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Role of technological innovation, renewable and non-renewable energy, and economic growth on environmental quality. Evidence from African countries

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This study examines the impact of renewable and non-renewable energy consumption on carbon emissions, considering the role of population density, urbanization, foreign direct investment, technological innovation, and trade openness for African countries from 1990 to 2019. We apply an advanced econometric methodology like the cross-sectional autoregressive distributed model (CS-ARDL) for long-run and short-run estimation, which allows for the cross-sectional dependencies and slope heterogeneity. Our finding shows that the non-renewable resources, population density, urbanization, and foreign direct investment contribute to the carbon emissions; in contrast, renewable resources and trade openness reduce the carbon emissions in African countries. Results also report a unidirectional causality from non-renewable energy consumption to carbon emissions, while there is evidence of a feedback hypothesis between renewable energy consumption and carbon emissions. This study provides several policy implications for sustainable development.

KEYWORDS

renewable energy, technology, urbanization, CO_2 emission, Africa

1 Introduction

Environmental degradation and climate change threaten human life worldwide (Li and Zhuo, 2019; Wang et al., 2015; Yang et al., 2020; Usman et al., 2022a; Zhang et al., 2022). With these ever-increasing worries, countries are under enormous pressure to achieve long-term growth, which is essential for the masses' well-being. Protecting the natural environment has been one of the most pressing worldwide problems for the past two decades. The hazard of environmental damage has grown significantly as temperatures have risen. The Kyoto Protocol, signed in 1997, aims to reduce greenhouse gas (GHG) emissions, which are a primary cause of environmental damage. Most GHG emissions come from fossil energy (Paramati et al., 2017). In its fifth assessment report, the Intergovernmental Panel on Climate Change (IPCC) concluded that there is a greater than 95% chance that human activities are to blame for global warming. Carbon emission (CO_2) is the most damaging greenhouse gas, accounting for more than 60% of worldwide greenhouse gas emissions (Baek and Pride, 2014; Jahanger et al., 2022b).

African countries as a whole have enjoyed less of energy-induced growth; this is for the reason that the energy in Africa seems to be a scarce commodity, where the annual energy consumption is placed at 518 KWh, which means this same proportion of energy use could be used by individual advanced countries as the OECD countries (Salim and Shafiei, 2014). However, energy use from non-renewable sources accounts for more than conventional energy use in Africa; these energy sources include the combustion of natural gas, coal, and oil. The sharp increase in this non-renewable energy (NREN) sources has led to a considerable rise in the GHG effect which is connected to carbon emission found in the atmosphere, which today is the leading cause of environmental and air pollution, especially in Africa and globally (Baeak, 2016; Nathaniel and Iheonu, 2019). Because of the effects of non-renewable energy sources, vast attention has propelled a parallel shift from fossil fuel burning to renewable energy for energy generation and industrial use, reducing environmental impacts (Asongu et al., 2020). Renewable energy (REN) is driven by technological innovations in the tides of biomass, geothermal, wind, and solar (IEA, 2021; Ellabban et al., 2014; Shahbaz et al., 2019a; Shahbaz et al., 2019b; Bilal et al., 2021). In the face of driving trade and foreign direct investments, renewable energy provides a minimal advantage to the environment over non-renewable energy sources, which lack the power to leverage the risk of environmental impacts and overall global climate warming. Thus, with the development and possible adoption of renewable energy, the various worries linked to the environment and climate are addressed, which will see the reduction of carbon emissions generated through trade, urbanization, and other economic activities, especially within Africa. The demand for traditional energy sources has increased recently due to economic and social development (Aslan and Ozlun, 2014). The International Energy Agency states that renewable sources such as wind and solar have risen quickly and are forecasted to increase more after the pandemic.

According to the IEA (2021), the amount of renewable electricity capacity added in 2020 rose by 45% in 2020 to 280 gigawatts (GW), which is the most significant year-on-year increase since 1999. That extra power is equal to the total installed capacity of ASEAN, a grouping of 10 dynamic south-east Asian economies. The federal tax credits spur American renewable capacity growth, and this forecast does not consider the administration’s target for reducing the new emission or the infrastructure bill. The global carbon emission reduced by 5.8% in 2020, corresponding to the most significant decline and almost five times greater than the 2009 decline following the global financial crisis. After the COVID-19 outbreak, the emission of CO_2 fell more than the demand for oil and coal, while that for renewable energy increased. In 2021, global energy-related carbon emissions were projected to rise again by approximately 5% as the economy’s demand for coal, oil, and gas rebounded. Sadorsky (2009) highlights the importance of energy for its contribution to economic growth, while Ellabban et al. (2014) and Jahanger (2022a) state that coal, gas, and petroleum are the most efficient energy sources.

However, in the face of reoccurring global climate issues, environmental researchers have to preoccupy new research schedules on foreign direct investment, trade, urbanization, and energy consumption and the impacts they have on the environment (Alola, 2019; Shahbaz et al., 2019b; Nathaniel and Iheonu, 2019; Asongu et al., 2020; Jahanger, 2021a; Usman and Jahanger, 2021). As economic activities increase, energy demands, which are said to be a driver for globalization and industrialization, also tend to increase in proportion to trade and foreign direct investment as countries attain economic growth (Nathaniel et al., 2020; Ahmad et al., 2022).

Numerous studies have adopted REN as a measure to reduce CO_2 and environmental impacts (Udemba and Alola, 2022; Ceglia et al., 2021; Nathaniel et al., 2020; Adebayo, 2021; Shafiei and Salim 2014; Hdom, 2019; Jebli et al., 2019; Yang et al., 2021b; Ke et al., 2022), while other few studies have examined REN and NREN to CO_2, and these include Calise et al. (2021), Awodumi and Adewuyi (2020), Salim and Shafiei (2014b), Kwakwa and Alhassan (2018), Dogan and Ozturk (2017), Chen et al. (2018), and Li, et al. (2022). While Udemba and Alola (2022), Abbasi and Shahbaz (2021), and Adebayo (2021) examine technology to environmental quality, large chunk of the studies agrees that REN encourages a sustainable environment with reduced carbon emission, which can promote trade and foreign direct investment, while only a few studies like Marques and Funihas (2012) exempt REN as a good measure for attaining environmental quality. Although many researchers have looked at the variables affecting CO_2 emissions from a single country, regional, and global perspective, relatively few studies look at the effects of economic growth, REN, NREN, and technology on carbon emissions within the same framework for African countries.

This study aims to examine the connections between technology, environmental degradation, energy consumption, and sustained economic growth in a few African economies. These factors are interconnected, and technological progress, in particular, has a significant impact on this subject by lowering environmental pollution and boosting economic growth. This study represents the first attempt to determine the causal relationship between these variables because there has not been a thorough investigation of the subject that adequately handles entire Africa while considering other variables such as population, trade, and foreign direct investment. The African economy has long been attempting to address the issue of climate change and environmental pollution over the last couple of decades to enhance its trade volume and sustainable economic growth. Finally, this study uses the most suitable panel data technique to attain reliable and robust estimations. The cross-sectional augmented autoregressive distributed lag (CS-ARDL) approach is most appropriate and consistent in checking cross-sectional dependency and country-specific heterogeneity slope. Other estimators include the augmented mean group (AMG) and common correlated effects mean group (CCEMG) estimators intended to solve endogeneity problems.

The remaining part of the article is developed as follows: Section 2 is the *literature review*, Sections 3, 4 deal with the *data and modeling* and *results and discussion*, Section 5 deals with the *conclusion*.

2 Literature review

This section could be divided into three sub-sections: first, we focus on treating renewable and non-renewable energy consumption-emission nexus (Sahoo and Sahoo, 2020). Second, we mention the role played by trade and FDI in carbon emission effects (Gizem et al., 2017; Shahbaz et al., 2015; Usman et al., 2022b; Sahoo et al., 2021a; Sahoo and Sahoo, 2019; Sahoo et al., 2021b; Villanthenkodath et al., 2021; Gupta et al., 2022; Rout et al., 2022; Sahoo and Sahoo, 2020; Ali et al., 2022), and finally, we show the inclusion of urbanization in energy and environmental function (Sheng et al., 2017; Yang et al., 2021a; Qayyum et al., 2021; Jahanger et al., 2022a).

2.1 Renewable and non-renewable energy consumption and carbon emission nexus

In the course of the literature synopsis, they are a few studies that made efforts to examine carbon emission and its impact on energy consumption (renewable and non-renewable energy); these studies include, for example, Shafiei and Salim (2014), Ito (2017), Sahoo and Sahoo (2020), and Thai-Ha et al. (2020).

Shafiei and Salim (2014) examined the relationship between non-renewable and renewable energy consumption and CO_2 in OECD countries from 1980 to 2011. The findings are that non-renewable energy consumption increases CO_2 emissions, whereas renewable energy consumption decreases CO_2. In contrast, they supported the existence of the environmental Kuznets curve between urbanization and CO_2 emissions. In the same way, Ito (2017) adopted panel data for 42 developed countries from 2002 to 2011 to establish the linkage between CO_2, renewable and non-renewable energy consumption, and GDP. The findings suggested that non-renewable energy consumption negatively impacts GDP, while renewable energy consumption contributes positively to economic growth over the long run.

Sahoo and Sahoo (2022a) looked into the effects of renewable and non-renewable energy consumption on CO_2 in India from 1965 to 2018 by employing the ARDL bound test and Toda-Yamamoto Granger causality approach. The finding indicated that hydro energy consumption contributes positively to CO_2 over the long run, yet no significant impact was found. In contrast, nuclear energy consumption contributed negatively to CO_2 emissions. However, non-renewable energy consumption sources positively and significantly affect CO_2 emissions.

Thai-Ha et al. (2020) re-examined how energy consumption interacts with economic growth and emissions using panel data from 102 countries from 1996 to 2012. The effects of renewable energy and non-renewable energy sources are separately examined. The findings suggested that the use of non-renewable energy consumption significantly raised the level of emissions across different income groups of countries.

2.2 Carbon emission, trade openness, and foreign direct investment nexus

Trade openness and foreign direct investment are few among several factors included in environmental and energy quality function through the following studies: Gizem et al. (2017), Yaya (2016), Yubin et al. (2014), Shahbaz et al. (2019a), Shahbaz et al. (2015), Tang and Tan (2015), Baeak (2016), Solarin et al. (2017), Sun et al. (2017), Salahuddin et al. (2018), and Jahanger et al (2022c).

The study by Gizem et al. (2017) discussed the role of foreign direct investment and trade on carbon emissions in Turkey from 1974 to 2010. The findings demonstrated that the inverted U-shaped relationship of the environmental Kuznets curve is valid for Turkey. In addition, there are positive long-run effects of foreign direct investment and trade openness on CO_2. The authors also find a bidirectional causality relationship between CO_2 emission and FDI. Yaya (2016) studied the effect of trade openness on the relationship between foreign direct investment (FDI) and carbon emission emissions in ECOWAS countries. The study applied the bound testing approach to cointegration from 1970 to 2010. The empirical evidence supports the environmental Kuznets curve for four countries (Cote d'Ivoire, Gambia, Mali, and Niger).

In most cases, economic growth and population contribute to environmental degradation. More interestingly, the effect of FDI on CO_2 emissions is contingent on trade openness. This positive effect increases with the degree of trade openness in Burkina

Faso, Gambia, and Nigeria, suggesting that trade and FDI are complementary in worsening environmental quality. The impact of FDI decreases with trade-in Ghana, Mali, and Togo, while in the case of Benin, Niger, Senegal, and Sierra Leone, FDI has no significant long-run effect on CO_2.

Yubin et al. (2014) examined the impacts of foreign direct investment and trade openness on carbon emission intensity in Shandong province from 1995 to 2012. The findings indicated that FDI had an inhibitory effect on carbon emission intensity. In contrast, foreign trade openness promotes carbon emission intensity, and the latter's elastic coefficient was 1.5 times as large as that of the former. Shahbaz et al. (2019b) studied the technical decomposition of carbon emissions and the concerns about FDI and trade openness effects in the United States. The empirical results confirm the existence of cointegration between the variables in the presence of structural breaks.

Moreover, the scale effect increases carbon emissions, but the technique effect reduces them as expected. Energy consumption also adds to carbon emissions, while the composition effect improves environmental quality by lowering carbon emissions. Furthermore, trade openness decreases carbon emission emissions. However, it increases in FDI hamper environmental quality by increasing carbon emissions.

Shahbaz et al. (2015) estimated the nonlinear relationship between FDI and carbon emission in countries with different income levels. The authors revealed that the increase in FD will raise carbon emissions. Tang and Tan (2015) focused on the relationship between FDI, carbon emission, energy consumption, and income in Vietnam. The results indicated that there is bidirectional causality between FDI and CO_2. Baeak (2016) studied the link between FDI, CO_2, energy consumption, and economic growth in five ASEAN countries from 1981 to 2010. The evidence shows that FDI does not reduce carbon emissions.

Similarly, Solarin et al. (2017) and Sun et al. (2017) estimated the same relation in Ghana and China and found the same supporting results. Finally, the study by Salahuddin et al. (2018) evaluated the link between FDI, economic growth, financial development, electricity consumption, and carbon emission in Kuwait. On the other hand, several studies argued that FDI improves energy efficiency and reduces carbon emission because FDI leads to better management practices, technology improvements, and an increase in the number of employees.

2.3 Energy consumption and urbanization nexus

There has been an intense debate in the energy and environmental function discourse on the inclusion of urbanization, especially regarding regional and environmental development. However, few works Poumanyvong and Kaneko (2010), Salim and Shafiei (2014), Sheng et al. (2017), Lui (2019), Jiang et al. (2022), Liu et al. (2022), and Wen et al. (2022) have documented the long relationship between urbanization and energy consumption and environmental quality.

Salim and Shafiei S (2014) analyzed the impact of urbanization on renewable and non-renewable energy consumption in OECD countries using the STIRPAT model and data from 1980 to 2011. Demographic factors, including total population, urbanization, and population density, are significant factors, particularly regarding non-renewable energy consumption. The results also reveal that while total population and urbanization positively influence non-renewable energy consumption, population density harms non-renewable energy consumption. From the demographic factors, only the total population significantly impacts renewable energy consumption. Granger causality results indicate unidirectional causality from non-renewable energy use to population density in the short run. However, no causal linkage is found between urbanization and non-renewable energy use. Likewise, no causal direction is seen between renewable energy use and demographic factors. Poumanyvong and Kaneko (2010) investigated the relationship between urbanization and energy use from 1975 to 2005, controlling for population size, GDP per capita, and the share of industry and service sectors in GDP. These authors demonstrate that while urbanization increases energy use in middle- and high-income countries, it decreases energy use in low-income countries.

Sheng et al. (2017) used data from 78 countries from 1995 to 2012 to examine the impact of urbanization on energy consumption and efficiency. Results of the generalized method of moment estimation indicate that the urbanization process leads to substantial increases in both the actual and the optimal energy consumption but a decrease in energy use efficiency. The result also shows the extent to which energy inefficiency correlates with urbanization is more significant in countries with the higher gross domestic product per capita.

Lui (2019) studied the relationship between urbanization and energy consumption, urbanization and haze, and energy consumption structure and haze from 1980 to 2016. From the findings, the study recommends that to reduce haze pollution, China should establish regional warning systems; incorporate regional differences in energy countermeasures; establish a scientific, efficient, clean, and sustainable coal supply system; promote ecological urbanization; implement technological innovation; adjust export patterns; and encourage energy alternatives.

Among the reviewed studies, the effects of structural changes regarding energy use were not extensively discussed and accounted for mainly in studies focused on Africa. The study introduced technological innovation, an essential feature for most economies. However, most studies on Africa have neglected this feature, but few remain a suitable gap in growth-energy-emission studies. The study filled this gap by introducing technological innovation while examining its effects on carbon emission and growth. By introducing over 12 selected countries, the study accounted for the majority of

African countries with less technological innovation grouped as underdeveloped or developing economies, while other studies based in Africa (Nathaniel and Iheonu, 2019; Wan et al., 2022) only considered stratified countries with similar economic strength.

2.3.1 Theoretical underpinning

The theoretical framework for this study is rooted in the work of Solow, which considers energy as a part of the production process in addition to capital and labor inputs. The ecological theorist has emphasized the unique role of energy as a sub-input to labor and capital. However, adopting the production function approach, which comprises labor, capital, and energy source within the growth model, makes it possible for electricity consumption to affect the manufacturing sector by increasing productivity through the means of technical conditions involving the mixture of non-renewable and renewable energy sources. Developed a conventional model that allows for economic progress through the accumulation of factor inputs such as labor inputs and capital inputs and, in addition, technological progress, which comes in the form of changes that is crucial for the accumulation of capital and labor inputs which enables growth in a productivity sector of the economy. The Solow model assumes that for capital to be reproduced, the total aggregate production function must be subject to constant returns to scale in labor needed to produce a composite commodity. However, the output from the production is regarded as the net output that is considered after capital depreciation; the marginal physical level of productivities assumed by capital and labor inputs becomes flexible in wages and price, thereby allowing for full employment of available capital stock which will lead to falling returns to labor and capital returns. This implies that as the rate where capital increases due to capital stock, the level of income will increase, labor will increase, and this will bring about growth in all productive sectors of the economy. To integrate this model into our study, energy consumption serves as a proxy for economic growth, where the level of long-run growth rate is the function of energy consumption. Thus, the production function for the manufacturing sector is given by

$$Y_{it} = A_{it} K_{it}^{\alpha i} L_{it}^{\beta i} Z_{it}^{ki} E_{it}^{gi}, \tag{1}$$

where Y_{it} is the output, K_{it}^{μ} for capital inputs, $L_{it}^{\beta i}$ for labor inputs, Z_{it}^{ki} for alternative or renewable energy sources, and E_{it}^{gi} for non-renewable energy sources.

The production function from the model shows the constant returns to scale while technological progress serves as an increasing variable as given in this $A_{it} F(K_{it}, L_{it}, Z_{it} E_{it})$. In an economy like this, the goods produced differ in the energy used and capital accumulation, while the total labor input required for this sector is given as

$$g_{yit} \approx \frac{1}{\beta_i + K_i + \epsilon_i} g_{A_{it}} + \frac{K_i}{\beta_i + K_i + \epsilon_i} (Z_t - S^z) - \frac{\epsilon_i}{\beta_i + K_i + \epsilon_i} S^E - \frac{K_i + \epsilon_i}{\beta_i + K_i + \epsilon_i} g_{L_{it}}, \tag{2}$$

where $\frac{1}{\beta_i + K_i + \varepsilon_i}$ represents where natural resource is not available, $\frac{K_i + \varepsilon_i}{\beta_i + K_i + \varepsilon_i} g_{L_{it}}$ represents an increase in population size to the size of the economy, and $\frac{\varepsilon_i}{\beta_i + K_i + \varepsilon_i} S^E$ represents the extraction of a non-renewable resource. Thus, the use of renewable energy source is an indication for input unit in the production process that can lead to growth in the use of exhaustible source S^E.

In our growth model, we can conclude that the growth rate is responsive to resource accumulation which is not responsive to price effects as there is no significant effect on energy consumption and growth. Based on the model, we could highlight that technological progress advances are assumed to be more effective for economic growth than resource endowment. Over time, the relationship between energy consumption and increase in production has received an increasing response from scholars. However, the hypothesis assumes that urbanization and population size have an immediate effect on carbon emission levels, while trade openness tends to affect carbon emission levels because the exports and imports are embedded as input from carbon. Thus, the response of growth to changes in energy use (renewable and non-renewable energy) may differ from time, either a negative change or positive change. This is a result of the attendant effects of environmental quality.

3 Data and methodology

3.1 Data

The primary aim of this study is to examine the impact of renewable energy, non-renewable energy, trade openness, urbanization, population density, foreign direct investment, and technological innovation on carbon emission emissions in the context of African countries. We use the annual panel data of the 12 African countries from 1990 to 2019. The sampled countries are Kenya, Ethiopia, Egypt, Algeria, Zimbabwe, South Africa, Morocco, Mozambique, Mauritius, Nigeria, Tunisia, and Zambia. The selection of the sample period depends on the availability of the data for the balanced panel data analysis. The data are sourced from the World Development Indicator (WDI). CO_2 is the explained variable in our model, and renewable energy, non-renewable energy, trade openness, urbanization, population density, foreign direct investment, and technological innovation are explanatory variables. Table 1 presents the definition and source of the stated variables.

TABLE 1 Descriptions of the variables and data sources.

Variable	Symbol	Measurement	Source
Foreign direct investment	FDI	Foreign capital inflow	WDI 2020
Economic growth	GDP	At constant $2010	WDI 2020
Carbon emission	CO_2	Metric tonnes	WDI 2020
Trade	TO	Total export plus import (% GDP)	WDI 2020
Urbanization	Urbanization	Urban population (% of the total population)	WDI 2020
Renewable energy	RE	Gigajoule (GJ)	BP 2020
Non-renewable energy	ARE	Gigajoule (GJ)	BP 2020
Population	PO	Population density	WDI 2020
Technology	TI	Patent application resident	WDI 2020

Source: Authors' compilation.

3.2 Econometric methods

3.2.1 Cross-sectional dependency and slope homogeneity test

Because of liberalization and globalization of the economy, mostly all countries are connected. Any shock in one country can significantly affect the other countries. The conventional panel data methods presume that no dependency exists between cross-sectional units and that slope coefficients are similar, but estimators shun cross-sectional dependence may cause false inferences (Chudik and Pesaran, 2013). Additionally, the estimated coefficients may vary across cross-sectional units. Hence, the presence of cross-sectional dependence and slope homogeneity will be examined first. The presence of cross-sectional support in the error term is acquired from the model analyzed by Pesaran (2007). The CSD equation is given as follows:

$$CD = \sqrt{\frac{2T}{N(N-1)}}\left(\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\hat{\rho}_{ij}\right). \tag{3}$$

We also apply the slope homogeneity test in our model, which was developed by Pesaran and Yamagata (2008). The test equation is calculated through delta tilde and adjusted delta tilde.

3.2.2 Panel unit root test

After examining the cross-sectional dependence and slope homogeneity, the next stage in the analysis is to check the order of cointegration of the various variables considered in this study. If cross-sectional dependence and slope homogeneity exist in the data set, the first-generation panel unit tests may yield spurious results (Dogan and Seker, 2016; Kamal et al., 2021). Therefore, to address this concern, Usman et al. (2021a), and Yang et al. (2022c) proposed parametric and non-parametric tests to avoid bias in results. Both CADF (cross-sectional augmented Dickey-Fuller) and CIPS (cross-sectional augmented Im, Pesaran, and Shin) tests can counter the cross-sectional dependency and slope heterogeneity from the data, and the results are more accurate and robust. The equation for the CADF is written as follows:

$$\Delta y_{it} = \alpha_i + \pi_i y_{i,t-1} + \varphi_i \bar{y}_{t-1} + \sum_{l=0}^{p} \varnothing_{il}\Delta\bar{y}_{t-1} + \sum_{l=1}^{p} \gamma_{il}\Delta\bar{y}_{i,\,t-1} + \epsilon_{it}. \tag{4}$$

In Eq. 3, $\bar{y}_{t-1}$ and $\Delta\,\bar{y}_{t-1}$ are the averages for lagged and first difference of each cross-section series.

From CADF, cross-sectional augmented Im, Pesaran, and Shin (CIPS) statistics are obtained and given as follows:

$$\mathrm{CIPS} = \frac{1}{N}\sum_{i=1}^{N} CADF_i, \tag{5}$$

where $\mathrm{CADF_i}$ represents the "cross-sectional augmented Dickey-Fuller test" and N is the number of observations.

3.2.3 Panel cointegration test

The present study intends to study the long-run relationship between variables like CO_2, renewable energy, non-renewable energy, trade openness, urbanization, population density, foreign direct investment, and technological innovation in African countries. To fulfill this objective, we apply the error correction model (ECM)-based cointegration method proposed by Westerlund (2008) cointegration techniques. This technique deals with the common factor constraint problem plaguing the first generation's cointegration testing. It produces accurate and robust results and helps to handle cross-sectional error term dependence. Apart from this, the test has no restriction for the common factor. In this case, the null hypothesis indicates that cointegration between cross section units does not exist. In addition to that, the alternative hypothesis implies the presence of cointegration between considered variables. The expression for the Westerlund cointegration test is as follows:

$$\alpha_i (L)\Delta y_{it} = \delta_{1i} + \delta_{2i}t + \alpha_i\left(y_{i,t-1} - \beta_1^{'} x_{it} + \lambda_i\left(L^{'}\right)v_{it} + e_{it}\right). \quad (6)$$

In this equation, β_i is an error correction coefficient, and α_i is the vector of the cointegration link between x and y.

3.2.4 Cross-sectional augmented autoregressive distributed model

The variables in the study are expected to be cross-sectional dependent because the African countries have so much in common. Additionally, they are linked *via* financial integration, trade relations, and information and communication technologies. Therefore, to establish the long-run and short-run relationships among CO_2, renewable energy, non-renewable energy, trade openness, urbanization, population density, foreign direct investment, and technological innovation, we use the CS-ARDL model proposed by Chudik and Pesaran (2013). In the presence of slope heterogeneity and cross-sectional dependence, conventional approaches such as random and fixed effect and first difference generalized method of moment (GMM) are not rational to use (Chudik et al., 2017). The CS-ARDL method is more appropriate when there is an issue of cross-sectional inter-dependence, endogeneity, robustness to omitted variables, and non-stationarity. It also produces reliable findings (Chudik et al., 2017; Jahanger et al., 2021b). The general form of CS-ARDL is as follows:

$$y_{it} = v_i + \sum_{j=1}^{p} \gamma_{ij} y_{i,t-1} + \sum_{j=0}^{q} \varnothing_{ij}^{'} x_{i,t-1} + \sum_{j=0}^{q} \delta_{ij}^{'} \bar{z}_{t-1} + \epsilon_{it}, \quad (7)$$

$$\bar{z}_t = \left(\bar{y}_t, \bar{x}_t^{'}\right), \quad (8)$$

$$\epsilon_{it} = \pi_i^{'} s_t + \mu_{it}. \quad (9)$$

Eq. 8, "denoted by $\bar{z}_t$," contains the cross-sectional averages for the covariates such as $\bar{x}_t^{'}$ and the dependent variable $\overline{\ y}_t$. Moreover, q indicates lag length for the cross-section averages, and the error term is denoted by ϵ_{it}; the unobserved common factor is shown through s_t , which causes dependency among cross-sectional units. For the robustness check of the results obtained through CS-ARDL, we use two approaches: common correlated effects mean group (CCEMG) and augmented mean group (AMG). Both of these approaches consider the problem of cointegration breaks, cross-section dependence, heterogeneity, and non-stationarity (Liddle, 2018).

3.2.5 Panel causality test

Finally, the study examines the causal relationship between the stated variables by employing the heterogenous Dumitrescu and Hurlin (2012) panel Granger causality test. D-H panel Granger causality test takes into account the cross-sectional dependence and heterogeneity (Koçak and Şarkgüneşi 2017). In this case, the null hypothesis of the D-H causality is assumed to reflect that no causal direction was found between variables in contrast to the alternative hypothesis, which directs the causal relationship among considered variables. The equation for the D-H test is as follows:

$$y_{it} = \varphi_i + \sum_{k=1}^{p} z_i^k y_{i,t-k} + \sum_{k=1}^{p} x_i^j T_{i,t-k} + \omega_{i,t} \quad (10)$$

Here, k represents the lag length, whereas $z^i\,(j)$ represents the autoregressive parameters.

4 Results and discussion

In this section, the study discusses the empirical relationship between urbanization, FDI, trade openness, renewable and non-renewable energy consumption, and CO_2 emissions in 12 African countries. Before proceeding with the long-run and short-run analyses, the researchers have to test whether there is a presence of cross-sectional dependency in the countries or not. After that, we check the homogeneity in the series. Table 2 discusses the results of the CD test. The results indicate that all the variables reject the null hypothesis of cross-sectional independence among the selected African countries. This shows how the African nations picked share common shock distortions. The presence of CD suggests the use of second-generation unit root tests instead of first-generation unit root tests.

Furthermore, the study has applied Pesaran and Yamagata (2008) slope homogeneity test, which is in Table 3. The cross-sectional heterogeneity of the data is checked with the slope homogeneity test. The null hypothesis for the slope homogeneity test is that the slope coefficients are homogenous (not heterogenous). The sloping homogeneity test is essential since it deals with the long-term homogeneity or heterogeneity of the countries. Because of the strong CSD, the processes of trade opening may be identical in any nation. If diverse, the panel data might lead to incorrect results if the pitch is homogenous (Pesaran and Smith, 1995). The slope homogeneity test, therefore, helps to recognize cross-sectional heterogeneity in the analysis of empirical results. The results of the slope homogeneity test portray that all variables in the model reject the null hypothesis of the slope homogeneity test against the alternative view of heterogeneity among the selected African countries.

Table 4 discusses the basic statics of the series, such as mean, median, standard deviation, skewness, and kurtosis. The mean value of non-renewable energy is 679.46, the second-highest after technological innovation in the model. Similarly, mean values of $CO_{2,}$ FDI, population, and renewable energy consumption are 1.67, 2.73, 97.84, and 43.03, respectively. The results of the correlation are present in Table 5. This indicates that population, non-renewable energy, renewable energy, and trade openness are positive and have very low degrees of correlation with CO_2 emissions.

As researchers have mentioned the presence of CD in the series in this scenario, the findings of the unit root test of first-

TABLE 2 Cross-sectional dependency test.

Variable	CO_2	URB	FDI	GDP	TO	RE	ARE	PO	TI
CD test	31.73	15.65	5.65	6.65	4.96	37.79	39.07	42.27	14.07
p-value	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Source: Authors' calculation.

TABLE 3 Slope homogeneity test.

	CO_2	URB	FDI	GDP	TO	RE	ARE	PO	TI
Delta	4.25*	10.42*	1.88*	5.54*	10.26*	9.34*	2.87*	23.42**	4.7*
Adjusted Delta	5.08*	12.46*	2.25*	7.56*	12.27*	11.18*	3.44*	4.61*	5.63*

Source: Authors' calculation. Notes: * represents a 1% level of significance.

TABLE 4 Descriptive statistics.

	CO_2	FDI	ARE	PO	RE	TI	TR	URB
Mean	1.67	2.73	679.46	97.84	43.03	817.33	62.17	42.71
Median	0.88	1.55	604.41	57.05	18.36	53.00	59.77	42.11
Maximum	9.98	39.46	2,950.15	623.30	97.74	8,317.00	137.11	72.41
Minimum	0.00	−0.60	0.00	0.00	0.00	0.00	0.00	12.62
Std. Dev.	2.28	4.31	606.07	151.29	38.68	1,824.46	29.72	16.35
Skewness	2.19	4.99	1.95	2.77	0.22	2.83	0.04	0.12
Kurtosis	7.38	33.95	7.29	9.34	1.22	9.89	3.16	2.05
Jarque-Bera	574.22	15,816.00	501.67	1,059.1	50.40	1,189.71	0.47	14.47
Probability	0.00	0.00	0.00	0.00	0.00	0.00	0.79	0.00
Observations	359.00	359.00	359.00	359.00	359.00	359.00	359.00	359.00

Source: Authors' calculation.

generation are less efficient. Therefore, in this article, we use second-generation unit root tests, that is, cross-sectional ADF (CADF) and cross-sectional CIPS in Table 6. The null hypothesis of both the tests is the presence of unit root in the series. The unit root test results indicate that not all variables have enough evidence to reject the null hypothesis at a level except FDI. It became stationary after the first differentiation. In contrast, the FDI is stationary at a level in both tests. The study can conclude from the results of both tests that all variables are stationary in a different order, that is, I (0) and I (1).

TABLE 5 Correlation matrix.

	CO_2	URB	FDI	TO	RE	ARE	PO	TI
CO_2	1							
URB	0.53*	1						
FDI	−0.16*	−0.1	1					
TO	0.12*	0.42*	0.22*	1				
RE	0.44*	−0.23*	0.12	−0.36	1			
ARE	0.15*	0.31**	−0.14*	0.03*	−0.12	1		
PO	0.04*	−0.03*	−0.07*	0.47*	−0.14*	0.05	1	
TI	0.82	0.39*	−0.11*	−0.07*	−0.34	0.67	−0.14	1

Source: Authors' calculation. Notes: * represents 1% level of significance.

After confirming the presence of stationarity in the series, in the next step, this study applies the Westerlund (2008) cointegration to know the long-run association among the variables such as CO_2, FDI, non-renewable and renewable energy, population density, trade openness, and technological innovation in the African countries in Table 7. The four tests to assess the non-cointegration hypothesis are group mean tests (Gt and Ga) and panels (Pt and Pa). The group mean tests are based upon the weighted sums of the estimated coefficients for individual nations, whereas the panel tests are based on the projected panel total coefficients. In addition, the standard errors of Ga and Pa were assessed using the statistics and adjusted for heteroscedasticity and self-correlation in models (Cialani, 2017). The results reject the null hypothesis of no cointegration and

TABLE 6 Unit root test.

	CALF		CIPS	
Variable	**Level**	**1st difference**	**Level**	**1st difference**
CO_2	3.20	−1.47*	1.18	−6.82*
URB	−1.87	−4.82*	4.48	−8.34*
FDI	−2.25*	—	−4.76*	—
GDP	−0.45	2.56*	−0.78	5.25*
TO	−1.58	−3.32*	0.25	−10.60*
RE	−1.74	3.90*	4.84	−8.40*
ARE	−1.08	−3.15*	3.03	−8.32*
PO	−2.09	−3.33*	−0.36	5.25*
TI	−2.12	−3.25*	−1.42	−3.57*

Source: Authors' calculation. Notes: * represents 1% level of significance.

TABLE 7 Westerlund cointegration.

Statistic	Value	Z-value	*p*-value
Gt	−4.896	−9.185	0.00
Ga	−4.481	3.268	0.00
Pt	−19.119	−10.311	0.00
Pa	−6.148	0.821	0.07

Source: Authors' calculation.

TABLE 8 Long-run results (CS-ARDL).

Dependent variable: CO_2	Coefficient	T Statistics	Prob.
FDI	−0.01	−2.81	0.00
ARE	0.23	19.57	0.00
PO	0.06	3.65	0.00
GDP	0.87	2.52	0.01
RE	−0.12	−9.07	0.00
TI	−1.39	3.36	0.00
TO	0.03	0.68	0.49
URB	0.24	4.53	0.00
Short run			
ECT_{t-1}	−0.73	−4.39	0.00
ΔCO_2	0.15	2.27	0.02
ΔFDI	0.02	3.53	0.00
ΔNRE	0.00	2.33	0.02
ΔPO	1.27	0.79	0.43
ΔGDP	0.56	3.54	0.00
ΔRE	0.01	−0.08	0.94
ΔTI	0.02	0.19	0.85
ΔTO	0.12	0.28	0.78
ΔURB	0.01	0.00	1.00
C	−0.93	−1.05	0.30

Source: Authors' calculation.

against the alternative hypothesis of the presence of cointegration among the stated variables.

After going through the preliminary results such as CD test, slope homogeneity test, and second-generation unit root test, the study found that the model has the presence of CD and heterogeneity in the nature, and variables are integrated in a different order. Finally, the model confirms that the long-run association exists among the stated variables. As per the data structure, we apply CS-ARDL for the long-run analysis, which is present in Table 8. The study found that FDI has a negative impact on CO_2 emissions. It means a 1% increase in the flow of foreign investment reduces the CO_2 emissions by −0.01%. FDI may offer cleaner technology and better management techniques to help host nations enhance their environmental quality. However, non-renewable energy consumption escalates CO_2 emissions in these countries. It states that a 1% increase in fossil fuels or non-renewable energy consumption increases carbon emissions by 0.23%. Compared to renewable energy consumption, non-renewable consumption raises real GDP quickly (Apergis and Payne, 2012; Jiang et al., 2022; Jahanger et al., 2022d). However, the carbon emissions are 87% different and are responsible for deforestation and harmful effects on human health and the environment (Preston, 1996). Non-renewable energy sources have a negative influence on the climate of our planet through increasing greenhouse gas emissions. They also produce various toxins, harming human health and the environment. These results coincide with the findings of Dogan and Seker (2016), Dogan and Öztürk (2017), and Sahoo and Sahoo (2020).

Likely, to the results of non-renewable energy consumption, population density also posits a similar sign to the decreasing environmental quality. High population density areas are typically considered a good location to reside. Simultaneously, the overall growth of the planet's population threatens to worsen many people, such as overfishing, increased pollution, biodiversity degradation, and water stress. The environmental impacts of so many people are in two primary forms: land, food, water, air, fossil fuels, and minerals. Waste products result from consumption, such as air and water pollution, poisonous substances, and greenhouse gases. The results support the findings of Gallego (2010), Ukaogo et al. (2020).

However, the coefficient of renewable energy is negative and significant; it means improving the environmental quality. It states that a 1% increase in renewable energy consumption led to reducing CO_2 emissions. In every global warming debate, clean energy generally leads the world's change list to avoid the worst consequences of increasing temperatures. This is because renewable energies such as wind and solar do not generate CO_2 and other gas emissions that contribute to climate change (Heryadi and Hartono, 2017). According to the International Energy Agency, renewable energies will make up 30% of the world's energy by 2024, mostly from solar and wind projects that will keep happening at an alarming speed (Dieck-Assad, 2014). Although renewable energy generates relatively less greenhouse gas emissions, the installation is costly, especially for African countries. By 2050, renewable power may cover up to 45% of global power supplies, dramatically reducing carbon emissions and mitigating climate change. Synergy works to enhance the use of renewable energy and energy efficiency. This result supports the findings of Sadorsky (2009) and Boontome et al. (2017).

Similarly, the coefficient of technological innovation is negative and significantly related to CO_2 emissions. It means a 1% increase in technological innovation led to reducing CO_2 emissions. New or better products or processes differ considerably in terms of technological features than previous technological innovations (Castellacci, 2008). Technological innovations in the energy and environmental sector that include wind power, photovoltaic cells, solar power concentration, geothermal energy, and ocean wave power are innovations that incorporate innovation. However, trade openness is positive but insignificantly related to CO_2 emissions.

The relationship between CO_2 emissions and urbanization is positive and statistically significant. It means a 1% increase in urbanization increases CO_2 emissions by 0.24%. Uncontrolled urbanization in many African countries has resulted in very rapid environmental damage. It has caused various difficulties such as insecurity on the ground, deteriorating water quality, excess air pollution, and noise and waste disposal concerns. Urban environments have several environmental health problems, including air, water, and soil pollution. Extensive metropolitan areas contribute to traffic congestion, which is affected worldwide by air pollution and noise and long travel times (Manisalidis et al., 2020). In urban areas, wealth is created, making urbanization a significant element in economic development. However, urbanization has resulted in environmental problems such as air and water pollution, land deterioration, and loss of biodiversity. It has forced millions of people to live without access to clean water, sanitation, or electricity. These results support the findings of Wang and Zhao (2018), Mahmood et al. (2020), and Ahmad et al. (2021).

Finally, the short-run results are discussed in the lower segment of Table 8. The coefficient value of the error correction term is negative and statistically significant. This means that the short-run disturbances are corrected at 0.73% to achieve the long-run equilibrium.

The robustness of the long-run results is examined through AMG and CCEMG, which is present in Table 9. Both techniques can be used in the presence of CD in the data set. Both approaches support the findings of CS-ARDL long-run results at different levels of elasticity; otherwise, the sign is the same.

TABLE 9 Robustness test of long-run results.

	AMG			CEM		
CO_2	Coef.	z	P > z	Coef.	z	P > z
URB	0.13	1.89	0.07	0.017	3.86	0.00
FDI	−0.52	−1.93	0.05	−0.12	−2.83	0.04
TO	0.19	2.19	0.01	0.14	3.18	0.00
GDP	0.78	2.82	0.00	0.19	4.54	0.00
RE	−0.44	−3.52	0.00	−0.01	−3.53	0.00
ARE	0.20	2.41	0.02	0.436	1.95	0.04
PO	0.25	0.26	0.80	0.05	1.90	0.07
TI	−0.65	−4.85	0.00	−6.50	−4.62	0.00

Source: Authors' calculation.

Table 10 discusses the Dumitrescu and Hurlin (D-H) panel causality. The result indicates that there is a unidirectional causality running from FDI to CO_2 emissions in these countries. Several pieces of literature highlighted the adverse effect of FDI on the environment; however, there is still a possibility of a cleaner environment through FDI through advanced and energy-efficient technology in developing countries. This result coincides with the findings of Demena and Afesorgbor (2020). Correspondingly, there is a unidirectional relationship between non-renewable energy consumption and CO_2 emissions in the sample countries. However, bidirectional causality runs between population to CO_2 emissions. As the population increases, they consume energy for their day-to-day life. Population density growth would increase the frequency of natural disasters due to climate change. Renewable energy and CO_2 emission also indicate the existence of a feedback hypothesis between them. Similarly, urbanization, non-renewable energy consumption, technological innovation, and trade openness show bidirectional causality. These results support the findings of Centi et al. (2013), Dogan and Seker (2016), Razzaq et al. (2021), Udemba et al. (2021), and Usman et al. (2022c).

5 Conclusion and policy implications

The present study adds to the growing literature by examining the linkages between CO_2 emissions and non-renewable energy, trade openness, urbanization, population density, foreign direct investment, and technological innovation. Our analysis used the second-generation panel cointegration technique and two tests to check the cross-sectional dependence and slope heterogeneity. The second-generation panel unit root tests CADF and CIPS are used to check the stationarity of the variables in the existence of cross-sectional dependence. The study applies the Westerlund (2008) cointegration technique to determine the long-run association among concerned variables. The long-run and short-run coefficients are computed using the CS-ARDL model; the AMG and CCEMG are used to verify the robustness of the results. Finally, the study examines the causal relationship

TABLE 10 Dumitrescu and Hurlin causality test.

Null hypothesis	W-Stat.	Prob.	Direction
FDI ≠ CO_2	1.39	0.25	Unidirectional
NRE ≠ CO_2	246.42	0.00	Unidirectional
GDP ≠ CO_2	45.25	0.00	Unidirectional
PO ≠ CO_2	4.25	0.00	Bidirectional
CO_2 ≠ PO	251.26	0.00	
RE ≠ CO_2	119.64	0.00	Bidirectional
CO_2 ≠ RE	4.24	0.00	
CO_2 ≠ TI	9.42	0.00	Unidirectional
URB ≠ CO_2	4.21	0.00	Unidirectional
FDI ≠ NRE	4.37	0.00	Unidirectional
PO ≠ FDI	3.89	0.01	Unidirectional
FDI ≠ TO	3.57	0.05	Unidirectional
FDI ≠ URB	3.34	0.10	Unidirectional
NRE ≠ PO	4.26	0.00	Unidirectional
URB ≠ NRE	4.81	0.00	Bidirectional
NRE ≠ URB	8.01	0.00	
RE ≠ PO	10.30	0.00	Unidirectional
PO ≠ URB	10.03	0.00	Unidirectional
TI ≠ RE	3.45	0.07	Bidirectional
RE ≠ TI	4.43	0.00	
TO ≠ RE	4.14	0.01	Unidirectional
TO ≠ TI	3.37	0.09	Bidirectional
TI ≠ TO	4.28	0.00	
TI ≠ URB	3.40	0.08	Unidirectional
TO ≠ URB	4.37	0.00	Unidirectional

Notes: ↔represents "does not homogeneously cause". Source: Authors' calculation.

between the stated variables by employing the heterogenous Dumitrescu and Hurlin (2012) panel Granger causality test.

The study finds the presence of cross-sectional dependence along with heterogeneity in data. Moreover, the CADF and CIPS second-generation unit root tests find a mixed order of integration of the concerned variables in the study. All the variables are cointegrated with CO_2 emissions in the long run. The researchers found that non-renewable resources, population density, trade openness, and urbanization increase CO_2 emissions. However, renewable energy, FDI, and technological innovation truncate CO_2 emissions in African countries. The results are also compatible with AMG and CCEMG model estimates. The researchers also find unidirectional causality from non-renewable energy consumption to CO_2 emissions, while there is evidence of a feedback hypothesis between renewable energy consumption and CO_2 emissions.

5.1 Policy implication

In line with the findings, efforts should be made by policymakers; first, in African countries to mitigate the continuous use of non-renewable energy as it has the potential to increase carbon emissions amongst African countries while switching to renewable energy sources such as solar, wind, and biomass which affords for affordable and clean energy in line with the sustainable development goals as this will further guaranty clean electricity supply for industries in Africa thereby facilitating trade tiers. Second, policymakers in Africa should take the issues of population and urbanization severe. This could be carried out through population control measures such as family planning, women empowerment, education, etc., and the building of environmental friendly cities where CO_2 emissions will be reduced, and renewable energy encouraged. Third, economic growth increases CO_2 emissions and worsens environmental degradation due to rising energy use. Governments should promote environmentally friendly renewable energy sources such as solar, wind, and hydroelectric power as they move to a green economy. Fourth, infrastructure for long-term investment in technological development should be encouraged. This appears to be significant since technological innovation has shown to be an effective strategy for mitigating the harmful effects of carbon emissions. Fifth, because trade openness is lowering environmental quality in African countries, the government should prevent damaging technology imports. Finally, authorities should encourage increased investment in energy-intensive industries in their nations through technological innovation.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material; further inquiries can be directed to the corresponding authors.

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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Conflict of interest

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

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Nomenclature

CO_2 carbon emission

GHG greenhouse gas

REN renewable energy

NARAN non-renewable energy

GW gigawatts

COVID-19 coronavirus

FDI foreign direct investment

CS-ARDL cross-sectional autoregressive distributed lag model

AMG augmented mean group

CCEMG common correlated effects mean group.