



Nexus between energy consumption and carbon dioxide emission: evidence from 10 highest fossil fuel and 10 highest renewable energy-using economies

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Abstract

The world, addressing to achieve rapid and drastic economic growth by relying on fossil fuel energy consumption, could increase already increasing level of carbon dioxide (CO₂). Therefore, there is a growing consensus that environmental sustainability by using renewable energy is the only option to avoid environmental calamity. Therefore, according to the authors' best knowledge, this is the first work to look into the short and long-run nexus between economic growth, trade openness, renewable and fossil fuel energy consumption, along with gross capital formation, population growth, and life expectancy as additional variables in top 10 highest renewable energy-using (TRU) economies and top 10 highest fossil fuel-using (TFU) economies from 1991 to 2020, by employing advanced panel data econometric approach. After demonstrating cross-sectional dependency in panel data, the Westerlund cointegration test verifies the long-term link between the variables. A cross-sectional autoregressive distributed lag (CS-ARDL) econometric technique is used to show short- and long-run coefficient values. CS-ARDL estimates confirm that the economic growth, fossil fuel energy, trade openness, and gross capital formation increase carbon dioxide (CO₂) emissions levels in the short run for TRU and FEU economies, except for gross capital formation for FEU economies. However, economic growth adds to CO₂ emissions for only TRU economies, while fossil fuel energy consumption enhances CO₂ emissions for both groups of economies in the long run. On the contrary, renewable energy reduces CO₂ emissions in the short and long run, while human capital in only the short run. The inferences of this study present new intuitions and urge governments and policymakers to develop a reliable mechanism for investing capital to diversify the energy portfolio through the energy transition process to attain sustainable economic growth and promote awareness campaigns to draw the attention of human capital to environmentally friendly, clean, and green energy sources. Overall, the results recommended energy efficiency usage and ecological friendly innovative technologies to enhance and protect environmental quality.

Keywords Renewable energy consumption · Fossil fuel energy · Carbon emission · CS-ARDL · Westerlund cointegration · Environment quality

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Introduction

Industrialized and developing economies share the common objective of achieving economic growth and long-term development. But there are inevitable roadblocks to achieving such objectives, such as environmental deterioration. Environmental degradation is the most commonly debated hazard in achieving the required level of sustainable development; the link between environmental degradation and sustainable economic development is complex (Asongu et al. 2020). CO₂ emissions wreak havoc on the world's climate, causing climate change and environmental degradation (Adebayo et al. 2021; Asongu et al. 2020), leading to

various environmental issues such as air and water pollution, ozone layer hazards, persistent organic pollutants, imposing hazardous consequences on the sea and high mortality rate in every viable state (Ali et al. 2021). CO₂ emission in the atmosphere has caused the earth to warmer about 1°, which is supposed to cross 1.5° from 2030 to 2050, as global emissions are rising (GSDR report 2019). COP26 represented the 200 nations around the world to discuss and agree on the Glasgow Climate Pact and ended on 13 November 2021. The Glasgow Climate Pact will agree to accelerate climate change actions such keep limiting the temperature to 1.5 °C, phasing down unabated coal power, reducing emissions (mitigations), helping climate change impacted countries (adaptation), financing to meet climate goals (finance), and working together to deliver greater actions against climate change (collaboration). Keeping in view the importance of climate change and its worst impact on the environmental quality, the world has become conscious to take the prudent strategic measures to mitigate it. Hence, there is significant proof of man-made global warming and climate change throughout the world, and the top ten fossil fuel energy-using economies (China, USA, India, Russia, Japan, Iran, Saudi Arabia, South Korea, Germany, and Canada) and top ten renewable energy-using economies “Germany, UK, Sweden, Spain, Italy, Brazil, Japan, Turkey, Australia, and the USA” are not immune to global warming wave.

Energy demand is critical to both emerging and established countries’ socioeconomic, economic growth, and development (Nathaniel et al. 2019), so as in fossil fuel and renewable energy-using economies, a well-balanced blend cannot be overlooked when it comes to economic growth and sustainable development. In China, the energy demand increase is striking, around 10% more than in 2019, and consumes 23.77% of fossil fuel and adds 27.82% of carbon dioxide (CO₂) emissions globally (Zhao et al. 2022). However, United States produces 20.4% of natural gas and consumes a major portion of it, causing environmental degradation (Korkmaz 2022). Whereas India is the 3rd largest CO₂ contributor in the world, consuming 7.1% coal, 2.9% oil, and 6% gas as fossil fuels (Sahoo and Sahoo 2020).

Therefore, Fossil fuel energy sources have resulted in a serious concern in international economies: increased CO₂ emissions. Economic development and fossil fuel energy use has a considerable positive relationship, supporting this nexus (Faisal et al. 2021a). Because of its unfavorable nature to the environment and ecology, increasing fossil fuel energy use leads to economic development and higher carbon dioxide emissions. The positive relationship between energy and economic growth renders to more energy consumption, resulting in higher CO₂ emissions from nonrenewable energy sources, which are harmful to the atmosphere and biosphere (Ramzan et al. 2022). Figure 1 shreds evidence that China’s economic growth uses environmentally unfriendly fossil fuel energy sources at the cost of increased CO₂ emissions. However, renewable energy sources provide a solution to international economies: decreased CO₂ emissions. This position is supported by higher renewable energy use and leads to sustainable economic development, resulting in decreased CO₂ emissions because of its clean and climate-friendly nature (Bekun, Alola et al. 2019; Yuping et al. 2021). Figure 2 depicts that Germany has adopted climate-friendly energy policies to attain sustained economic development.

This study parallels the existing literature (Adams et al. 2020; Adedoyin et al. 2020b, 2021; Aslam et al. 2021; Bekun 2022; Bekun et al. 2022; Dingru et al. 2021; He et al. 2021; Islam and Abdul Ghani 2018; Li et al. 2020; Martins et al. 2021; Nathaniel et al. 2021a; Nawaz et al. 2021; Naz et al. 2019; Sheraz et al. 2021) embraces CO₂ in place to comprehensively understand the environmental quality.

For the following reasons, this study focuses on the top 10 fossil fuel energy-using economies and top 10 renewable energy-using economies: (1) The fossil fuel energy-using economies are the top ten in the world relying heavily on fossil fuels such as 33,512 TWh (China), 21,891 TWh (USA), 8613 TWh (India), 7276 TWh (Russia), 4536 TWh (Japan), 3340 TWh (Iran), 3061 TWh (Saudi Arabia), 2988 TWh (South Korea), 2826 TWh (Germany), and 2608 TWh (Canada) for economic development. At the same time, the top 10 renewable energy-using economies of the world

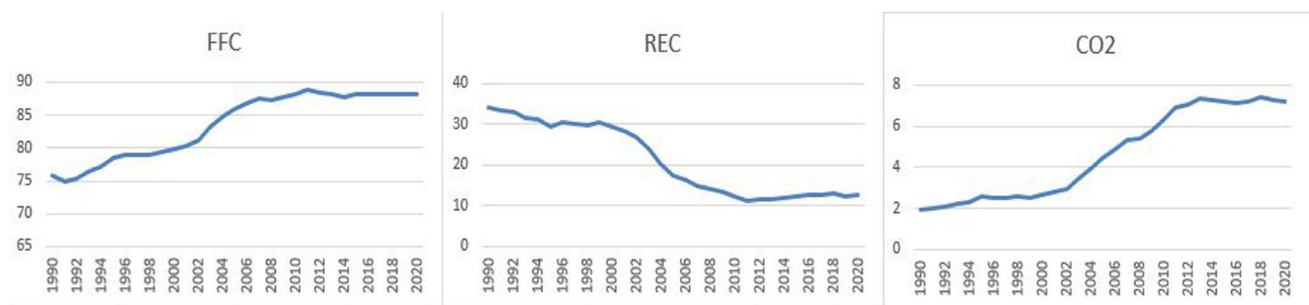


Fig. 1 CO₂ emissions, renewable energy consumption, and fossil energy consumption in China. Source: This study

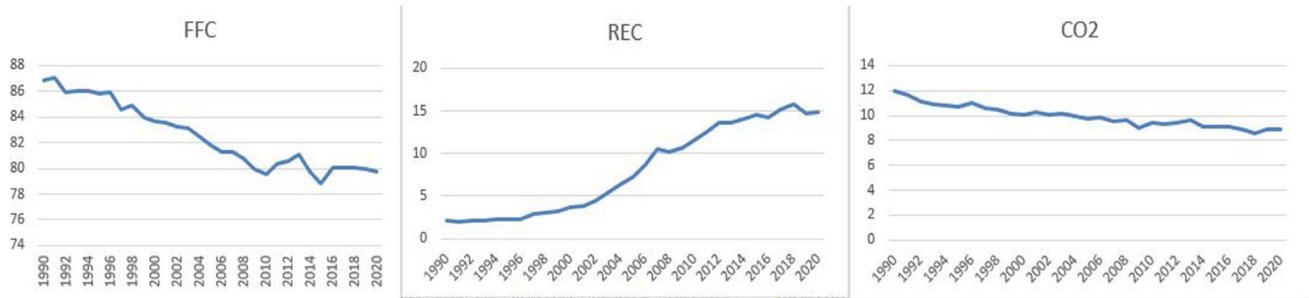


Fig. 2 CO₂ emission, renewable energy consumption, and fossil energy consumption in Germany. Source: This study

are engaged in energy efficiency transition and consume a higher proportion of renewable energy to total energy, such as 12.74% (Germany), 11.95% (UK), 10.96% (Sweden), 10.14% (Spain), 8.80% (Italy), 7.37% (Brazil), 5.30% (Japan), 5.25% (Turkey), 4.75% (Australia), and 4.32% (USA) for economic development. As seen through economic growth, fossil fuel-dependent economies consume more traditional energy than renewable energy, thereby indicating a significant contribution of CO₂ emission globally and imposing environmental challenges. (2) Contrary to the rest of the world economies, most economies in the current study are economic world leaders, embraced rapid economic growth, and control higher chunk of the world economy, such as China, the USA, and India. All together (the top ten fossil and top 10 renewable energy-using economies) contribute 74% of the world GDP and account for the US \$42.75 trillion of foreign deposits. The average annual economic growth of fossil fuel energy-using economies is higher than renewable energy-using economies. For instance, in 2019, China, the USA, India, and Japan have an average annual growth of 5.9%, 2.2%, 4%, and 3%, respectively, as compared to the UK (1.4%), Italy (0.3%), Spain (2%), and Sweden (1.4%) (World Bank 2019). As seen through economic growth, fossil fuel-dependent economies consume more traditional energy than renewable energy, thereby indicating a significant contribution of CO₂ emission globally. As a result, solid policies are necessary to comprehend the environmental implications of this economic development to reverse the current trend, particularly in fossil-fuel-dependent nations. Both groups of economies are now at a fork in the road in terms of new environmental regulations, making the area an appealing case study for examining the causal link between environmental preservation, economic development, and human capital development. Furthermore, the findings of this research will aid policymakers in developing effective policies to combat environmental degradation and improve human capital development.

This research aims to look at the impact of human resource development on environmental quality in the top ten fossil fuel and renewable energy-using economies. This

research will reveal the environmental impact of human resource development and inform the strategies needed to mitigate the consequences of carbon dioxide CO₂ in the environment. This study also considers exploring the possible nexus between economic growth, fossil fuel energy, renewable energy, gross capital formation, population expansion, and trade openness on environmental protection in both groups of economies.

Several previous studies have looked into the impact of economic expansion, fossil fuel energy, renewable energy, gross fixed capital formation, population increase, trade openness, and human capital on environmental devastation (Adedoyin et al. 2020c; Bekun et al. 2019a, b; Islam and Abdul Ghani 2018; Khan et al. 2019; Naz et al. 2019; Nguyen et al. 2021; Shen et al. 2021; Talbi et al. 2022; Zafar et al. 2019a). Unfortunately, these studies have focused directly or indirectly on a single country or group of countries while ignoring the comparative analyses of the top 10 economies heavily dependent on fossil fuel energy and the top 10 economies consuming renewable as a major proportion of total energy. As a result, the scope of this research will be expanded with the goal of better understanding environmental quality. It is expected that using such a comprehensive measure of environmental quality, the effect of economic expansion, fossil fuel energy, renewable energy, gross fixed capital formation, population growth, trade openness, and human capital on environmental degradation will provide more perceptive directions to both groups of policymakers to attain sustainable economic development under sustainable development goal (SDG-7).

This research study has an enormous contribution: (1) as per the authors' best knowledge, and it's the first study to look at the comparative nexus between economic development, fossil fuel energy, renewable energy, gross fixed capital formation, population growth, trade openness, human capital, and carbon emissions in the top 10 FF and top 10 RE energy-using economies. (2) The impact of economic development on the environment, fossil fuel energy, renewable energy, gross fixed capital creation, population growth, trade openness, and human capital were all constrained in

previous research. Environmental deterioration and climate change are worsened by human activity. Despite the growing number of research on how to mitigate the threat of environmental degradation and climate change, the challenges remain unabated. As a result, to limit environmental deterioration, it is necessary to look beyond traditional thinking and examine other factors such as education and awareness. As a result, human capital was included in the nexus for the economies investigated in this study. This is a big step forward from prior research, which largely overlooked the critical importance of human capital in maintaining environmental quality. (3) This study is also much stronger in terms of methodology than previous studies of the environment and human capital nexus because, unlike previous empirical literature, it employs a set of second-generation panel data techniques that address some potentially important panel data estimation issues such as cross-country heterogeneity and cross-sectional dependence (CD). In addition, this study used the cross-sectional autoregressive distributed lag (CS-ARDL) approach, which produces more reliable findings than other panel data estimators. This will aid policy alignment to meet the unique characteristics of blocs under study. As a result, a more policy-oriented outcome.

The rest of this work is structured as follows: the literature survey is summarized in the “[Literature review](#)” section; the data and methodology are outlined in the “[Method and data](#)” section; the results and discussion are presented in the “[Empirical results](#)” section; and the conclusion and policy suggestions are presented in the “[Concluding remark and policy implications](#)” section.

Literature review

Existing research has shown a nexus between economic growth, trade openness, renewable energy, fossil fuel energy, and CO₂ emissions, while others have found a link between human capital, gross fixed capital formation, population, and CO₂ emissions, with varied findings. Therefore, the literature is broken down into two categories.

Trade openness, economic growth, renewable energy, fossil fuel energy, and CO₂ emissions

The nexus between trade openness and environmental deterioration has received a great deal of consideration in the literature, with blended findings. Ramzan et al. (2022) examined the potential consequences of trade openness on the ecological footprint in Pakistan from 1960 to 2019. They testified that economic growth, trade openness, foreign direct investment, fossil fuels, and information and communication technologies add to the ecological footprint. Likewise, for Malaysia, Aslam et al. (2021) had used the

autoregressive distributive lag (ARDL) model on the data from 1971-to 2016 and stated that trade openness intensifies CO₂ emissions, along with economic growth, industry, and liquid fossil fuel consumption. Nguyen et al. (2021) extracted parallel inferences like Ramzan et al. (2022) and Aslam et al. (2021) even though the research was conducted for G-6 countries. Solarin et al. (2021) utilized the dynamic ARDL technique to inspect the effect of trade openness and economic growth on the ecological footprint of the Nigerian economy on data spanning from 1977 to 2016. They revealed that trade openness increases carbon dioxide CO₂, similar to findings of Yu et al. (2019), Ali et al. (2020a), and Zameer et al. (2020); however, economic growth and foreign direct investment wrested a more exacerbate impact on the environment. Ahmad et al. (2020) examined the trade openness and CO₂ emission hypothesis existence in bet and road countries for the period 1990–2017, employing a panel regression estimator. The results supported the hypothesis in low-income countries. However, foreign development, energy consumption, and urbanization degrade the environment, with economic growth having U shape association, whereas foreign direct investment improves it. Similar results have been supported by Munir and Ameer (2018), Ibrahim and Ajide (2021), and Saud et al. (2019).

There are numerous research studies that show that trade openness has no adverse impact on environmental quality. For instance, Alola et al. (2019) examined the effect of trade policy on environmental quality (ecological footprint) in 16 Europe countries on data spanning from 1997 to 2014. Results from panel pool mean group autoregressive distributive lag (PMGARDL) estimator evidenced that trade openness, renewable energy, and fertility rate are responsible for decreasing environmental degradation. However, economic growth and nonrenewable energy add to worsen the environment. Similar inferences have been extracted by Khan et al. (2021) in Bangladesh. Shahbaz et al. (2018) explored facets influencing CO₂ in G-7 countries on the data ranging from 1980 to 2014, employing the generalized moment method (GMM). They found that trade openness, capitalization, and financial development improve the environmental quality, whereas biomass energy consumption and financial development have a worse impact on the environment. Analogously, Park et al. (2018) examined the link between trade openness and CO₂ in elected European countries on the data from 2001 to 2014. The results of pooled mean group (PMG) estimator evidenced that the trade coefficient lessens CO₂ emission and increases environmental quality. These results are supported by Nathaniel and Bekun (2019) for Nigerian countries and Destek and Sinha (2020) for OECD countries (particularly Belgium, Canada, Germany, Greece, Japan, South Korea, Spain, Switzerland, and Turkey). Furthermore, Nawaz et al. (2021), similar to Adedoyin et al. (2020c), Omoke et al. (2021), Soyulu et al. (2021), and Shen et al.

(2021) found that trade openness has no significant effect on environmental quality, however, economic growth, fossil fuel energy damages, while renewable energy and gross capital formation improves the quality of the environment.

Human capital, gross fixed capital formation, population, and CO₂ emissions

Human capital and gross capital formation may be the answer to long-term environmental sustainability. The literature has also established its relation to environmental damage, with varied findings. Nathaniel et al. (2021b) inspected the impact of human capital on carbon dioxide (CO₂) emissions in Latin American and Caribbean countries (LACCs) from 1990 to 2017. They found that human capital mitigates the CO₂, while globalization, urban population, and economic growth natural resources rent add to it. Similar results have been found by Sheraz et al. (2021), Paiho et al. (2021), Ahmed et al. (2020), Tran et al. (2019), and Zafar et al. (2019a). However, Nathaniel et al. (2021a) measured the link between human capital and the environment in BIRCS countries, employing the common correlated effects mean group (CCEMG) and the pool mean group (PMG). The result evidenced that human capital has a positive but not desirable level effect on the environment. Furthermore, Nawaz et al. (2021) found that gross fixed capital formation has a negative impact on carbon dioxide (CO₂) emissions, suggesting that it enhances the environment quality of BRICS and OECD countries. On the contrary, Zafar et al. (2019b) in the USA found that human capital, natural resources, and foreign direct investment enhances ecological footprint, whereas economic growth and energy consumption mitigate it. Additionally, Adams et al. (2020) investigated the role of capital formation in OCED countries over the period of 1996 to 2017, and the panel pooled mean group autoregressive distributed lag model (PMG-ARDL) found that human capital does not contribute to environmental quality, as economic growth and nonrenewable energy consumption, whereas renewable energy enhances it. Doğan et al. (2020) revealed that in OECD countries, total population growth enhances CO₂ emissions and deteriorating environmental quality. Finally, Danish et al. (2019) revealed that human capital does not have a significant influence on the ecological footprint in Pakistan.

Based on the contradictory findings in the literature reviewed above, more research is needed to clarify the complex interrelationships between economic growth, renewable energy consumption, fossil fuel consumption, human capital, fixed capital formation, population, and carbon dioxide emissions in the context of the world's top 10 fossil fuel and renewable energy-using economies, using novel approaches and new environmental quality metrics. Therefore, this research study will not only bridge the research gap in the

existing literature, but will provide direction to the government, policymakers, stakeholders, and environmentalists of the 10 highest fossil fuel energy-consuming and 10 highest renewable energy-consuming countries.

Method and data

Theoretical framework and model construction

The theoretical framework on which the model variables will be selected must be provided before the empirical modelling can begin. Moving on to the research's theoretical foundation, the carbon dioxide (CO₂) emissions measured in metric tons per capita is employed as the respondent variable as a proxy for the environmental quality in the model. This variable's apriority expectation might be positive or negative. The deteriorated environmental quality would be evidenced by a positive change in CO₂ emissions; however, enhanced environmental quality would be evidenced by negative variation in CO₂ emissions. With a share of nearly 70%, CO₂ is considered the most significant component of greenhouse gas emissions. This explains why CO₂ emissions are chosen as an environmental quality gauge. Also, adopting CO₂ emission as a measure of environmental quality is vibrant for a vivid and thorough study of this issue.

Furthermore, the most of countries in 10 highest fossil fuel energy-consuming and 10 highest renewable energy-consuming countries belongs to advanced economies known for rapid economic development, fueled by energy consuming from fossil fuel energy sources and renewable energy sources. Economic growth is measured in the gross domestic product growth rate (GDPGR) across the economies under study. Economic expansion has an influence on carbon emissions since economic activities demand energy as an input, resulting in more waste and pollution (He et al. 2021). This shift uplifts energy consumption and escalates the level of carbon emission (Ali et al. 2021; Aslam et al. 2021; Faisal et al. 2021b; Nguyen et al. 2021). As nations' economies grow, people's living standards rise, causing customer preferences and needs. This shift uplifts energy consumption and escalates the level of carbon emission. Hence, theories (such as EKC) have revealed the pattern of relationship that exists between economic growth (GDP) and the environment (He et al. 2021). Therefore, this justified our use of economic growth in our study as an explanatory variable.

Additionally, nations are moving towards a clean and renewable energy transition to develop the most sustainable and compatible substructure for energy. Modern technologies can be used to produce clean and sustainable energy with renewable sources, including hydropower, wind, and solar power. While most nations still use traditional fossil-fuel-based energy to satisfy the demand and supply of

energy by nation, due to a lack of investment and develop renewable technologies. Hence, renewable energy and fossil fuel energy consumption are used as explanatory variables collaborating with Abbas et al. (2021) and Yuping et al. (2021). In addition to that, trade openness has emerged as one of the best tools to boost the economic growth of the nations, but there has been a link between trade and climate change, as suggested by He et al. (2021) and Ramzan et al. (2022). Therefore, trade openness has been included in the model as a determinant of carbon dioxide, in line with the work of Aslam et al. (2021), Khan et al. (2021), and Shen et al. (2021).

Gross fixed capital formation measures the amount of stock invested in the economy; thus, growth in investment leads to an increase in industrial output, resulting in a boom in the economy at the expense of increased carbon dioxide emissions and harming the clean environment. Therefore, gross fixed capital formation has been taken in the model in line with previous studies (Faisal et al. 2021a; Majeed et al. 2021; Nawaz et al. 2021; Nguyen et al. 2021). Furthermore, the population growth rate of the sample economies has an increasing trend, showing more demand for energy consumption. Hence, an increase in the population increase energy consumption resulting increase in the emission of CO₂ level. Therefore, the population has been taken in in the model as studies in previous work (Doğan et al. 2020; Nathaniel and Adeleye 2021). Finally, life expectancy has been used as a proxy for the human capital in the model as it has a decreasing effect on emissions. Therefore, in line with a previous study by Sheraz et al. (2021) proxy of human capital has been used in the model.

Subsequent to the latest research studies by He et al. (2021), Asongu et al. (2020), Nathaniel et al. (2021b), and Adams et al. (2020) research model is developed as under:

$$CO_{2,it} = f (GDPGR_{it}, REC_{it}, FFC_{it}, TR_{it}, GCF_{it}, POGR_{it}, LE_{it}) \quad (1)$$

$$CO_{2,it} = \beta_0 + \beta_1 GDPGR_{it} + \beta_2 REC_{it} + \beta_3 FFC_{it} + \beta_4 TR_{it} + \beta_5 GCF_{it} + \beta_6 POGR_{it} + \beta_7 LE_{it} + \mu_{it} \quad (2)$$

where i denotes cross section (top 10 renewable energy-using economies), t denotes time period of study (1991–2020), GDPGR_{it} denotes economic growth rate, REC_{it} denotes renewable energy consumption, FFC_{it} denotes fossil fuel energy consumption, TR_{it} denotes trade openness, GCF_{it} denotes gross fixed capital formation, POGR_{it} denotes population growth rate, LE_{it} denotes life expectancy (proxy of human capital), β_0 denotes intercept, $\beta_1, 2, 3, 4, 5, 6, 7$ denote coefficients, and μ_{it} denotes error term.

Data

This study employed panel data from 1991 to 2020 for the top 10 fossil fuel energy-using economies “China, the USA, India, Russia, Japan, Iran, Saudi Arabia, South Korea, Germany, and Canada”) and the top 10 renewable energy-using economies (“Germany, UK, Sweden, Spain, Italy, Brazil, Japan, Turkey, Australia, and USA”). This study includes carbon dioxide (CO₂) emission as a respond variable, while economic growth (GDPGR), renewable energy consumption (REC), fossil fuel energy consumption (FFC), trade openness (TR), gross capital formation (GCF), population growth rate (POGR), and life expectancy (LE-proxy of human capital) are included as explanatory variables. Table 1 shows additional information of description, measurement, and sources of data.

Estimation procedures

CSD test

This study used a cross-sectional dependency (CSD) test to decide the right econometric approach to utilize. The CSD test results aid in deciding whether to use the first- or second-generation panel data analytical techniques. The

Table 1 Variable’s description

Variable	Abbreviation	Measurement	Source
Carbon emissions	CO ₂	Metric tons per capita	WB-2020
Fossil fuel energy consumption	FFC	Fossil fuel energy consumption (% of total)	WB-2020
Renewable energy consumption	REC	% of total final energy consumption	WB-2020
Trade openness	TR	Trade (% of GDP)	WB-2020
Gross fixed capital formation	GFCF	Gross fixed capital formation (% of GDP)	WB-2020
Economic growth	GDPGR	GDP growth (annual %)	WB-2020
Life expectancy (proxy of human capital)	LE	Life expectancy at birth, total (years)	WB-2020
Population growth	POGR	Population growth (annual %)	WB-2020

Source: This author

estimations of this study will be inconsistent, unreliable, skewed, biased, and useless when CSD is not performed (Bekun et al. 2022; Dong et al. 2018; He et al. 2021; Nathaniel et al. 2020). Therefore, to ensure that the aforementioned issues do not arise, this study utilized Pesaran (2007), (2015) scaled LM. For robustness purposes, Breusch-Pagan’s LM test developed in 1980 is utilized by authors. Because of the greater figure of cross sections (N) as compared to time periods (T), as depicted in this study dataset, more attention was paid to the Pesaran (2007) scaled CD test and Breusch and Pagan (1980) LM. Furthermore, Eq. 3 presents CSD test.

$$CD = \left(\frac{TN(N-1)^{\frac{1}{2}-\delta}}{2} \right) \tag{3}$$

However, $\delta = \left(\frac{2}{N(N-1)} \right) \sum_{i=1}^{N-1} \cdot \sum_{j=i+1}^N \delta_{ij}$, where δ_{ij} denotes the CS correlation coefficient estimates of residuals obtained from ADF regression. Additionally, T denotes the cross sections, and N denotes time.

Panel stationarity technique

The estimated proof of CD reveals inefficiencies in the first-generation stationarity approach (Im et al. 2003). Consequently, to tackle the problem of inefficiencies in the estimation, this study utilized the second-generation stationary test (CIPS-2007). Equation 4 shows Pesaran (2007) stationary test (CIPS).

$$\Delta Y_{it} = \Delta \varnothing_{it} + \beta_i X_{it} + \gamma_{iT} + \sum_{j=1}^n \varphi_{ij} \Delta X_{i,t-j} + \mu_{it} \tag{4}$$

where $\Delta \varnothing_{it}$ denotes intercept, X_{it} denotes factors analysis, Δ denotes variance operator, T denotes time period, and μ_{it} denotes white noise term. A second-generation test is carried out in the vicinity of the first differences stationary variables to evaluate the long-run impacts of parameters under discussion.

Panel cointegration approach

The results are connected to the Westerlund (2007) experiment, which was used to prove that the parameters were cointegrated. The estimation’s error rectification technique (ECM) is shown in Eq. 5.

$$\Delta y_{it} = \gamma_i d_t + \theta_i y_{it} + \sum_{j=1}^{p_i} \varnothing_{ij} \Delta y_{i,t-1} + \sum_{j=0}^{p_i} \pi_{ij} \Delta x_{i,t-j} + \varepsilon_{it} \tag{5}$$

where $\gamma_i = (\gamma_{i1}, \gamma_{i2})'$, signifies vectors of parameters, $d_t = (1, t)$ signifies deterministic mechanism and \varnothing signifies error correction parameter. To detect the existence of

cointegration, four tests were built on the OLS approach of \varnothing_i in Eq. (5). The equations of these four tests are as under:

$$G_\tau = \frac{1}{N} \sum_{i=1}^N \cdot = \frac{\hat{\alpha} \alpha i}{SE(\hat{\alpha} \alpha i)} \tag{6}$$

$$G_\alpha = \frac{1}{N} \sum_{i=1}^N \cdot \frac{T \hat{\alpha} \alpha i}{\hat{\alpha} \alpha i(1)} \tag{7}$$

$$P_\tau = \frac{\hat{\alpha} \alpha i}{SE(\hat{\alpha} \alpha i)} \tag{8}$$

$$P_\alpha = T1\alpha' \tag{9}$$

where the group statistics are Ga and Gt, and the panel statistics are Pa and Pt. Cointegration is placed against the null hypothesis of no cointegration.

CS-ARDL approach

The CS-ARDL approach developed by Chudik et al. (2016) is employed as suggested by He et al. (2021) to investigate the long and short-run nexus among carbon dioxide, economic growth, renewable energy, fossil fuel energy, gross capital formation, human capital, trade openness, and population. This method address the issues of endogeneity, unobserved shared variables, cross-sectional dependency, heterogeneous slop coefficients, and non-stationarity. The CS-ARDL approach is as follows:

$$Y_{it} = \sum_{i=1}^{qy} \partial_{it} Y_{i,t} + \sum_{i=0}^{qz} \sigma'_{i1} Z_{i,t-1} + \sum_{i=0}^{qT} \theta'_{i1} Z_{i,t-1} + \epsilon_{it} \tag{10}$$

where the average cross-sections $X^-_{t-1} = (Y^-_{t-1}, Z^-_{t-1})l$, are denoted by \bar{Y}_t and \bar{Z}_t . Furthermore, X^-_{t-1} denotes the averages of explanatory and explained variables. The CS-ARDL produces results that are strong against heterogeneity, misspecification bias, endogeneity, mixed integration, and cross-sectional dependencies (He et al. 2021).

Empirical results

Analysis of findings is presented in this section. The order of the test results is ascending. Table 2 depicts the findings of the cross-sectional dependency test to avoid the bias cointegration, spurious regression, and policy guidance by extension. The null hypothesis of no CD for our study model is rejected at a 1% significant level, revealing the existence of cross dependency in the dataset. Therefore, we advanced with second-generation estimator. Table 3

Table 2 Cross-sectional dependence test results

	Breusch and Pagan LM Test (1980)	Pesaran scaled LM test (Pesaran 2015)	Pesaran CD test (Pesaran 2007)
CO ₂ = f (LnGDPGR, LnREC, LnFFC, LnTR, LnGCF, LnPOGR, LnLE)	189.23***(0.00)	15.2***(0.00)	2.42**(0.05)

***, **, * represent the level of significance at 1%, 5%, and 10%, respectively

Table 3 Panel unit root test with cross-sectional dependence results

Variables	Pesaran (CIPS-2007)		
	Constant	Constant and trend	None
CO ₂	- 1.79	- 3.13***	- 1.39
GDPGR	- 2.86***	- 2.70***	- 2.64***
REC	- 1.26	- 1.88	- 2.62***
FFC	- 1.98	- 3.08***	- 1.88
TR	- 2.73***	- 2.15	- 2.17
GCF	- 1.16	- 2.59***	- 1.33
POGR	- 1.69	- 1.53	- 2.69***
LE	- 3.79***	- 3.43	- 0.91

Statistics shows *t*-test; 1%, 5%, and 10% critical values for CIPD are - 2.57, - 2.33, and - 2.21 respectively

***, **, * show the significance level at 1%, 5%, and 10%, respectively

presents the results of the panel unit root test with cross-sectional dependence. In Table 4, the Westerlund cointegration test results are presented. The findings show that there is cointegration (long-run association) between the studied variables; hence the null hypothesis of no cointegration is rejected.

Results for the short and long run

The next step is to determine the coefficient values of independent variables after validating Cointegration among the panel data. The CS-ARDL is used in this study for the purpose. The CS-ARDL technique is effective in producing reliable findings because it incorporates the CD among the panel data when delivering the coefficient values. The

experimental outcomes of CS-ARDL-ECT present the speed of adjustment towards long-term equilibrium. ECT-1 value for model I is - 0.86 and - 0.93 for model II, indicating 86% and 93% rate of convergence for both models, respectively.

Table 5 shows the results of CS-ARDL for model I and model II in the short and long run. In both models (model I and model II), the nexus between economic growth rate and carbon dioxide emissions is confirmed to be positive and significant in the short run only, while on the contrary, GDPGR exerts an insignificant positive effect on CO₂ in the long run. For model I, increase in GDPGR per capita by 1% boosts CO₂ emissions by 0.03%; however, for model II, a 1% increase in GDP per capita upsurges CO₂ emissions by 0.04% in the short run. Hence, results show that the prediction of the environmental Kuznets curve (EKC) is constant in the short run (Adams et al. 2020). Furthermore, renewable energy has a negatively significant impact on CO₂ emissions in the short and long run. Incisively, in model I, a 1% increase in REC decreases CO₂ emissions levels by - 0.25% and 0.15% in the short and long run, respectively. From model II, an increase in 1% of REC reduces CO₂ levels by - 0.26% and - 0.25% in the short and long run, respectively. This indicates that environmental quality increases with the increased use of renewable energy.

The findings reveal that fossil fuel energy triggers the CO₂ emissions for the models I and II in the short and long run. The results indicate that a 1% upsurge in FFC impedes the CO₂ emissions level by 0.10% and 0.09% in the short and long run, respectively. However, for model II, a 1% rise in fossil fuel consumption raises CO₂ emissions levels by 0.10% and 0.03% in the short and long

Table 4 Westerland test for cointegration

Model	Group statistics		Panel statistics	
	Gτ	Gα	Pτ	Pα
CO ₂ = f (LnGDPGR, LnREC, LnFFC, LnTR, LnGCF, LnPOGR, LnLE)	- 2.63***(0.00)	- 2.66(1.00)	- 13.633***(0.00)	- 1.006(0.99)

***, **, * represents the level of significance at 1%, 5%, and 10%, respectively

Table 5 CS-ARDL test results

Dependent variable- CO ₂	Top 10 renewable energy-using economies		Top 10 fossil fuel energy-using economies	
	Model I		Model II	
	Coefficients	Prob	Coefficients	Prob
Short-run				
ΔGDPGR	0.03*	0.09	0.04**	0.03
ΔREC	- 0.28*	0.07	- 0.26**	0.05
ΔFFC	0.10*	0.09	0.09*	0.07
ΔTR	0.04**	0.05	0.01*	0.08
ΔGCF	0.01*	0.06	0.05	0.14
ΔPOGR	0.13*	0.06	0.10*	0.07
ΔLE	- 0.05*	0.07	- 0.03*	0.09
Long run				
CO ₂ (-1)	0.13***	0.01	0.06**	0.05
GDPGR	0.01	0.19	0.01	0.57
REC	- 0.15***	0.01	- 0.25*	0.08
FFC	0.10*	0.08	0.03*	0.09
TR	0.02**	0.04	0.01	0.43
GCF	0.03	0.37	0.04	0.25
POGR	0.05	0.82	0.02	0.93
LE	0.08	0.60	- 0.27	0.14
ECT(-1)	- 0.86***	0.00	- 0.93***	0.00

The 1%, 5%, and % significant level is shown by ***, **, and *, respectively

run, respectively. The results of the study show that trade openness has a significant and positive nexus with CO₂ in the short run for both models; however, it has a significant positive association with CO₂ in model I, contrary to model II having a positively insignificant association in the long run. The findings reveal that a 1% increase in TR increases CO₂ by 0.04% and 0.01% in the short run for models I and II, respectively. Also, a 1% rise in TR increases 0.02% the CO₂ emissions level by 0.02% in the long run for model A, while for model B, it has a positive and insignificant association with CO₂. The result reveals that gross capital formation deteriorates the environmental quality in the short run in the model I only. A 1% increase in GCF increases 0.01% of CO₂ emissions level. It is estimated from results that renewable energy-using economies might be using capital for construction and manufacturing of machinery, having a potential negative impact on the environment. However, in the long run, models I and II have a positive and insignificant association with CO₂.

Finally, our outcomes of the study reveal that population growth has a potentially positive and significant effect, and human capital has a significantly negative effect on CO₂ emissions in the short run but a positive and insignificant effect in the long run for models I and II. According to the results 1% increase in POGR increases 0.13% and 0.10% CO₂ emissions level in the short run for both models. However, according to the results 1% increase in HC reduces CO₂ emission levels by - 0.13% and - 0.10% in the short run for both models. The efficacy of human capital in renewable energy-using countries is more than in fossil fuel energy-using economies, as could be seen through coefficients of HC for both models.

Discussion

Results of this study reveal that economic growth has a positive and significant nexus in the short run while a positive and insignificant association with CO₂ emissions in the long run for both models. The implication of the results is that the boom of economic activities in the short run imposes a greater degree of environmental degradation on both groups of economies. However, the results contrast with Adams et al. (2020), Asongu et al. (2020), Adebayo (2022b), and Ramzan et al. (2022), who found a positive effect of economic growth on CO₂ in the long run. Adebayo (2022b) found the positive association of economic growth in the long run while negative and significant association in short run in the context of Canada, which contrast our findings. The lack of unanimity in the results could be attributed to the difference in the scope of the study. Most importantly, the coefficient of GDPGR for fossil fuel economies is greater than for renewable energy-using economies. This implies that policymakers of particularly fossil fuel energy-using economies should address the problem of environmental degradation in the short run by formulating policies that promote the efficient use of CO₂ materials during the production process.

Furthermore, renewable energy has a negatively significant impact on CO₂ emissions in the short and long run. This indicates that environmental quality increases with the increased use of renewable energy in the top 10 renewable energy-using economies (model I) and top 10 fossil fuel energy-using economies (model II). Interestingly, findings indicate that coefficients of REC for fossil fuel energy-using economies are greater than renewable energy-using economies suggesting that a little addition of renewable energy sources reduces the negative repercussions of human activities and is considered a helpful tool to attain

sustainable long-term economic growth with environmental sustainability. Moreover, renewable energy sources such as wind, photovoltaic, and biofuel are the pathways to clear the environment and, in particular, to attain the SDG-7 goal by 2030. The results are in line with He et al. (2021), which relied on CS-ARDL and CCEMG econometric estimators; Ramzan et al. (2022) for Pakistan, which utilized nonparametric causality in quantile approach for the period of 1960Q1 to 2019Q4; Yuping et al. (2021) for Argentina; Dingru et al. (2021) for BRICS nations; Adebayo (2022a) for Spain; Bekun et al. (2022) for sub-Saharan Africa; Bekun et al. (2022) for India; and Adebayo (2022b) for Canada.

The findings reveal that fossil fuel energy triggers CO₂ emissions for models I and II in the short and long run. The results are in line with Ali et al. (2021) and Ramzan et al. (2022) in the context of Pakistan; Yuping et al. (2021) found the same results, utilizing ARDL econometric technique on data in G7 countries; Yuping et al. (2021) in Argentina; Somoye et al. (2022b) in Nigeria; Adebayo (2022b) in Canada; and Bekun et al. (2022) in India. Furthermore, the reason for this is because for industrial and manufacturing, transportation, and home activities, the conventional source of fossil energy is lavishly used for energy generation, accelerating the rate of environmental deterioration in both groups of economies. However, in these economies, the use of fossil fuels has greatly increased air pollution. Fossil fuel energy usage intensively depletes the environmental quality, which in turn increases global greenhouse gas emissions. As a result, reducing fossil dependency is once again deemed necessary for improving the overall quality of the environment in both groups of economies. Replacing the unfriendly fossil fuel energy use with friendly renewable energy use will assist them in reducing CO₂ emissions and advance the green environment in the long run.

The results of the study show that trade openness has a significant and positive nexus with CO₂ in the short run for both models; however, it has a significant positive association with CO₂ in model I, contrary to model II having a positively insignificant association in the long run. The estimations suggest that high demand for goods to trade between countries leaves higher pressure on production activities and energy consumption, resulting in an increased level of economic growth at the cost of environmental quality in the short and long run for renewable economies and in only the short run in fossil fuel economies. The results affirm the pollution haven hypothesis (PHH) in renewable energy-using economies in the short and long term, while in the short term in fossil fuel energy-using economies (Copeland and Taylor

1994). According to this, trade openness makes host economies with lax environmental standards dirtier. Results are in line with Talukdar and Meisner (2001), Xing and Kolstad (2002), Ramzan et al. (2022), Aslam et al. (2021), Somoye et al. (2022a), Idris et al. (2022) and Munir and Ameer (2018), finding that growing free trade pressure on natural resources is to blame for these environmental consequences. Moreover, we extracted that the scale impact entails trade liberalization, which boosts exports and GDP. But depletes resources and causes environmental degradation in the short run for both groups of economies. Hence, through trade liberalization, the composition impact alters an economy's industrial structure, while the technique effect encourages nations to adopt more efficient and cleaner technologies. As a result, comparative developments in ecologically clean sectors and increases in energy efficiency might justify the net effect of a reduction in CO₂ emissions (Balsalobre et al. 2015; Lorente and Alvarez-Herranz 2016; Shahbaz et al. 2013).

The result discloses that gross capital formation deteriorates the environmental quality in the short run in a model I only. However, in the long run, models I and II have a positive and insignificant association with CO₂. Therefore, it is suggested that renewable energy-using economies require more investment funds in the renewable energy sector and energy-efficient technologies to capture carbon in the short run. The results are in line with Mujtaba et al. (2022), who investigated that environmental quality is dampened by the capital formation in the OECD region (Faisal et al. 2021a) and found similar results to Ottman et al. (2019) and Auclair et al. (2020). Though, Nathaniel and Adeleye (2021) and Chen et al. (2020) found a positive and insignificant association between capital formation and CO₂ in selected African countries and OECD countries, respectively.

The population growth has a potentially positive and significant effect on CO₂ emissions in the short run but a positive and insignificant effect in the long run for models I and II. The results suggest that the population growth rate upsurge the level of energy consumption demanded, leading to the environment quality deterioration likewise, the demand for water, housing, transportation, food, commercial building, electric appliances, public utilities, etc. increase, leading to increased pollution and drives climate change. The results are in line with Saidi and Hammami (2015) for 58 countries, Waheed et al. (2019) for Chinese provinces, and Doğan et al. (2020) for 28 OECD countries, who investigated that increase in population leads to a rise in the level of carbon dioxide emissions resulting environmental degradation.

Lastly, the human capital has a significantly negative effect on CO₂ emissions in the short run but a positive and insignificant effect in the long run for models I and II. The efficacy of human capital in renewable energy-using countries is more than in fossil fuel energy-using economies, as could be seen through coefficients of HC for both models. Therefore, we suggest that fossil fuel energy-using economies to improve human capital development strategy so as to generate more meaningful outcomes. Furthermore, they must improve the human capital to transit energy use from fossil to renewable energy (Yang et al. 2017) and enhance the energy efficiency, adopt new technologies free from pollution, abide by rules related to the environment, and improve energy efficiency by human capital. Results are in line with Nathaniel et al. (2021a), who found that in BRICS, human capital efficiency is at a lower scale to mitigate environmental degradation and requires a desirable level to reduce it. Sheraz et al. (2021) and Nathaniel et al. (2021b) found negative and significant results in the context of G20 countries and Latin American and Caribbean countries, respectively.

Concluding remark and policy implications

This study investigates the nexus between CO₂ emission, economic growth, fossil fuel consumption, renewable energy consumption, gross fixed capital formation, population growth rate, life expectancy, and trade openness in the top 10 highest renewable energy-using economies and top 10 highest fossil fuel energy-using economies between 1991 and 2020. This study utilized Pesaran (2007), (2015), and Breusch and Pagan LM (1980) tests to decide the right econometric approach, Pesaran (CIPS-2007) to examine the stationarity of data, and Westerland test to evaluate cointegration among variables. Moreover, we used cross-sectional autoregressive distributive lag (CS-ARDL) econometric approach to estimate the short- and long-run nexus.

The results reveal that all variables (GDPGR, FFC, TR, GCF) are positive and significant for models I and II, except GCF, which is positive and insignificant in model II in the short run. However, REC and HC are negative

and significant in both models in the short run. Moreover, FFC contributes to CO₂ emissions in the long run in both models, whereas TR contributes to CO₂ emission in the model I only. In addition to that, only REC significantly negatively affects the CO₂ emissions levels and play vital role in mitigating the harmful effects of CO₂ emissions on the environment in the top 10 renewable energy-using economies and top 10 fossil fuel-using economies in the long run. The findings reveal necessary information for policy directions for the top 10 renewable and top 10 fossil fuel energy-using economies. (1) Both groups of economies must ponder over energy efficiency policies in each sector of the economy to attain sustainable economic development goals. As a need of a green economy is a major millstone while facing the challenges of environmental degradation, government and policymakers of both groups of economies must develop and put several plans into action, such as a Green Finance Plan (GFP), a National Renewable Energy Policy Plan (NREPP) aligning them to green economy to overcome climate change with sustainable development. (2) Both group of economies must boost their momentum in order to increase the proportion of renewable energy to total energy use, particularly fossil fuel energy, to meet SDG (7) by 2030. (3) Human capital development is vital for long-term prosperity and environmental protection. In both groups of economies, it is vital to develop a skilled workforce and educate and aware them to transit fossil fuel energy businesses into environmentally friendly businesses. However, it can be only possible by launching green awareness campaigns regarding environmental degradation and climate change mitigation population hazards. (4) Governments of both groups of economies must promote green and clean environmental policies and impose strict laws pertaining to a green environment. There are some limitations to this study. The sample span is just 30 years. Due to the lack of data on the nature of the data set, some antecedents of CO₂ emissions were not considered and analyzed in this research, such as green finance or green investment, research and development (R&D), and foreign assets. For the future endeavor (gap), it would be worth noting to investigate if green investment and research and development (R&D) could help to mitigate environmental degradation caused by CO₂.

Appendix

Table 6 Synopsis of existing literature

Article	Author	Variables	Techniques	Outcomes
Malaysia's economic growth, consumption of oil, industry, and CO ₂ emissions: evidence from the ARDL model	Aslam et al. (2021)	(1) Carbon dioxide (CO ₂) (DV) (2) Liquid fuel consumption COL2 (3) Industry (IND) (4) Trade openness (TR) (5) Economic growth (GDP)	ARDL ECM	COL2 (+), Sig → CO ₂ IND (+), Sig → CO ₂ TR (+), Sig → CO ₂ GDP (+), Sig → CO ₂
Effects of energy consumption and ecological footprint on CO ₂ emissions: an empirical evidence from Pakistan	Abbas et al. (2021)	(1) Carbon dioxide (CO ₂)(DV) (2) Urbanization (URB) (CV) (3) Traditional energy (TE) (4) Renewable energy consumption (REC)	ARDL FMOLS DOLS	REC (-), Sig → CO ₂ TE (+), Sig → CO ₂ EF (+), Sig → CO ₂ TRN (+), Sig → CO ₂ URB (+), Sig → CO ₂ CO ₂ (+), Sig → TEM
The nexus between environmental degradation and industrial development in Pakistan and roles of financial development and fossil fuel	Ali et al. (2021)	(5) Transportation (TRN) (CV) (6) Ecological footprint (EF) (7) Temperature (TEM) (DV) (1) Carbon dioxide (CO ₂) (DV) (2) Industrial development (ID) (3) Industrial development (ID2) (4) Fossil oil consumption (FOC) (5) Financial development (FD)	ARDL	FOC (+), Sig → CO ₂ FD (-), Insig → CO ₂ ID (+), Sig → CO ₂ ID2 (-), Sig → CO ₂
Fossil energy consumption, economic development, inward FDI impact on CO ₂ emissions in Pakistan: testing EKC hypothesis through ARDL model	Ali et al. (2020b).	(1) Carbon dioxide (CO ₂) (DV) (2) Economic development (ED) (3) EDqs (ED2) (4) Fossil energy consumption (FEC) (5) Inward FDI (IFDI)	ARDL ECM	ED (+), Sig → CO ₂ ED2 (-), Insig → CO ₂ FEC (+), Sig → CO ₂ IFDI (-), Sig → CO ₂
Fossil fuels consumption and carbon dioxide emissions in G7 countries: empirical evidence from ARDL bounds testing approach	Martins et al. (2021)	(1) Carbon dioxide (CO ₂) (DV) (2) Coal (3) Oil (4) Gas	ARDL ECM	COAL (+), Sig → CO ₂ OIL (-), Sig → CO ₂ GAS (+), Sig → CO ₂
Does green investment, financial development and natural resources rent limit carbon emissions? A provincial panel analysis of China	Shen et al. (2021)	(1) Carbon dioxide (CO ₂) (DV) (2) Natural resources rent (NRR) (3) Green investment (GI) (4) Energy consumption (EC) (5) Financial development (FD)	CS-ARDL AMG CCEMG	FD (+), Sig → CO ₂ EC (+), Sig → CO ₂ NRR (+), Sig → CO ₂ GI (-), Sig → CO ₂

Table 6 (continued)

Article	Author	Variables	Techniques	Outcomes
Environmental preservation amidst carbon emissions, energy consumption, and urbanization in selected African countries: implication for sustainability	Nathaniel and Adeleye (2021)	(1) Carbon dioxide (CO ₂) (DV) (2) Energy use (ENGY) (3) Urbanization (URB) (4) Real GDPPC (CV) (5) Financial development (FIN) (CV) (6) Gross fixed capital formation (GFCF)(CV) (7) Urban population growth (URBN) (CV) (8) Ecological footprint (EF) (DV)	FGLS GMM ARDL	ENGY (+), Sig → CO ₂ FIN (+), Sig → CO ₂ GDPPC (+), Sig → CO ₂ URB (-), Sig → CO ₂ GFCF no effect → CO ₂ URB (-), Sig → CO ₂ CO ₂ (+), Sig → EF
Carbon emissions determinants and forecasting: evidence from G6 countries	Nguyen et al. (2021)	(1) Carbon dioxide (CO ₂) (DV) (2) Trade (TR) (3) GDP growth (GDP) (4) Financial direct investment (FDI) (5) Financial development: (a) Stock market value (SMV) (b) Nonlisted firms (NLF) (c) Loans (LON)	FMOLS DOLSGM M	TR (+), Sig → CO ₂ GDP (+), Sig → CO ₂ NLF (+), Sig → CO ₂ FDI (+), Sig → CO ₂ LON (-), Sig → CO ₂ SMV (-), Sig → CO ₂
Effects of biomass energy consumption on environmental quality: the role of education and technology in Asia-Pacific Economic Cooperation countries	Zafar et al. (2021)	(1) Carbon dioxide (CO ₂) (DV) (2) Economic growth (GDP) (3) Technological innovation (TI) (4) Financial development (FD) (5) Biomass energy (BE) (6) Education (ED)	FE Panel Quantile regression	GDP (+), Sig → CO ₂ TI (+), Sig → CO ₂ FD (-), Sig → CO ₂ BE (+), Sig → CO ₂ ED (-), Sig → CO ₂
Determinants of carbon emissions in Argentina: the roles of renewable energy consumption and globalization	Yuping et al. (2021)	(1) Environmental sustainability (CO ₂)(DV) (2) Economic growth (GDP) (3) Nonrenewable energy (NREN) (4) Renewable energy (REN) (5) Economic globalization (GLO)	ARDL	GDP (+), Sig → CO ₂ NREN (+), Sig → CO ₂ REN (-), Sig → CO ₂ GLO (-), Sig → CO ₂

Table 6 (continued)

Article	Author	Variables	Techniques	Outcomes
Modelling the connection between energy consumption and carbon emissions in North Africa: Evidence from panel models robust to cross-sectional dependence and slope heterogeneity	Musah et al. (2021)	(1) Carbon emissions (CO ₂) (DV)	AMG	EC (+), Sig → CO ₂
		(2) Gross domestic product (GDP)	CCEMG	GDP (+), Sig → CO ₂ URB (+), Sig → CO ₂ FDI (+), Sig → CO ₂
Trilemma association of energy consumption, carbon emission, and economic growth of BRICS and OECD regions: quantile regression estimation	Nawaz et al. (2021)	(4) Energy consumption (EC)		DGP Sq (-), Sig → CO ₂
		(5) Urbanization (URB)		REE (-), Sig → CO ₂
		(1) Carbon emissions (CO ₂) (DV)	QARDLV	GDP (+), Sig → CO ₂
		(2) Renewable energy usage (REE)	ARECM	GDP2 (-), Sig → CO ₂
		(3) Fossil fuel energy usage (FFE)		FFE (+), Sig → CO ₂
		(4) Economic growth (GDP)		TRD no Sig effect
		(5) DGP Sq (GDP2)		GCF (-), Sig → CO ₂
The mitigating effects of economic complexity and renewable energy on carbon emissions in developed countries	Doğan et al. (2020)	(6) Gross capital formation (GCF)		ECI (-), Sig → CO ₂
		(7) Trade openness (TRD)		GDP (+), Sig → CO ₂
		(1) Carbon emissions (CO ₂) (DV)	Augmented Mean Group (AMG)	POP (+), Sig → CO ₂
		(2) Economic complex index (ECI) (IDV)		REC (-), Sig → CO ₂
		(3) RE consumption (REC)(IDV)		
		(4) Total population (POP) (CV)		
		(5) Gross DP (GDP-CV)		
Theoretical framework for the carbon emissions effects of technological progress and renewable energy consumption	Hasanov et al. (2021)	(1) Carbon emissions (CCO ₂ it) (DV) International trade:	CS-ARDL	TEPit (-), Sig → CO ₂
		(2) Export (Xit)		ERit (-), Sig → CO ₂
		(3) Import (Mit)		Xit (-), Sig → CO ₂
		(4) Gross domestic product (Yit)		Mit (+), Sig → CO ₂
		(5) Technological progress (TFPit)		GDP (+), Sig → CO ₂
Moderating the effect of globalization on financial development, energy consumption, human capital, and carbon emissions: evidence from G20 countries	Sheraz et al. (2021)	(5) RE consumption (ERit)		
		(1) Carbon dioxide (CO ₂) (DV)	FE OLS	FD (-), Sig → CO ₂
		(2) Financial development (FD)		GB (-), Sig → CO ₂
				EC (+), Sig → CO ₂
				HE (-), Sig → CO ₂
				GDP (+), Sig → CO ₂
		(3) Energy consumption (EC)		
		(4) Human capital (HC)		
		(5) Gross domestic product (GDP)		
		(6) Globalization (GB) (Moderating)		

Table 6 (continued)

Article	Author	Variables	Techniques	Outcomes
The criticality of growth, urbanization, electricity and fossil fuel consumption to environment sustainability in Africa	Asongu et al. (2020)	(1) Carbon dioxide (CO ₂) (DV)	ARDL-PMG	GDP (+), Sig → CO ₂
		(2) Urbanization (URB)		URB (+), Sig → CO ₂
		(3) Natural rent resource (NET)		NET (+), Sig → CO ₂
		(4) Electricity (ELE)		ELE (+), Sig → CO ₂
		(5) Nonrenewable energy (NRE)		NRE (+), Sig → CO ₂
		(6) Economic growth (GDP)		GDP (+), Sig → CO ₂
Toward a sustainable environment: Nexus between CO ₂ emissions, resource rent, renewable and nonrenewable energy in 16-EU countries	Bekun et al. (2019a)	(1) Carbon dioxide (CO ₂) (DV)	PMG-ARDL	NET (+), Sig → CO ₂
		(2) Economic growth (GDP)		REN (-), Sig → CO ₂
		(3) Natural rent resource (NET)		NREN (+), Sig → CO ₂
		(4) Renewable energy (NRE)		
		(5) Nonrenewable energy (NRE)		
Dynamic impact of trade policy, economic growth, fertility rate, renewable and non-renewable energy consumption on ecological footprint in Europe	Alola et al. (2019)	(1) Ecological footprint (EFP) (DV)	PMG-ARDL	GDP (+), Sig → EFP
		(2) Economic growth (GDP)		NET (+), Sig → EFP
		(3) Renewable energy (NRE)		REN (-), Sig → EFP
		(4) Nonrenewable energy (NRE)		TO (-), Sig → EFP
		(5) Trade openness (TO)		FR (-), Sig → EFP
		(6) Fertility rate (FR)		
Contemporaneous interaction between energy consumption, economic growth and environmental sustainability in South Africa: what drives what?	Akadiri et al. (2019)	(1) Ecological footprint (EFP) (DV)	ARDL	GDPC (+), Sig → EFP
		(2) Economic growth (GDPC)		EC (-), Sig → EFP
		(3) Energy consumption (EC)		
An assessment of environmental sustainability corridor: the role of economic expansion and research and development in EU countries	Adedoyin et al. (2020a)	(1) Ecological footprint (EFP) (DV)	FMOLS and DOLS	GDP (+), Sig → EFP
		(2) Economic growth (GDP)		R&D (-), Sig → EFP
		(3) Research and development (R&D)		REN (-), Sig → EFP
		(4) Renewable energy (NRE)		NRE (+), Sig → EFP
		(5) Nonrenewable energy (NRE)		
Assessing the environmental sustainability corridor: linking natural resources, renewable energy, human capital, and ecological footprint in BRICS.	Nathaniel et al. (2021a)	(1) Ecological footprint (EFP) (DV)	CCEMG, AMG, and PMG	GDP (+), Sig → EFP
		(2) Economic growth (GDP)		NR (+), Sig → EFP
		(3) Renewable energy (RE)		RE (-), Sig → EFP
		(4) Natural resources rent (NR)		HC (-), Sig → EFP
		(5) Human capital (HC)		URB (+), Sig → EFP
		(6) Urbanization (URB)		

Table 6 (continued)

Article	Author	Variables	Techniques	Outcomes
Symmetric and asymmetric impact of economic growth, capital formation, renewable and non-renewable energy consumption on environment in OECD countries	Mujtaba et al. (2022)	(1) Carbon dioxide (CO ₂) (DV) (2) Economic growth (EG) (3) Capital formation (CF) (4) Renewable energy (RE) (5) Nonrenewable energy (NRE)	ARDL & NARDL	EG (+), Sig → CO ₂ CF (+), Sig → CO ₂ RE (-), Sig → CO ₂ NREN (+), Sig → CO ₂
Tourism-induced emission in sub-Saharan Africa: a panel study for oil-producing and non-oil-producing countries	Bekun et al. (2022)	(1) Carbon dioxide (CO ₂) (DV) (2) Economic growth (GDP) (3) Tourism (TA) (4) Foreign direct investment (FDI) (5) Renewable energy (RE) (6) Fossil fuel (NREC) (7) Urbanization (UB)	OLS and QR	GDP (+), Sig → CO ₂ TA (+), Sig → CO ₂ FDI (+), Sig → CO ₂ RE (-), Sig → CO ₂ NREC (+), Sig → CO ₂ UB (+), Sig → CO ₂
Natural resource, globalization, urbanization, human capital, and environmental degradation in Latin American and Caribbean countries	Nathaniel et al. (2021b)	(1) Carbon dioxide (CO ₂) (DV) (2) Economic growth (GDP) (3) Urbanization (UB) (4) Globalization (GLO) (5) Natural rent (NRE) (6) Human capital (HC)	CCEMG	GDP (+), Sig → CO ₂ UB (+), Sig → CO ₂ GLO (+), Sig → CO ₂ NREC (+), Sig → CO ₂ HC (-), Sig → CO ₂
Mitigating emissions in India: accounting for the role of real income, renewable energy consumption and investment in energy	Bekun et al. (2022)	(1) Carbon dioxide (CO ₂) (DV) (2) Economic growth (GDP) (3) Renewable energy consumption (REC) (4) Fossil fuel energy consumption (NREC) (5) Investment in energy with private participation (IEC)	CCR, FMOLS, DOLS	GDP (+), Sig → CO ₂ REC(-), Sig → CO ₂ NREC (+), Sig → CO ₂ ICE (-), Sig → CO ₂
Appraisal of CO ₂ emission in Tunisia's industrial sector: a dynamic vector auto-regression method	Talbi et al. (2022)	(1) Carbon dioxide (CO ₂) (DV) (2) Economic growth (EG) (3) Urbanization (URB) (4) Energy consumption (EC) (5) Energy efficiency (EE)	VAR	EE (-), Sig → CO ₂ URB(+), Sig → CO ₂ EG (+), Sig → CO ₂ EC (-), Sig → CO ₂

Table 6 (continued)

Article	Author	Variables	Techniques	Outcomes
The role of renewable energy consumption towards carbon neutrality in BRICS nations: does globalization matter?	Dingru et al. (2021)	(1) Ecological footprint (ECF) (DV) (2) Globalization (GLO) (3) Renewable energy consumption (REC) (4) Economic growth (GDP) (5) Technological innovation (TI)	MMQR	GLO (-), Sig → EFP REC (-), Sig → EFP GDP (+), Sig → EFP TI No relationship
The environmental sustainability effects of financial development and urbanization in Latin American countries	Adebayo et al. (2021)	(1) Carbon dioxide (CO ₂) (DV) (2) Economic growth (EG) (3) Urbanization (URB) (4) Energy consumption (EC) (5) Foreign direct index (FD)	FMOLS and DOLS	EG (+), Sig → CO ₂ URB(+), Sig → CO ₂ EC (+), Sig → CO ₂ FD (+), Insig → CO ₂
Environmental cost of non-renewable energy and economic progress: do ICT and financial development mitigate some burden?	Ramzan et al. (2022)	(1) Ecological footprint (ECF) (DV) (2) Financial development (FD) (3) Trade openness (TRO) (4) Information and communication technologies (ICT) (5) Fossil FUELS (FOS) (6) Economic growth (GDP) (7) Energy consumption (ENR)	non-parametric causality-in-quantiles techniques	FD (+), Sig → EFP TRO (+), Sig → EFP ICT (+), Sig → EFP FOS (+), Sig → EFP GDP (+), Sig → EFP ENR (+), Sig → EFP

Author contribution MA participated in writing the whole paper. MS supervised, prepared the methodologies, and brought crucial ideas for this paper. All authors read and approved the final manuscript.

Availability of data and material This study inspects the link between economic growth, renewable energy, fossil fuel energy, gross capital formation, trade openness, population, human capital, and emission of carbon dioxide in TTHREC and TTHFFEC economies. The panel data has been used, spanning from 1991 to 2020. All data was collected from World Development Indicators (WDI).

Declarations

Ethics approval and consent to participate This paper does not contain any studies with human participants performed by any of the authors.

Consent for publication The authors guarantee that this manuscript has not been previously published in other journals and is not under consideration by other journals. The authors also guarantee that this manuscript is original and is their own work.

Conflict of interest The authors declare no competing interests.

References

- Abbas S, Kousar S, Pervaiz A (2021) Effects of energy consumption and ecological footprint on CO2 emissions: an empirical evidence from Pakistan. *Environ Dev Sustain* 23(9):13364–13381. <https://doi.org/10.1007/s10668-020-01216-9>
- Adams S, Adedoyin F, Olaniran E, Bekun FV (2020) Energy consumption, economic policy uncertainty and carbon emissions; causality evidence from resource rich economies. *Econ Anal Policy* 68:179–190. <https://doi.org/10.1016/j.eap.2020.09.012>
- Adebayo TS (2022a) Environmental consequences of fossil fuel in Spain amidst renewable energy consumption: a new insights from the wavelet-based Granger causality approach. *International Journal of Sustainable Development & World Ecology* 1–14. <https://doi.org/10.1080/13504509.2022.2054877>
- Adebayo TS (2022b) Renewable energy consumption and environmental sustainability in Canada: does political stability make a difference? *Environ Sci Pollut Res* 1–16. <https://doi.org/10.1007/s11356-022-20008-4>
- Adebayo TS, Ramzan M, Iqbal HA, Awosusi AA, Akinsola GD (2021) The environmental sustainability effects of financial development and urbanization in Latin American countries. *Environ Sci Pollut Res Int* 28(41):57983–57996. <https://doi.org/10.1007/s11356-021-14580-4>
- Adedoyin F, Ozturk I, Abubakar I, Kumeka T, Folarin O, Bekun FV (2020a) Structural breaks in CO2 emissions: Are they caused by climate change protests or other factors? *J Environ Manag* 266:110628. <https://doi.org/10.1016/j.jenvman.2020.110628>
- Adedoyin FF, Alola AA, Bekun FV (2020b) An assessment of environmental sustainability corridor: The role of economic expansion and research and development in EU countries. *Sci Total Environ* 713:136726. <https://doi.org/10.1016/j.scitotenv.2020.136726>
- Adedoyin FF, Gumede MI, Bekun FV, Etokakpan MU, Balsalobre-Lorente D (2020c) Modelling coal rent, economic growth and CO2 emissions: does regulatory quality matter in BRICS economies? *Sci Total Environ* 710:136284. <https://doi.org/10.1016/j.scitotenv.2019.136284>
- Ahmad M, Jiang P, Majeed A, Raza MY (2020) Does financial development and foreign direct investment improve environmental quality? Evidence from belt and road countries. *Environ Sci Pollut Res Int* 27(19):23586–23601. <https://doi.org/10.1007/s11356-020-08748-7>
- Ahmed Z, Asghar MM, Malik MN, Nawaz K (2020) Moving towards a sustainable environment: The dynamic linkage between natural resources, human capital, urbanization, economic growth, and ecological footprint in China. *Res Policy* 67:101677. <https://doi.org/10.1016/j.resourpol.2020.101677>
- Akadiri SS, Bekun FV, Sarkodie SA (2019) Contemporaneous interaction between energy consumption, economic growth and environmental sustainability in South Africa: what drives what? *Sci Total Environ* 686:468–475. <https://doi.org/10.1016/j.scitotenv.2019.05.421>
- Ali MU, Gong Z, Ali MU, Wu X, Yao C (2020a) Fossil energy consumption, economic development, inward FDI impact on CO2 emissions in Pakistan: Testing EKC hypothesis through ARDL model. *Int J Financ Econ* 26(3):3210–3221. <https://doi.org/10.1002/ijfe.1958>
- Ali S, Yusop Z, Kaliappan SR, Chin L (2020b) Dynamic common correlated effects of trade openness, FDI, and institutional performance on environmental quality: evidence from OIC countries. *Environ Sci Pollut Res Int* 27(11):11671–11682. <https://doi.org/10.1007/s11356-020-07768-7>
- Ali MU, Zhimin G, Asmi F, Xue Z, Muhammad R (2021) The nexus between environmental degradation and industrial development in Pakistan and roles of financial development and fossil fuel. *Environ Prog Sustain Energy* 40(4):e13621. <https://doi.org/10.1002/ep.13621>
- Alola AA, Bekun FV, Sarkodie SA (2019) Dynamic impact of trade policy, economic growth, fertility rate, renewable and non-renewable energy consumption on ecological footprint in Europe. *Sci Total Environ* 685:702–709. <https://doi.org/10.1016/j.scitotenv.2019.05.139>
- Aslam B, Hu J, Ali S, AlGarni TS, Abdullah MA (2021) Malaysia's economic growth, consumption of oil, industry and CO2 emissions: evidence from the ARDL model. *Int J Environ Sci Technol*. <https://doi.org/10.1007/s13762-021-03279-1>
- Asongu SA, Agboola MO, Alola AA, Bekun FV (2020) The criticality of growth, urbanization, electricity and fossil fuel consumption to environment sustainability in Africa. *Sci Total Environ* 712:136376. <https://doi.org/10.1016/j.scitotenv.2019.136376>
- Auclair J, Quinn B, Peyrot C, Wilkinson KJ, Gagné F (2020) Detection, biophysical effects, and toxicity of polystyrene nanoparticles to the cnidarian *Hydra attenuata*. *Environ Sci Pollut Res* 27(11):11772–11781
- Balsalobre D, Álvarez A, Cantos JM (2015) Public budgets for energy RD&D and the effects on energy intensity and pollution levels. *Environ Sci Pollut Res* 22(7):4881–4892
- Bekun FV (2022) Mitigating Emissions in India: Accounting for the Role of Real Income, Renewable Energy Consumption and Investment in Energy. *Int J Energy Econ Policy* 12(1):188–192. <https://doi.org/10.32479/ijeep.12652>
- Bekun FV, Alola AA, Sarkodie SA (2019a) Toward a sustainable environment: nexus between CO2 emissions, resource rent, renewable and nonrenewable energy in 16-EU countries. *Sci Total Environ* 657:1023–1029. <https://doi.org/10.1016/j.scitotenv.2018.12.104>
- Bekun FV, Emir F, Sarkodie SA (2019b) Another look at the relationship between energy consumption, carbon dioxide emissions, and economic growth in South Africa. *Sci Total Environ* 655:759–765. <https://doi.org/10.1016/j.scitotenv.2018.11.271>
- Bekun FV, Gyamfi BA, Bamidele RO, Udemba EN (2022) Tourism-induced emission in Sub-Saharan Africa: A Panel Study for Oil-Producing and Non-oil-Producing countries. *Environ Sci Pollut Res Int*. <https://doi.org/10.1007/s11356-021-18262-z>
- Breusch TS, Pagan AR (1980) The Lagrange multiplier test and its applications to model specification in econometrics. *Rev Econ Stud* 47(1):239–253.

- Chen T, Gozgor G, Koo CK, Lau CKM (2020) Does international cooperation affect CO₂ emissions? Evidence from OECD countries. *Environ Sci Pollut Res* 27(8):8548–8556
- Chudik A, Mohaddes K, Pesaran MH, Raissi M (2016) Long-run effects in large heterogeneous panel data models with cross-sectionally correlated errors. In: *Essays in Honor of Aman Ullah*. Emerald Group Publishing Limited, Bingley
- Copeland BR, Taylor MS (1994) North-South trade and the environment. *Q J Econ* 109(3):755–787
- Danish, Hassan ST, Baloch MA, Mahmood N, Zhang J (2019) Linking economic growth and ecological footprint through human capital and biocapacity. *Sustain Cities Soc* 47:101516. <https://doi.org/10.1016/j.scs.2019.101516>
- Destek MA, Sinha A (2020) Renewable, non-renewable energy consumption, economic growth, trade openness and ecological footprint: Evidence from organisation for economic Co-operation and development countries. *J Clean Prod* 242:118537. <https://doi.org/10.1016/j.jclepro.2019.118537>
- Dingru L, Ramzan M, Irfan M, Gülmez Ö, Isik H, Adebayo TS, Husam R (2021) The role of renewable energy consumption towards carbon neutrality in BRICS nations: does globalization matter? *Front Environ Sci* 9:569. <https://doi.org/10.3389/fenvs.2021.796083>
- Doğan B, Driha OM, Balsobre Lorente D, Shahzad U (2020) The mitigating effects of economic complexity and renewable energy on carbon emissions in developed countries. *Sustain Dev* 29(1):1–12. <https://doi.org/10.1002/sd.2125>
- Dong K, Sun R, Li H, Liao H (2018) Does natural gas consumption mitigate CO₂ emissions: Testing the environmental Kuznets curve hypothesis for 14 Asia-Pacific countries. *Renew Sust Energ Rev* 94:419–429. <https://doi.org/10.1016/j.rser.2018.06.026>
- Faisal F, Khan MN, Pervaiz R, Muhamad PM, Rashdan MOJ (2021a) Exploring the role of fossil fuels, hydroelectricity consumption, and financial sector in ensuring sustainable economic development in the emerging economy. *Environ Sci Pollut Res Int* 28(5):5953–5965. <https://doi.org/10.1007/s11356-020-10608-3>
- Faisal F, Pervaiz R, Ozatac N, Tursoy T (2021b) Exploring the relationship between carbon dioxide emissions, urbanisation and financial deepening for Turkey using the symmetric and asymmetric causality approaches. *Environ Dev Sustain* 23(12):17374–17402. <https://doi.org/10.1007/s10668-021-01385-1>
- Global Sustainable Development Report (2019) <https://sustainabledevelopment.un.org/gedr2019>
- Hasanov FJ, Khan Z, Hussain M, Tufail M (2021) Theoretical framework for the carbon emissions effects of technological progress and renewable energy consumption. *Sustain Dev* 29(5):810–822
- He K, Ramzan M, Awosusi AA, Ahmed Z, Ahmad M, Altuntaş M (2021) Does Globalization Moderate the Effect of Economic Complexity on CO₂ Emissions? Evidence From the Top 10 Energy Transition Economies. *Front Environ Sci* 9:778088. <https://doi.org/10.3389/fenvs.2021.778088>
- Ibrahim RL, Ajide KB (2021) Nonrenewable and renewable energy consumption, trade openness, and environmental quality in G-7 countries: the conditional role of technological progress. *Environ Sci Pollut Res Int* 28(33):45212–45229. <https://doi.org/10.1007/s11356-021-13926-2>
- Idris FM, Seraj M, Özdeşer H (2022) Renewable energy consumption, CO₂ emissions and trade balance nexus in OECD countries: evidence from ARDL bounds approach. *International Journal of Energy Sector Management*(ahead-of-print). <https://doi.org/10.1108/IJESM-02-2022-0009>
- Im KS, Pesaran MH, Shin Y (2003) Testing for unit roots in heterogeneous panels. *J Econ* 115(1):53–74
- Islam R, Abdul Ghani AB (2018) Link among energy consumption, carbon dioxide emission, economic growth, population, poverty, and forest area. *Int J Soc Econ* 45(2):275–285. <https://doi.org/10.1108/ijse-12-2016-0351>
- Khan MK, Teng JZ, Khan MI, Khan MO (2019) Impact of globalization, economic factors and energy consumption on CO₂ emissions in Pakistan. *Sci Total Environ* 688:424–436. <https://doi.org/10.1016/j.scitotenv.2019.06.065>
- Khan AG, Hossain MA, Chen S (2021) Do financial development, trade openness, economic development, and energy consumption affect carbon emissions for an emerging country? *Environ Sci Pollut Res Int* 28(31):42150–42160. <https://doi.org/10.1007/s11356-021-13339-1>
- Korkmaz Ö (2022) What is the role of the rents in energy connection with economic growth for China and the United States? *Res Policy* 75:102517. <https://doi.org/10.1016/j.resourpol.2021.102517>
- Li K, Hu E, Xu C, Musah M, Kong Y, Mensah IA et al (2020) A heterogeneous analysis of the nexus between energy consumption, economic growth and carbon emissions: Evidence from the Group of Twenty (G20) countries. *Energy Explor Exploit* 39(3):815–837. <https://doi.org/10.1177/0144598720980198>
- Lorente D, Alvarez-Herranz A (2016) An approach to the effect of energy innovation on environmental Kuznets curve: an introduction to inflection point. *Bull Energy Econ* 4(3):224–233
- Majeed MT, Tauqir A, Mazhar M, Samreen I (2021) Asymmetric effects of energy consumption and economic growth on ecological footprint: new evidence from Pakistan. *Environ Sci Pollut Res Int*. <https://doi.org/10.1007/s11356-021-13130-2>
- Martins T, Barreto AC, Souza FM, Souza AM (2021) Fossil fuels consumption and carbon dioxide emissions in G7 countries: Empirical evidence from ARDL bounds testing approach. *Environ Pollut* 291:118093. <https://doi.org/10.1016/j.envpol.2021.118093>
- Mujtaba A, Jena PK, Bekun FV, Sahu PK (2022) Symmetric and asymmetric impact of economic growth, capital formation, renewable and non-renewable energy consumption on environment in OECD countries. *Renew Sust Energ Rev* 160:112300. <https://doi.org/10.1016/j.rser.2022.112300>
- Munir K, Ameer A (2018) Effect of economic growth, trade openness, urbanization, and technology on environment of Asian emerging economies. *Manag Environ Qual: Int J* 29(6):1123–1134
- Musah M, Kong Y, Mensah IA, Antwi SK, Osei AA, Donkor M (2021) 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* 23(10):15225–15239. <https://doi.org/10.1007/s10668-021-01294-3>
- Nathaniel SP, Adeleye N (2021) Environmental preservation amidst carbon emissions, energy consumption, and urbanization in selected african countries: implication for sustainability. *J Clean Prod* 285:125409. <https://doi.org/10.1016/j.jclepro.2020.125409>
- Nathaniel SP, Bekun FV (2019) Environmental management amidst energy use, urbanization, trade openness, and deforestation: The Nigerian experience. *J Public Affairs* 20(2):e2037. <https://doi.org/10.1002/pa.2037>
- Nathaniel S, Nwodo O, Adediran A, Sharma G, Shah M, Adeleye N (2019) Ecological footprint, urbanization, and energy consumption in South Africa: including the excluded. *Environ Sci Pollut Res Int* 26(26):27168–27179. <https://doi.org/10.1007/s11356-019-05924-2>
- Nathaniel S, Aguegbogh E, Iheonu C, Sharma G, Shah M (2020) Energy consumption, FDI, and urbanization linkage in coastal Mediterranean countries: re-assessing the pollution haven hypothesis. *Environ Sci Pollut Res Int* 27(28):35474–35487. <https://doi.org/10.1007/s11356-020-09521-6>
- Nathaniel SP, Nwulu N, Bekun F (2021a) Natural resource, globalization, urbanization, human capital, and environmental degradation in Latin American and Caribbean countries. *Environ Sci Pollut Res Int* 28(5):6207–6221. <https://doi.org/10.1007/s11356-020-10850-9>

- Nathaniel SP, Yalçiner K, Bekun FV (2021b) Assessing the environmental sustainability corridor: Linking natural resources, renewable energy, human capital, and ecological footprint in BRICS. *Res Policy* 70:101924. <https://doi.org/10.1016/j.resourpol.2020.101924>
- Nawaz MA, Hussain MS, Kamran HW, Ehsanullah S, Maheen R, Shair F (2021) Trilemma association of energy consumption, carbon emission, and economic growth of BRICS and OECD regions: quantile regression estimation. *Environ Sci Pollut Res Int* 28(13):16014–16028. <https://doi.org/10.1007/s11356-020-11823-8>
- Naz S, Sultan R, Zaman K, Aldakhil AM, Nassani AA, Abro MMQ (2019) Moderating and mediating role of renewable energy consumption, FDI inflows, and economic growth on carbon dioxide emissions: evidence from robust least square estimator. *Environ Sci Pollut Res Int* 26(3):2806–2819. <https://doi.org/10.1007/s11356-018-3837-6>
- Nguyen DK, Huynh TLD, Nasir MA (2021) Carbon emissions determinants and forecasting: Evidence from G6 countries. *J Environ Manag* 285:111988. <https://doi.org/10.1016/j.jenvman.2021.111988>
- Omoke PC, Opuala-Charles S, Camarero M (2021) Trade openness and economic growth nexus: Exploring the role of institutional quality in Nigeria. *Cogent Econ Finance* 9(1):1868686. <https://doi.org/10.1080/23322039.2020.1868686>
- Ottman N, Ruokolainen L, Suomalainen A, Sinkko H, Karisola P, Lehtimäki J et al (2019) Soil exposure modifies the gut microbiota and supports immune tolerance in a mouse model. *J Allergy Clin Immunol* 143(3):1198–1206 e1112
- Paiho S, Wessberg N, Pippuri-Mäkeläinen J, Mäki E, Sokka L, Parvainen T et al (2021) Creating a Circular City—An analysis of potential transportation, energy and food solutions in a case district. *Sustain Cities Soc* 64:102529. <https://doi.org/10.1016/j.scs.2020.102529>
- Park Y, Meng F, Baloch MA (2018) The effect of ICT, financial development, growth, and trade openness on CO2 emissions: an empirical analysis. *Environ Sci Pollut Res Int* 25(30):30708–30719. <https://doi.org/10.1007/s11356-018-3108-6>
- Pesaran MH (2007) A simple panel unit root test in the presence of cross-section dependence. *J Appl Econ* 22(2):265–312. <https://doi.org/10.1002/jae.951>
- Pesaran MH (2015) Testing weak cross-sectional dependence in large panels. *Econ Rev* 34(6–10):1089–1117
- Ramzan M, Raza SA, Usman M, Sharma GD, Iqbal HA (2022) Environmental cost of non-renewable energy and economic progress: Do ICT and financial development mitigate some burden? *J Clean Prod* 333:130066. <https://doi.org/10.1016/j.jclepro.2021.130066>
- Sahoo M, Sahoo J (2020) Effects of renewable and non-renewable energy consumption on CO2 emissions in India: Empirical evidence from disaggregated data analysis. *J Public Aff* 22(1):e2307. <https://doi.org/10.1002/pa.2307>
- Saidi K, Hammami S (2015) The impact of CO2 emissions and economic growth on energy consumption in 58 countries. *Energy Rep* 1:62–70. <https://doi.org/10.1016/j.egy.2015.01.003>
- Saud S, Chen S, Danish, Haseeb A (2019) Impact of financial development and economic growth on environmental quality: an empirical analysis from Belt and Road Initiative (BRI) countries. *Environ Sci Pollut Res Int* 26(3):2253–2269. <https://doi.org/10.1007/s11356-018-3688-1>
- Shahbaz M, Tiwari AK, Nasir M (2013) The effects of financial development, economic growth, coal consumption and trade openness on CO2 emissions in South Africa. *Energy Policy* 61:1452–1459
- Shahbaz M, Shahzad SJH, Mahalik MK, Hammoudeh S (2018) Does globalisation worsen environmental quality in developed economies? *Environ Model Assess* 23(2):141–156
- Shen Y, Su ZW, Malik MY, Umar M, Khan Z, Khan M (2021) Does green investment, financial development and natural resources rent limit carbon emissions? A provincial panel analysis of China. *Sci Total Environ* 755(Pt 2):142538. <https://doi.org/10.1016/j.scitotenv.2020.142538>
- Sheraz M, Deyi X, Ahmed J, Ullah S, Ullah A (2021) Moderating the effect of globalization on financial development, energy consumption, human capital, and carbon emissions: evidence from G20 countries. *Environ Sci Pollut Res Int* 28(26):35126–35144. <https://doi.org/10.1007/s11356-021-13116-0>
- Solarin SA, Nathaniel SP, Bekun FV, Okunola AM, Alhassan A (2021) Towards achieving environmental sustainability: environmental quality versus economic growth in a developing economy on ecological footprint via dynamic simulations of ARDL. *Environ Sci Pollut Res Int* 28(14):17942–17959. <https://doi.org/10.1007/s11356-020-11637-8>
- Somoye OA, Ozdeser H, Seraj M (2022a) The impact of renewable energy consumption on economic growth in Nigeria: fresh evidence from a non-linear ARDL approach. *Environ Sci Pollut Res* 1–15. <https://doi.org/10.1007/s11356-022-20110-7>
- Somoye OA, Ozdeser H, Seraj M (2022b) Modeling the determinants of renewable energy consumption in Nigeria: Evidence from Autoregressive Distributed Lagged in error correction approach. *Renew Energy* 190:606–616
- Soylu ÖB, Adebayo TS, Kirikkaleli D (2021) The imperativeness of environmental quality in China amidst renewable energy consumption and trade openness. *Sustainability* 13(9):5054. <https://doi.org/10.3390/su13095054>
- Talbi B, Ramzan M, Iqbal HA, Dogan B (2022) Appraisal of CO2 emission in Tunisia's industrial sector: a dynamic vector autoregression method. *Environ Sci Pollut Res Int*. <https://doi.org/10.1007/s11356-022-18805-y>
- Talukdar D, Meisner CM (2001) Does the private sector help or hurt the environment? Evidence from carbon dioxide pollution in developing countries. *World Dev* 29(5):827–840
- Tran NV, Tran QV, Do LTT, Dinh LH, Do HTT (2019) Trade off between environment, energy consumption and human development: Do levels of economic development matter? *Energy* 173:483–493. <https://doi.org/10.1016/j.energy.2019.02.042>
- Waheed R, Sarwar S, Wei C (2019) The survey of economic growth, energy consumption and carbon emission. *Energy Rep* 5:1103–1115. <https://doi.org/10.1016/j.egy.2019.07.006>
- Westerlund J (2007) Testing for error correction in panel data. *Oxf Bull Econ Stat* 69(6):709–748
- World Bank Developing Indicators (2019) <https://databank.worldbank.org/source/world-development-indicators>
- Xing Y, Kolstad CD (2002) Do lax environmental regulations attract foreign investment? *Environ Resour Econ* 21(1):1–22
- Yang L, Wang J, Shi J (2017) Can China meet its 2020 economic growth and carbon emissions reduction targets? *J Clean Prod* 142:993–1001. <https://doi.org/10.1016/j.jclepro.2016.08.018>
- Yu C, Nataliia D, Yoo S-J, Hwang Y-S (2019) Does trade openness convey a positive impact for the environmental quality? Evidence from a panel of CIS countries. *Eurasian Geogr Econ* 60(3):333–356. <https://doi.org/10.1080/15387216.2019.1670087>
- Yuping L, Ramzan M, Xincheng L, Murshed M, Awosusi AA, Bah SI, Adebayo TS (2021) Determinants of carbon emissions in Argentina: The roles of renewable energy consumption and globalization. *Energy Rep* 7:4747–4760. <https://doi.org/10.1016/j.egy.2021.07.065>
- Zafar MW, Mirza FM, Zaidi SAH, Hou F (2019a) The nexus of renewable and nonrenewable energy consumption, trade openness, and CO2 emissions in the framework of EKC: evidence from emerging economies. *Environ Sci Pollut Res Int* 26(15):15162–15173. <https://doi.org/10.1007/s11356-019-04912-w>

- Zafar MW, Zaidi SAH, Khan NR, Mirza FM, Hou F, Kirmani SAA (2019b) The impact of natural resources, human capital, and foreign direct investment on the ecological footprint: The case of the United States. *Res Policy* 63:101428. <https://doi.org/10.1016/j.resourpol.2019.101428>
- Zafar MW, Sinha A, Ahmed Z, Qin Q, Zaidi SAH (2021) Effects of biomass energy consumption on environmental quality: The role of education and technology in Asia-Pacific Economic Cooperation countries. *Renew Sust Energ Rev* 142:110868. <https://doi.org/10.1016/j.rser.2021.110868>
- Zameer H, Yasmeen H, Zafar MW, Waheed A, Sinha A (2020) Analyzing the association between innovation, economic growth, and environment: divulging the importance of FDI and trade openness in India. *Environ Sci Pollut Res Int* 27(23):29539–29553. <https://doi.org/10.1007/s11356-020-09112-5>
- Zhao X, Mahendru M, Ma X, Rao A, Shang Y (2022) Impacts of environmental regulations on green economic growth in China: New guidelines regarding renewable energy and energy efficiency. *Renew Energy* 187:728–742. <https://doi.org/10.1016/j.renene.2022.01.076>

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