -0.209 |

n denotes significant loadings under comp 1, while *represents significant loadings under comp 1.

Model specification

This study examined the link between energy consumption (EC) and environmental quality (proxied by CO2 emissions) in China, while controlling for industrialization (IND), technological innovation (TI), and urbanization (URB). In achieving this goal, the following econometric model was proposed.

\[ CO_{2it} = a_i + \beta_1 EC_{it} + \beta_2 IND_{it} + \beta_3 TI_{it} + \beta_4 URB_{it} + \mu_{it} \] (1)

where \( CO_{2it} \) is the response variable representing environmental quality (EQ) and EC is the main explanatory variable of concern. Also, \( \beta_1, \beta_2, \beta_3, \) and \( \beta_4 \) are the parameters of the regressors, while \( \alpha_i \) is the constant term. Moreover, \( \mu_{it} \) is the error term, while \( i \) and \( t \) denote the country and time respectively. To help reduce heterocedasticity issues, natural logarithm was taken on both sides of Eq. 1. The resulting log-linear model therefore became:

\[ \ln CO_{2it} = a_i + \beta_1 \ln EC_{it} + \beta_2 \ln IND_{it} + \beta_3 \ln TI_{it} + \beta_4 \ln URB_{it} + \mu_{it} \] (2)

where \( \ln CO_{2it} \) is the logarithm of the explained variable, while \( \ln EC, \ln IND, \ln TI, \) and \( \ln URB \) are the log conversions of the explanatory variables. After transforming the variables into natural logarithms, the coefficients could be interpreted as elasticities. The study expected EC to have a positive influence on CO2 effusions (\( \beta_1 > 0 \)), if residential and nonresidential energies consumed in the countries are carbon-intensive. Otherwise, EC was to exert a negative effect on CO2 exudates (\( \beta_1 < 0 \)), if energies consumed in the country were from clean sources that could help to boost EQ in the nation (\( \beta_2 > 0 \)). Also, IND was to positively influence CO2 effluents (\( \beta_2 > 0 \)), if the energies utilized at the industrial level in the country were not environmentally friendly. Otherwise, IND was to negatively impact the emissivities of CO2 in the nation (\( \beta_2 < 0 \)), if IND was linked to the use of green energy. Additionally, TI was to mitigate the emanation of CO2 in the country (\( \beta_3 < 0 \)) because it promotes less polluting activities in an economy. Finally, URB was to have a positive impact on CO2 emittance (\( \beta_3 > 0 \)), if URB led to the utilization of polluting energies in the country both domestically and industrially. Otherwise, URB was to negatively affect CO2 emissions and were, therefore, appropriate to predict the emanation of CO2 in the country.
excretions ($\beta_2 < 0$), if the migration of people to big cities in China resulted in the utilization of green energy.

**Analytical process**

To comprehensively examine the EC-EQ linkage in China, a four-staged econometric procedure was followed. Firstly, the ADF and the PP tests for unit root were conducted to examine the integration order of the variables. Afterwards, following Murshed (2021), the ARDL bound test and the Johansen test were performed to check the cointegration attributes of the series. Following Pesaran et al. (2001), the ARDL bound test specification for this study is expressed as;

$$
\Delta \ln CO_{2t} = \varphi_0 + \varphi_1 \ln CO_{2t-1} + \varphi_2 \ln EC_{t-1} + \varphi_3 \ln IND_{t-1} + \varphi_4 \ln TI_{t-1} + \varphi_5 \ln URB_{t-1} + \sum_{i=1}^{q} \beta_i \Delta CO_{2t-1}
$$

where the change operator is denoted by $\Delta$, the optimal lags selected via the AIC is represented by $t-1$, and the estimated parameters are denoted by $\varphi$ and $\beta$. It should be noted that the Johansen cointegration test was employed to authenticate the bound test results. This test is advantageous because it can detect multiple cointegrating vectors (Johansen 1991). At the third phase of the analysis, the elasticities of the predictors were first estimated via the ARDL approach. This method was adopted because it produces valid results even in short-time datasets. Also, if the integration order of investigated series is mixed, the estimator can still produce vigorous results (Khan et al. 2021b). The ARDL model developed to explore the long-run connections amidst the variables is specified as;

$$
\ln CO_{2t} = a_0 + \sum_{j=1}^{m} \sigma_j \ln CO_{2t-j} + \sum_{j=1}^{m} \sigma_j \ln EC_{t-j}
+ \sum_{j=1}^{m} \sigma_j \ln IND_{t-j} + \sum_{j=1}^{m} \sigma_j \ln TI_{t-j} + \sum_{j=1}^{m} \sigma_j \ln URB_{t-j} + \nu_t
$$

where $\sigma$ denotes the long-term variance in the variables and $q$ represents the lags selected through the AIC. The short-run ARDL model for the exploration is expressed as;

$$
\ln CO_{2t} = a_0 + \sum_{j=1}^{m} \sigma_j \Delta \ln CO_{2t-j}
+ \sum_{j=1}^{m} \sigma_j \Delta \ln EC_{t-j}
+ \sum_{j=1}^{m} \sigma_j \Delta \ln IND_{t-j}
+ \sum_{j=1}^{m} \sigma_j \Delta \ln TI_{t-j}
+ \sum_{j=1}^{m} \sigma_j \Delta \ln URB_{t-j} + \phi ECT_{t-j} + \nu_t
$$

where the variance of the short run is symbolized by $\sigma$, the error correction term is represented by $ECT_{t-1}$, and $\phi$ is the parameter of the ECT. For robustness purpose, the FMOLS and the DOLS estimators were also adopted. These estimators were adopted because they mitigate issues of heteroscedasticity (Kiefer and Vogelsang 2002). The techniques are also advantageous because they are vigorous to endogeneity and autocorrelation in regression analysis (Funk and Strauss 2000). The FMOLS estimator is specified as;

$$
\hat{\beta}_{FMOLS} = \left[ \frac{1}{T} \sum_{t=1}^{T} \left( \sum_{j=1}^{m} R_{i,j} R_{i,j}^T \right)^{-1} \right]^{-1}
\left( \sum_{t=1}^{T} R_{i,t} \tilde{\nu}_t \right)
$$

In Eq. 6, $r$ and $h$ symbolize the regressors and the regressand correspondingly, while $\Delta_{cu}$ is the covariance term. Also, $\Delta_{cu}$ is the estimated value of the covariance term,

while $T$ and $N$ are the time frame and the dimension of the data respectively. The DOLS estimator on the other hand is expressed as;

$$
\hat{\beta}_{DOLS} = \left[ \frac{1}{N} \sum_{i=1}^{N} \left( \sum_{t=1}^{T} \left( \sum_{j=1}^{m} R_{i,j} R_{i,j}^T \right)^{-1} \right) \left( \sum_{t=1}^{T} R_{i,t} \tilde{\nu}_t \right) \right]^{-1}
$$

where $R$ epitomizes the set of predictors that are $2(k + 1) \times 1$ and $R_{i,t} = (r_{i,1} - \bar{r}_1, \Delta r_{i,2-k}, \ldots, \Delta r_{i,K}) - K$ is the number of covariates. Finally, the VECM of Engle and Granger (1987) was engaged to examine causations amidst the series. This estimator was adopted because it yields consistent and reliable results in time series analysis. The test began by first estimating Eq. 2 to recover residuals considered as lagged error correction terms (ECT). Afterwards, the ensuing dynamic error correction models were estimated to unravel the causalities amidst the series;

$$
\Delta \ln CO_{2t} = a_0 + \sum_{j=1}^{m} \varphi_{1,j} \Delta \ln CO_{2t-j} + \sum_{j=1}^{m} \varphi_{2,j} \Delta \ln EC_{t-j}
+ \sum_{j=1}^{m} \varphi_{2,j} \Delta \ln IND_{t-j} + \sum_{j=1}^{m} \varphi_{2,j} \Delta \ln TI_{t-j}
+ \sum_{j=1}^{m} \varphi_{2,j} \Delta \ln URB_{t-j} + \phi ECT_{t-j} + \nu_t
$$

$$
\Delta EC_t = a_0 + \sum_{j=1}^{m} \varphi_{1,j} \Delta \ln EC_{t-j} + \sum_{j=1}^{m} \varphi_{2,j} \Delta \ln CO_{2t-j}
+ \sum_{j=1}^{m} \varphi_{2,j} \Delta \ln IND_{t-j} + \sum_{j=1}^{m} \varphi_{2,j} \Delta \ln TI_{t-j}
+ \sum_{j=1}^{m} \varphi_{2,j} \Delta \ln URB_{t-j} + \phi ECT_{t-j} + \nu_t
$$
The analysis began by testing for unit root in the variables. From the results displayed in Table 5, all the series had a level order of integration. Based on the estimates indicated in Table 7, EC spurred CO₂ emissions in China. *Ceteris paribus*, a 1% rise in EC surged CO₂ effusions by 6.227% and 4.145% in both the long and the short run respectively. This means that the country’s economic activities were linked to the utilization of polluting energies like coal and fossil fuel among other, which exacerbated the rate of emissions in the nation. Explorations by Abbasi and Adedoyin (2021) and Musah et al. (2021c) offer support to the study’s finding, but those by Kirikkaleli and Adebayo (2021a, b) and Anwar et al. (2021) are conflicting to the above disclosure. Also, IND worsened environmental quality by 2.172% and 1.395% in both the long and the short run correspondingly. This revelation is not surprising in that China has witnessed a major economic expansion of late, thanks to the rise in the country’s industrial activities. However, majority of the industries in the nation are highly reliant on carbon-intensive energies sources, which pollute the environment. Studies by Ullah et al. (2020) and Rehman et al. (2021a) align the outcome of the study, but those by Appiah et al. (2021) and Zhou and Li (2020) deviate from

\[
\Delta \text{IND}_t = \alpha_1 + \sum_{j=1}^{q} \phi_{1,j} \Delta \ln \text{IND}_{t-j} + \sum_{j=1}^{q} \phi_{2,j} \Delta \ln \text{EC}_{t-j}
\]

(10)

\[
\Delta \text{TI}_t = \alpha_1 + \sum_{j=1}^{q} \phi_{1,j} \Delta \ln \text{TI}_{t-j} + \sum_{j=1}^{q} \phi_{2,j} \Delta \ln \text{URB}_{t-j} - \varphi_1 ECT_{t-1} + \mu_1
\]

(11)

\[
\Delta \text{URB}_t = \alpha_1 + \sum_{j=1}^{q} \phi_{1,j} \Delta \ln \text{URB}_{t-j} + \sum_{j=1}^{q} \phi_{2,j} \Delta \ln \text{TI}_{t-j}
\]

(12)

The top values for the variables denote unit root statistics, while the down values represent probabilities. Also, ***, **, and * denote significance at the 1%, 5%, and the 10% levels respectively.
the above discovery. Moreover, TI improved environmental quality in the country. Specifically, a 1% surge in TI mitigated CO2 emissivities by 3.214% and 2.293% in the long and the short run respectively. This finding suggests that technology was key in the nation’s strive towards a low-carbon economy. Empirical explorations by Chen and Lee (2020) and Yu and Du (2019) agree with the discovery of the study, but those by Khattak et al. (2020) and Villanthen-kodath and Mahalik (2020) vary from the above disclosure.

Furthermore, URB worsened environmental quality in China. Ceteris paribus, a 1% change in URB escalated CO2 effusions by 4.411% and 3.332% in both the long and the short run correspondingly. This result implies, URB led to developments in economic activities like industrialization and the creation of basic infrastructure like roads, bridges, and markets, which are heavily reliant on the utilization of polluting energies, leading to more effusions. Put simply, URB policies of the nation did not help to propel ecological welfare targets of the country. The discovery collabo-

\begin{table}[h]
\centering
\caption{ARDL estimation results} \label{tab:ARDL_estimation}
\begin{tabular}{lccccc}
\hline
Variable & Coeff & SE & t statistic & Prob \\
\hline
lnEC_{t-1} & 6.227 & 1.5151 & 4.11 & 0.005*** \\
∆ln EC & 4.145 & 1.2833 & 3.23 & 0.007*** \\
lnIND_{t-1} & 2.172 & 0.9568 & 2.27 & 0.025** \\
∆lnIND & 1.395 & 0.6940 & 2.01 & 0.043** \\
lnTI_{t-1} & −3.214 & 0.8262 & −3.89 & 0.059* \\
∆lnTI & −2.293 & 1.1943 & −1.92 & 0.028*** \\
lnURB_{t-1} & 4.111 & 2.0234 & 2.18 & 0.003*** \\
∆lnURB & 3.332 & 2.1497 & 1.55 & 0.007** \\
Constant & 5.248 & 1.3526 & 3.88 & 0.001*** \\
ECT_{t-1} & −0.716 & 0.2295 & −3.12 & 0.004*** \\
R² & 0.821 & \text{B-G test} & 0.821(0.556) \\
Adjusted R² & 0.805 & \text{ARCH test} & 0.725(0.646) \\
F statistic & 116.334 & \text{RESET test} & 0.641(0.477) \\
(0.008)*** & & & \\
B-G LM test & 1.102(0.913) & \text{J-B test} & 1.882(0.712) \\
\hline
\end{tabular}
\end{table}

\textit{lnCO2} the response variable, SE for standard errors, B-G \textit{LM test} Breusch-Godfrey LM test, B-P-G \textit{test} Breusch-Pagan-Godfrey test, ARCH signifies autoregressive conditional heteroscedastic test, J-B Jarque–Bera test, and \textit{RESET test} Ramsey regression equation specification error test. Also, *, **, *** denote significance at the 1%, 5%, and the 10% levels respectively, while values in parenthesis () represent probabilities.
worsened EQ by 0.827%, 0.692%, and 1.868% respectively. However, TI improved EQ by 0.017%. The weight of the coefficients and the levels of significance under the two estimators were dissimilar from the ARDL technique. However, the parameters of the predictors in terms of sign were the same under the three approaches. This underscores the robustness of the study’s results. The elastic effects of the predictors on the response variable are illustrated in Fig. 1.

At the final stage, the VECM of Engle and Granger (1987) was engaged to explore the causalities between the variables. Based on the estimates displayed in Table 9, a causation from EC to CO₂ effusions was unfolded. This implies carbon emissivities were reliant on energy consumption in the country. Studies by Musah et al. (2021a) and Li et al. (2020a) align the finding of the study, but those by Doğanlar et al. (2021) deviate from the above outcome. Also, IND and CO₂ emissions were mutually related. This means the two variables were dependent on each other. Thus, a rise in IND led to a rise in CO₂ effusions and vice versa. Empirical explorations by Liu and Bae (2018) and Al-Mulali and Ozturk (2015) support the above revelation, but that of Musa et al. (2021) contradicts the study’s discovery. Moreover, there was no causality between TI and CO₂ emanations in the country. This signposts that the two series did not cause each other. Investigations by Bashir et al. (2020) and Abid et al. (2021) are in tandem with the above revelation, but that of Sana et al. (2021) varies from the study’s finding. Finally, a double-headed causality between CO₂ effluents and URB was disclosed. This means, the two variables caused each other or were inter-dependent on each other. Implying a rise in one variable led to a rise in the other variable and vice versa. Studies by Ahmed et al. (2019) and Salahuddin et al. (2019) offer support to the study’s outcome, but those by Haseeb et al. (2018) and Mesagan and Nwachukwu (2018) contrast the outcome of the study.

### Conclusions and policy recommendations

This study examined the connection between energy utilization and environmental quality in China for the period 1971 to 2018. Robust econometric methods that offer valid and reliable results were used for that analysis. From the results, all the variables had I(1) order of integration and were flanked by a long-term cointegration association. The coefficients of the predictors were first explored via the ARDL estimator and from the discoveries, energy utilization degraded ecological quality in the country via high CO₂ effusions. Also, industrialization and urbanization deteriorated the country’s environmental quality; however, technological innovations improved ecological quality in the nation. The FMOLS and the DOLS estimates were also explored to help check the vigorousness of the ARDL results, and from the revelations, the parameters of the predictors in terms of sign under the FMOLS and the DOLS techniques were the same as those under the ARDL approach. This suggests that the results were valid and reliable. The causal connections between the series were explored via the VECM of Engle and Granger (1987) and from the results, a unidirectional causality from energy consumption to CO₂ effluents was discovered. Also, feedback causalities between industrialization and CO₂ secretions, and between urbanization and CO₂ exudates were disclosed. However, there was no causality between the variables.

### Table 8 FMOLS and DOLS estimation results

| Variable | Coefficient | Std. error | t statistic | Prob  |
|----------|-------------|------------|------------|-------|
| lnEC     | 0.827       | 0.097      | 8.526      | 0.000***|
| lnIND    | 0.692       | 0.163      | 4.245      | 0.086* |
| lnTI     | -0.017      | 0.008      | -2.125     | 0.019**|
| lnURB    | 1.868       | 0.592      | 3.155      | 0.025**|
| R-squared|             |            |            | 0.891  |
| Adjusted R-squared| | 0.802 |

| Variable | Coefficient | Std. error | t statistic | Prob  |
|----------|-------------|------------|------------|-------|
| lnEC     | 0.858       | 0.111      | 7.730      | 0.000***|
| lnIND    | 0.376       | 0.179      | 2.101      | 0.017**|
| lnTI     | -0.912      | 0.209      | -4.364     | 0.072* |
| lnURB    | 2.407       | 0.657      | 3.664      | 0.061* |
| R-squared|             |            |            | 0.791  |
| Adjusted R-squared| | 0.719 |

lnCO₂ response variable; and ***, **, and * denote significance at the 1%, 5%, and the 10% levels respectively.
between technological innovations and CO2 emanations. The causal connections amidst the series are depicted in Fig. 2.

Based on the findings, the study concludes that energy consumption, industrialization, and urbanization are harmful to environmental quality in China, but technological innovations help to advance ecological quality in the country. With reference to the above conclusions, the study recommends that since energy consumption pollutes the environment, the country should transition to the utilization of renewable energies. Also, the government should allocate more resources to the renewable energy sector. This will help increase the portion of clean energy in the country’s total energy mix. Furthermore, research and development that are linked to the utilization of green energies should be supported by the government. Moreover, majority of people are not aware of the environmental consequences of dirty energies and the health benefits of green energies. Therefore, the government should intensify its awareness creation strategies to help attain the aforesaid issues. Since industrialization added to environmental pollution in the country, the Chinese government should ban the establishment of polluting industries in the country. However, industries that factor ecologically friendly issues in their operations should be permitted to operate in the country. Also, the government can reduce the tax burden of environmentally friendly industries, while increasing that of environmentally unfriendly ones. This will propel the latter to shift to ecologically friendly activities. From the discoveries, urbanization also degraded environmental quality in the country. As a recommendation, the Chinese government should improve the living standards of people in remote areas. This will prevent them from migrating to urban cities. Also, basic infrastructural facilities that attract people to move to urban centers should be provided for them in their respective localities. According to Behera and Dash (2017), sustainable urbanization model rather than unsustainable urbanization model should adopted in managing the rate of urbanization in economies. Therefore, following the above authors, sustainable urbanization model should be adopted to control the rate of urbanization in the country. Finally, because technological innovations helped to improve environmental quality in the country, the government should advocate for the adoption of environmentally friendly technologies in all organizations and institutions. Data constraints was the main limitation of this exploration. For instance, there was no data available for the proxy of environmental quality (CO2 emissions) after 2018. Also, data for energy consumption was not available from 1960 to 1970 and after 2014. Therefore, using the explained variable as the determining factor, the period 1971 to 2018 was deemed

Table 9 Pairwise Granger causality tests results

| Variable | lnCO2  | lnEC  | lnIND | lnTI  | lnURB | ECT  |
|----------|--------|-------|-------|-------|-------|------|
| lnCO2    | -      | 3.351 | 4.194 | 2.192 | 4.143 | -0.772 |
| lnEC     | (0.147)| -     | 6.656 | 2.421 | 8.074 | -0.662 |
| lnIND    | (0.004)***| (0.411)| (0.035)**| (0.078)*| (0.008)***|
| lnTI     | (0.016)**| (0.044)**| (0.783)| (0.080)| (0.037)**|
| lnURB    | (0.053)*| (0.145) | (0.345)| (0.034)**| (0.048)**|

lnCO2 response variable, while values in parenthesis () represent probabilities. Finally, ***, **, * denote significance at the 1%, 5%, and the 10% levels respectively.

Fig. 2 The causal connections between the explained and the explanatory variables. Note: (↔) signifies a two-way causality between variables, (←) denotes a one-way causality between variables, and (–-) represents no causality between variables.

Springer
appropriate. This implies the data used for the analysis was not balanced. In future if the missing data become available, similar explorations could be conducted to check the robustness of the study’s outcomes.

**Author contribution** KL conceptualized the study; HY drafted the original manuscript; YN helped in analysis and discussions; XW provided data; MM1 wrote the final manuscript; MM2 conducted the literature review and helped in analysis and discussions; MA helped in analysis and discussions; YC helped in analysis and discussions; HX helped in analysis and discussions; QH helped in analysis and discussions; QI helped in analysis and discussions; QH edited the final manuscript. All authors read and approved the final manuscript.

**Data availability** The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

**Declarations**

**Ethics approval and consent to participate** Not applicable.

**Consent for publication** Not applicable.

**Competing interests** The authors declare no competing interests.

**References**

Abbasi KR, Adebayin FF (2021) Do energy use and economic policy uncertainty affect CO2 emissions in China? Empirical evidence from the dynamic ARDL simulation approach. Environ Sci Pollut Res 28:23323–23335. https://doi.org/10.1007/s11356-020-12217-6

Abid A, Mehmood U, Tariq S et al (2021) The effect of technological innovation, FDI, and financial development on CO2 emission: evidence from the G8 countries. Environ Sci Pollut Res. https://doi.org/10.1007/s11356-021-15993-x

Agbede EA, Bani Y, Azman-Saini W et al (2021) The impact of energy consumption on environmental quality: empirical evidence from the MINT countries. Environ Sci Polliut Res. https://doi.org/10.1007/s11356-021-14407-2

Ahmad M, Khan Z, Ur Rahman Z, Khan S (2018) Does financial development asymmetrically affect CO2 emissions in China? An application of the nonlinear autoregressive distributed lag (NARDL) model. Carbon Management 9(6):631–644

Ahmad M, U1 Haq Z, Khan Z, Khattak SI, Ur Rahman Z, Khan S (2019) Does the inflow of remittances cause environmental degradation? Empirical evidence from China. Economic Research-Ekonomska Istraživanja 32(1):2099–2121

Ahmad M, Muslija A, Satrovic E (2021a) Does economic prosperity lead to environmental sustainability in developing economies? Environmental Kuznets curve theory. Environ Sci Pollut Res. https://doi.org/10.1007/s11356-020-12276-9

Ahmed Z, Wang Z, Ali S (2019) Investigating the non-linear relationship between urbanization and CO2 emissions: an empirical analysis. Air Qual Atmos Health 12:945–953. https://doi.org/10.1007/s11869-019-00711-x

Alharthi M, Dogan E, Taskin D (2021) Analysis of CO2 emissions and energy consumption by sources in MENA countries: evidence from quantile regressions. Environ Sci Pollut Res 28(29):38901–38908. https://doi.org/10.1007/s11356-021-13356-0

Ali R, Bakhsh K, Yasmin MA (2019) Impact of urbanization on CO2 emissions in emerging economy: evidence from Pakistan. Sust Cities Soc 48:101553

Ali A, Usman M, Usman O, Sarkodie SA (2021) Modeling the effects of agricultural innovation and biocapacity on carbon dioxide emissions in an agrarian-based economy: evidence from the dynamic ARDL simulations. Front Energy Res 8:592061. https://doi.org/10.3389/fenrg.2020.592061

Al-Mulali U, Ozturk I (2015) The effect of energy consumption, urbanization, trade openness, industrial output, and the political stability on the environmental degradation in the MENA (Middle East and North African) region. Energy 84:382–389. https://doi.org/10.1016/j.energy.2015.03.004

Alola AA, Adebayo TS, Onifade ST (2021) Examining the dynamics of ecological footprint in China with spectral Granger causality and quantile-on-quantile approaches. Int J Sustain Dev World Ecology. https://doi.org/10.1080/13504509.2021.1990158

Anwar A, Younis M, Ullah I (2021) Impact of urbanization and economic growth on CO2 emission: a case of far East Asian countries. Int J Environ Res Publ Health 17:2531. https://doi.org/10.3390/ijerph17072531

Appiah M, Li F, Koranyke B (2021) Modeling the linkages among CO2 emission, energy consumption, and industrialization in Sub-Saharan African (SSA) countries. Environ Sci Pollut Res. https://doi.org/10.1007/s11356-021-12412-z

Azam M, Khan AQ (2016) Urbanization and environmental degradation: evidence from four SAARC countries-Bangladesh, India, Pakistan, and Sri Lanka. Environ Prog and Sustain Energ 35:823–832. https://doi.org/10.1002/ep.12282

Bali E, Nugent JB, Coskun N et al (2020) The relationship between energy consumption, CO2 emissions, and economic growth in Turkey: evidence from Fourier approximation. Environ Sci Pollut Res 27:44148–44164. https://doi.org/10.1007/s11356-020-10254-9

Bashir MF, MA B, Shahbaz M, Jiao Z (2020) The nexus between environmental tax and carbon emissions with the roles of environmental technology and financial development. PLoS ONE 15(11):e0242412. https://doi.org/10.1371/journal.pone.0242412

Baydoun H, Aga M (2021) The effect of energy consumption and economic growth on environmental sustainability in the GCC countries: does financial development matter? Energies 14:5897. https://doi.org/10.3390/en14185897

Behera SR, Dash DP (2017) The effect of urbanization, energy consumption, and foreign direct investment on the carbon dioxide emission in the SSEA (South and Southeast Asian) region. Renew Sust Energ Rev 70:96–106. https://doi.org/10.1016/j.rser.2016.11.201

Bekun FV, Alola AA, Gyamfi AB, Ampomah AB (2021) The environmental aspects of conventional and clean energy policy in sub-Saharan Africa: is N-shaped hypothesis valid? Environ Sci Pollut Res. https://doi.org/10.1007/s11356-021-14758-w

Bibi A, Zhang X, Umar M (2021) The imperative nature of biomass energy consumption to the environmental sustainability of the United States revisited. Environ Ecol Stat 28:821–841. https://doi.org/10.1007/s10651-021-00500-9

Chen H, Tackie EA, Akahwa I, Musah M et al. (2022) Does energy consumption, economic growth, urbanization, and population growth influence carbon emissions in the BRICS? Evidence from panel models robust to cross-sectional dependence and
slopes heterogeneity. Environ Sci Pollut Res. https://doi.org/10.1007/s11356-021-17671-4
Chen Y, Lee CC (2020) Does technological innovation reduce CO₂ emissions? Cross-Country Evidence J Clean Prod 263:121550. https://doi.org/10.1016/j.jclepro.2020.121550
Chien F, Sadiq M, Nawaz MA, Hussain MS, Tran TD, Thanh TL (2021) A step toward reducing air pollution in top Asian economies: the role of green energy, eco-innovation, and environmental taxes. J Environ Manage 297:113420. https://doi.org/10.1016/j.jenvman.2021.113420
China Electricity Council (2020), National Electric Power Industry Statistics Express List. Retrieved on 25/12/2021 from https://www.cce.org.cn/upload/1/editor/1611623903447.pdf
China National Bureau of Statistics (2020), China Statistical Yearbook. Retrieved on 25/12/2021 from http://www.stats.gov.cn/tjsj/ndsj/2020/indexch.htm
Chontanawat J (2020) Relationship between energy consumption, CO₂ emission and economic growth in ASEAEN: Cointegration and causality model. Energy Rep 6(1):660–665. https://doi.org/10.1016/j.egyrep.2019.09.046
Chunyu L, Zain-ul-Abidin S, Majeed W, Raza SMF, Ahmad I (2021) The non-linear relationship between carbon dioxide emissions, financial development and energy consumption in developing European and Central Asian economies. Environ Sci Pollut Res. https://doi.org/10.1007/s11356-021-15225-2
Copenhagen Accord (2009). https://unfccc.int/process-and-meetings/conferences/past-conferences/copenhagen-climate-change-conference-december-2009/copenhagen-climate-change-conference-december-2009
Danish OB, Ulucak R (2020) An empirical investigation of nuclear energy consumption on CO₂ emissions in Turkey: new evidence from the BRCIS economies. Environ Sci Pollut Res. https://doi.org/10.1007/s11356-021-12661-y
Danish OB, Ulucak R (2020) An empirical investigation of nuclear energy consumption and carbon dioxide (CO₂) emission in India: Bridging IPAT and EKC hypotheses. Nuclear Engineer Tech. https://doi.org/10.581/2020.12.008
Doğanlar M, Mike F, Kızılkaya O, Karlılar S (2021) Testing the long-run effects of economic growth, financial development and energy consumption on CO₂ emissions in Turkey: new evidence from RALS cointegration test. Environ Sci Pollut Res. https://doi.org/10.1007/s11356-021-12661-y
Dong K, Sun R, Jiang H, Zeng X (2018) CO₂ emissions, economic growth, and the environmental Kuznets curve in China: What roles can nuclear energy and renewable energy play? J Clean Prod 196:51–63
Engle RF, Granger CW (1987) Co-integration and Error Correction: Representation, Estimation, and Testing. Econometrica 55(2):251–276
Funk M, Strauss J (2000) The long-run relationship between productivity and capital. Econ Let 69(2):213–217. https://doi.org/10.1016/s0165-1765(00)00281-0
Hasan A, Xia E, Danish BMA, Abbas K (2018) Financial development, globalization, and CO₂ emission in the presence of EKC: evidence from BRICS countries. Environ Sci Pollut Res 25:31283–31296. https://doi.org/10.1007/s11356-018-3034-7
Iqbal S, Wang Y, Shaikh PA, Maaqbool A, Hayat K (2021) Exploring the asymmetric effects of renewable energy production, natural resources, and economic progress on CO₂ emissions: fresh evidence from Pakistan. Environ Sci Pollut Res. https://doi.org/10.1007/s11356-021-16138-w
Jian J, Fan X, He P, Xiong H, Shen H (2019) The effects of energy consumption, economic growth and financial development on CO₂ emissions in China: a VECM approach. Sustainability 11:4850. https://doi.org/10.3390/su11184850
Johansen S (1991) Estimation and hypothesis testing of cointegration vectors in Gaussian vector autoregressive models. Econometrica 59(6):1551–1580
Kao C and Chiang MH (2000) On the estimation and inference of a cointegrated regression in panel data, in nonstationarity panels, panel cointegration and dynamic panels. Advances in Econometrics, Vol. 15, ed. by Baltagi BH. Amsterdam, JAI Press (Elsevier Science), pp. 179–222.
Khan R (2021) Beta decoupling relationship between CO₂ emissions by GDP, energy consumption, electricity production, value-added industries, and population in China. PLoS ONE 16(4):e0249444. https://doi.org/10.1371/journal.pone.0249444
Khan MK, Teng J-Z, Khan MI (2019) Effect of energy consumption and economic growth on carbon dioxide emissions in Pakistan with dynamic ARDL simulations approach. Environ Sci Pollut Res. https://doi.org/10.1007/s11356-019-05640-x
Khan H, Weili L, Khan I (2021) Institutional quality, financial development and the influence of environmental factors on carbon emissions: evidence from a global perspective. Environ Sci Pollut Res. https://doi.org/10.1007/s11356-021-16626-z
Khan H, Weili L, Khan I, LiK O (2021) Recent advances in energy usage and environmental degradation: Does quality institutions matter? A worldwide evidence. Energy Rep 7:1091–1103. https://doi.org/10.1016/j.egyr.2021.01.085
Khan H, Weili L, Khan I et al (2021) The effect of income inequality and energy consumption on environmental degradation: the role of institutions and financial development in 180 countries of the world. Environ Sci Pollut Res. https://doi.org/10.1007/s11356-021-17278-9
Khan I, Han L, Khan H (2021) Oanh LTK (2021) Analyzing renewable and nonrenewable energy sources for environmental quality: dynamic investigation in developing countries. Math Probl Eng 2:1–12. https://doi.org/10.1155/2021/3399049
Khan NH, Ju Y, Danish, Latif Z, Khan K (2020) Nexus between carbon emission, financial development, and access to electricity: Incorporating the role of natural resources and population growth. J Public Affairs e2131. https://doi.org/10.1002/pa.2131
Khattak SI, Ahmad M, Khan ZU, Khan A (2020) Exploring the impact of innovation, renewable energy consumption, and income on CO₂ emissions: new evidence from the BRCIS economies. Environ Sci Pollut Res 27:13866–13881
Khurshid A, Rauf A, Calin AC, Qayyum S, Mian AH, Qayyum S Fatima T (2021) Technological innovations for environmental protection: role of intellectual property rights in the carbon mitigation efforts. Evidence from western and southern Europe. Int J Environ Sci Tech.https://doi.org/10.1007/s13762-021-04391-z
Kiefer NM, Vogelsang TJ (2002) Heteroskedasticity-autocorrelation robust standard errors using the Bartlett Kernel without truncation. Econometrica 70:2093–2095. https://doi.org/10.2307/3082033
Kirikkaleli D, Adebayo TS (2021) Do public-private partnerships in energy and renewable energy consumption matter for consumption-based carbon dioxide emissions in India? Environ Sci Pollut Res 28:30139–30152. https://doi.org/10.1007/s11356-021-02177-2
Kirikkaleli D, Adebayo TS (2021a) Do renewable energy consumption and financial development matter for environmental sustainability? New global evidence. Sustain Dev 1–12. https://doi.org/10.1002/pa.2131
Kripfganz S, Schneider DC (2018) Ardl: Estimating autoregressive-distributed lag and equilibrium correction models. Paper presented at the Proceedings of the 2018 London Stata Conference. London
Kyoto Protocol (2005). https://unfccc.int/kyotoprotocol
Lauri M (2020) Analysis: China’s COVID stimulus plans for fossil fuels three times larger than low-carbon. Retrieved on 25/12/2021
from https://www.carbonbrief.org/analysis-chinas-covid-stimulus-plans-for-fossil-fuels-three-times-larger-than-low-carbon
Lauri M (2021) China’s five-year plan: baby steps towards carbon neutrality, Center for Research on Energy and Clean Air. Retrieved on 25/12/2021 from https://energyandcleanair.org/china-14th-five-year-plan-carbon-neutrality/
Li K, Hu E, Xu C, Musah M, Yusheng K, Mensah IA, Zu J, Jiang W, Su Y (2020b) A heterogeneous analysis of the nexus between energy structure, economic growth and carbon emissions: evidence from the Group of Twenty (G20) countries. Energy Explorat Exploit 39(3):797–814. https://doi.org/10.1016/j.eex.2019.09.098
Li K, Musah M, Kong Y, Mensah IA, Antwi SK, Bawuah J, Donkor M, Coffie CPK, Andrew OA (2020a) Liquidity and firms’ financial performance nexus: panel evidence from non-financial firms listed on the Ghana Stock Exchange. SAGE Open 10(3):2158244020950363
Li Y, Yang X, Ran Q, Wu H, Irfan M, Ahmad M (2021) Energy structure, digital economy, and carbon emissions: evidence from China. Environ Sci Pollut Res 28(45):64606–64629. https://doi.org/10.1007/s11356-021-15304-4
Li H, Khattak SI, Ahmad M (2021) Measuring the impact of higher education on environmental pollution: new evidence from thirty provinces in China. Environ Ecol Stat 28(1):187–217
Li R, Wang Q, Liu Y, Jiang R (2021) Per-capita carbon emissions in 147 countries: The effect of economic, energy, social, and trade structural changes. Sustainable Production and Consumption 27:1149–1164. https://doi.org/10.1016/j.spc.2021.02.031
Li ZZ, Li RYM, Malik MY, Murshed M, Khan Z, Umar M (2021) Determinants of carbon emission in China: How good is green investment? Sustainable Production and Consumption 27:392–401. https://doi.org/10.1016/j.spc.2020.11.008
Li K, Zu J, Musah M, Mensah IA, Kong Y, Owusu-Akomemeh, Shi S, Jiang Q, Antwi SK, Agyemang JK (2021) The link between urbanization, energy consumption, foreign direct investments and CO2 emissions: An empirical evidence from the emerging seven (E7) countries. Energy Explorat Exploit 0(0): 1–24. https://doi.org/10.1016/j.eex.2019.2019.02.006
Liu X, Bae J (2018) Urbanization and industrialization impact of CO2 emissions in China. J Clean Prod 172:178–186. https://doi.org/10.1016/j.jclepro.2017.10.156
Liu J, Murshed M, Chen F, Shabbaz M, Kirikkaleli D, Khan Z (2021) An empirical analysis of the household consumption-induced carbon emissions in China. Sustainable Production and Consumption 26:943–957. https://doi.org/10.1016/j.spc.2021.01.006
Ma X, Wang C, Dong B, Gu G, Chen R, Li Y, Zou H, Zhang W, Li Q (2019) Carbon emissions from energy consumption in China: its measurement and driving factors. Sci Total Environ 648:1411–1420
Ma Q, Murshed M, Khan Z (2021) The nexuses between energy investments, technological innovations, R&D expenditure, emission taxes, tertiary sector development, and carbon emissions in China: a roadmap to achieving carbon-neutrality. Energy Policy 155:112345. https://doi.org/10.1016/j.enpol.2021.112345
MacKinnon JG, Haug AA, Michielis L (1999) Numerical distribution functions of likelihood ratio tests for cointegration. J Appl Econ 14(5):563–577
Marques LM, José AF, António CM (2021) China’s effect on world energy-growth nexus: spillovers evidence from financial development and CO2 emissions. Economies 9:136. https://doi.org/10.3390/economies9040136
Mesagan E, Nwachukuw M (2018) Determinants of environmental quality in Nigeria: assessing the role of financial development. Econ Res Fin 3: 55–78. http://erfin.org/journal/index.php/erfin/article/view/35
Mikhail G, Kate L (2020) Preliminary China emissions estimates for 2019, Rodium Group. Retrieved on 25/12/2021 from https://rhg.com/research/preliminary-china-emissions-2019/
Mursheed M (2021) Modeling primary energy and electricity demands in Bangladesh: An autoregressive distributed lag approach. Sustain Prod Consum 27:C:698–712. https://doi.org/10.1016/j.spc.2021.01.035
Musu KS, Majiamaa’R, Yakubu M (2021) The causality between urbanization, industrialization and CO2 emissions in Nigeria: evidence from Toda and Yamamoto approach. Energy Economies Letters 8(1):1–14. https://doi.org/10.18488/journal.82.2021.81.1.14
Musa MS, Jelilov G, Iorember PT, Usman O (2021) Effects of tourism, financial development, and renewable energy on environmental performance in EU-28: does institutional quality matter? Environ Sci Pollut Res. Environ Sci Pollut Res. https://doi.org/10.1007/s11356-021-14450-z
Musah M, Kong Y, Mensah IA, Antwi SK, Donkor M (2020a) The link between carbon emissions, renewable energy consumption, and economic growth: a heterogeneous panel evidence from West Africa. Environ Sci Pollut Res 27:28867–28889. https://doi.org/10.1007/s11356-020-08488-8
Musah M, Kong Y, Mensah IA et al (2020c) The connection between urbanization and carbon emissions: a panel evidence from West Africa. Environ Dev Sustain. https://doi.org/10.1007/s10668-020-01124-y
Musah M, Kong Y, Xuan VV (2020b) Predictors of carbon emissions: an empirical evidence from NAFTA countries. Environ Sci Pollut Res 28(9):11205–11223. https://doi.org/10.1007/s11356-020-11197-x
Musah M, Kong Y, Mensah IA et al (2021a) Modelling the connection between energy consumption and carbon emissions in North Africa: evidence from panel models robust to cross-sectional dependence and slope heterogeneity. Environ Dev Sustain. https://doi.org/10.1007/s10668-021-01294-3
Musah M, Kong Y, Mensah IA et al (2021b) Trade openness and CO2 emissions: a heterogeneous analysis on the developing eight (D8) countries. Environ Sci Pollut Res. https://doi.org/10.1007/s11356-021-13816-7
Musah M, Mensah IA, Alfred M et al (2022a) Reinvestigating the pollution haven hypothesis: the nexus between foreign direct investments and environmental quality in G-20 countries. Environ Sci Pollut Res. https://doi.org/10.1007/s11356-021-17508-0
Musah M, Michael OA, Joseph DN, Morrison A, Isaac AM (2021d) Financial development and environmental sustainability in West Africa: evidence from heterogeneous and cross-sectionally correlated models. Environ Sci Pollut Res 1–23. https://doi.org/10.1007/s11356-021-16512-8
Musah M, Owusu-Akomemeh, Boateng F et al (2021c) Long-run equilibrium relationship between energy consumption and CO2 emissions: a dynamic heterogeneous analysis on North Africa. Environ Sci Pollut Res. https://doi.org/10.1007/s11356-021-16360-6
Musah M, Owusu-Akomemeh M, Kumah EA et al (2022b) Green investments, financial development, and environmental quality in Ghana: evidence from the novel dynamic ARDL simulations approach. Environ Sci Pollut Res. https://doi.org/10.1007/s11356-021-17685-y
Nawaz SMN, Alvi S, Akmal T (2021) The impasse of energy consumption coupling with pollution haven hypothesis and environmental Kuznets curve: a case study of South Asian economies. Environ Sci Pollut Res. https://doi.org/10.1007/s11356-021-14164-2
Osohajo OA, Oritoju A, Oritoju MA, Oke A (2020) The impact of energy consumption and economic growth on carbon dioxide emissions. Sustainability 12:7965. https://doi.org/10.3390/su12197965
Paris Agreement (2015). https://unfccc.int/process-and-meetings/the-paris-agreement

Pedroni P (2001) Purchasing power parity tests in cointegrated panels. Rev Econ Stat 83:727–731

Pesaran MH, Shin Y, Smith RJ (2001) Bounds testing approaches to the analysis of level relationships. J Appl Econom 16:289–326

Phale K, Li F, Mensah IA, Omari-Sasu AY, Musah M (2021) Knowledge-based economy capacity building for developing countries: a panel analysis in Southern African Development Community. Sustainability 13:2809. https://doi.org/10.3390/su13052809

Qayyum M, Ali M, Nizamani MM, Li S, Yu Y, Jhanger A (2021) Nexus between financial development, renewable energy consumption, technological innovations and CO2 emissions: the case of India. Energies 14:4505. https://doi.org/10.3390/en14154505

Qin L, Raheem S, Murshed M, Miao X, Khan Z, Kirikkaleli D (2021) Does financial inclusion limit carbon dioxide emissions? Analyzing the role of globalization and renewable electricity output. Sustain Dev 29:1138–1154. https://doi.org/10.1002/sd.2208

Rafiq S, Salim R, Nielsen I (2016) Urbanization, openness, emissions, and energy intensity: a study of increasingly urbanized emerging economies. Energy Econ 56:20–28. https://doi.org/10.1016/j.eneeco.2016.02.007

Rahman MM, Vu X-B (2021) Are energy consumption, population density and exports causing the environmental damage in China? Autoregressive Distributed Lag and Vector Error Correction Model Approaches. Sustainability 13:3749. https://doi.org/10.3390/su13073749

Rehman A, Ma H, Ozturk I (2021a) Do industrialization, energy importations, and economic progress influence carbon emission in Pakistan. Environ Sci Pollut Res. https://doi.org/10.1007/s11356-021-13916-4

Rehman A, Ulucak R, Murshed M, Ma H, Isik C (2021b) Carbonization and atmospheric pollution in China: The asymmetric impacts of forests, livestock production, and economic progress on CO2 emissions. J Environ Manag 294:113059. https://doi.org/10.1016/j.jenvman.2021.113059

Rong PJ, Zhang Y, Qin YC, Liu GJ, Liu RZ (2020) Spatial differentiation of carbon emissions from residential energy consumption: a case study in Kaifeng. China J Environ Manag 271:110895

Salahuddin M, Gow J, Ali I, Hossain R, Al-Azami KS, Akbar D, Gedikli A (2019) Urbanization-globalization-CO2 emissions nexus revisited: empirical evidence from South Africa. Heliyon 5(6):e01974. https://doi.org/10.1016/j.heliyon.2019.e01974

Sana U, Ilhan O, Muhammad TM, Waheed A (2021) Do technological innovations have symmetric or asymmetric effects on environmental quality? Evidence from Pakistan. J Clean Prod 13:1613. https://doi.org/10.1016/j.jenvman.2021.13041613

Yao S, Zhang S (2021) Energy mix, financial development, and carbon emissions in China: a directed technical change perspective. Environ Sci Pollut Res. https://doi.org/10.1007/s11356-021-15186-6

Yiping G (2021) Financial development and carbon emissions: analyzing the role of financial risk, renewable energy electricity, and human capital for China. Discrete Dynamics in Nature and Society 4235076(9). https://doi.org/10.1155/2021/4235076

Yu Y, Du Y (2019) Impact of technological innovation on CO2 emissions and emissions trend prediction on ‘New Normal’ economy in China. Atmos Pollut Res 10:152–161. https://doi.org/10.1016/j.apr.2018.07.005

Yuelan P, Akbar MW, Haifeez M, Ahmad M, Zia Z, Ullah S (2019) The nexus of fiscal policy instruments and environmental degradation in China. Environ Sci Pollut Res 26(28):28919–28932

Zeraibi A, Balsalobre-Lorente D, Murshed M (2021) Nexus between renewable electricity generation capacity, technological innovations, financial development, economic growth and ecological footprints in selected ASEAN countries. Environ Sci Pollut Res 28(37):51003–51021. https://doi.org/10.1007/s11356-021-14301-x

Zhang X, Yu Y, Du Y (2020) Drivers of change in China’s energy-related CO2 emissions. PNAS 117(1):29–36. https://doi.org/10.1073/pnas.1908513117

Zhong J, Li J (2020) The nonlinear impact of industrial restructuring on economic growth and carbon dioxide emissions: a panel threshold regression approach. Environ Sci Pollut Res. https://doi.org/10.1007/s11356-020-07778-5

Publisher’s note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.