Journal of Energy in Southern Africa

Volume 37 Number 1 2026

The role of energy intensity and renewable energy in achieving environmental sustainability in African countries: A panel data analysis

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Abstract

The effects of renewable energy use and energy intensity on environmental sustainability constitute one of the main problems of the clean energy transition process, especially in Africa. This study analyses the impacts of renewable energy use and energy intensity on environmental sustainability, as represented by CO_2 emissions, in 24 African countries. Using the annual panel data set for the period 1990–2021, firstly the cross-sectional dependence, slope heterogeneity and stationarity properties of the variables were tested. Then, the panel cointegration relationship was examined by Kao and Pedroni methods. Following these, common correlated effects estimator, augmented mean group estimator, and mean group estimator tests were applied for estimations. In terms of robustness, simultaneous quantile regression and generalised method of moments methods were used. The general results show that renewable energy reduces CO_2 emissions for all three tests, while energy intensity increases them. Therefore, technology and infrastructure programmes that will increase energy efficiency should be implemented together with financial incentives to increase renewable energy investments in these countries. At the same time, sustainable growth targets can be achieved while reducing emissions by introducing regulations that discourage carbon-intensive activities.

Keywords: *Energy intensity, renewable energy, sustainability, augmented mean group estimator, mean group estimator, common correlated effects estimator*

Journal of Energy in Southern Africa 37(1),1–20

DOI: https://dx.doi.org/10.17159/2413-3051/2026/v37i1a25383

Published by the University of Cape Town ISSN: 2413-3051 https://journals.assaf.org.za/jesa

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1. Introduction

The rapid increase in energy consumption has made environmental degradation, which initially had a negative impact on environmental quality and raised concerns on a global scale, more visible (Khan et. al., 2017; Danish et. al., 2018). Carbon dioxide (CO_2) stands out as the most harmful compound among greenhouse gas emissions, threatening both human health and ecosystems (IPCC, 2013). This degradation also disrupts the economic growth performance of countries, making it difficult to achieve higher development goals. Despite this, many countries still turn to non-renewable energy sources, and this preference leads to an increase in CO_2 emissions (Fallahi, 2020). In this context, the widespread use of renewable energy options and the rapid implementation of policies to limit CO_2 emissions are more critical and undelayable than ever before. In line with the aim of combating climate change, the framework of global climate governance was established through the process that started with the Framework Convention on Climate Change adopted by the United Nations in 1992, and included the Kyoto Protocol (1997), the Copenhagen Accord (2009), the China-US Joint Announcement (2014), and the Paris Agreement (2015) (Falkner, 2016). The common denominator of these steps has been to strengthen environmental sustainability by reducing greenhouse gas emissions from fossil fuels and other non-renewable energy sources (Ford, 2016). The regional impacts of these efforts are partly observed in Sub-Saharan Africa, where the energy access gap and climate vulnerability are high. Despite this, African countries continue to be amongst those most affected by climate change, due to their agriculture-based economies, socio-economic vulnerabilities, and limited adaptation capacities (Desanker, 2002; Simbi et al., 2023; Fotso-Nguemo et al., 2023; Htike et al., 2023). Africa has young and rapidly urbanising economies that are growing faster than the global average, and this demographic and economic momentum is increasing energy consumption and CO_2 emissions. Projections suggest that Egypt, South Africa and Nigeria will be among the largest global economies by 2050 (Tenaw, 2020), while the 2021 Global Climate Risk Index reveals that five of the ten most affected countries are also in Africa (Kalisa et al., 2021).

The continent also has a unique energy transition opportunity, however, as Sub-Saharan Africa is home to the highest solar radiation and extensive wind belts in the world (IRENA, 2022). In this context, Africa is an ideal region for renewable energy investments thanks to its rich solar, wind and hydropower potential. The use of these resources can meet rapidly increasing energy demand, alleviate energy poverty, combat climate change and reduce fossil fuel imports. Renewable projects provide local employment and economic growth, empower rural communities and strengthen energy security through regional electricity trading (Adem and Çetin, 2024). In 2023, renewable energy investments in Africa were mainly focused on solar, wind and hydropower projects, with solar energy being the most common technology for new capacity additions in 21 countries (BloombergNEF, 2024) (Figure 1). However, fossil fuel investments are still prominent in hydrocarbon-rich countries such as

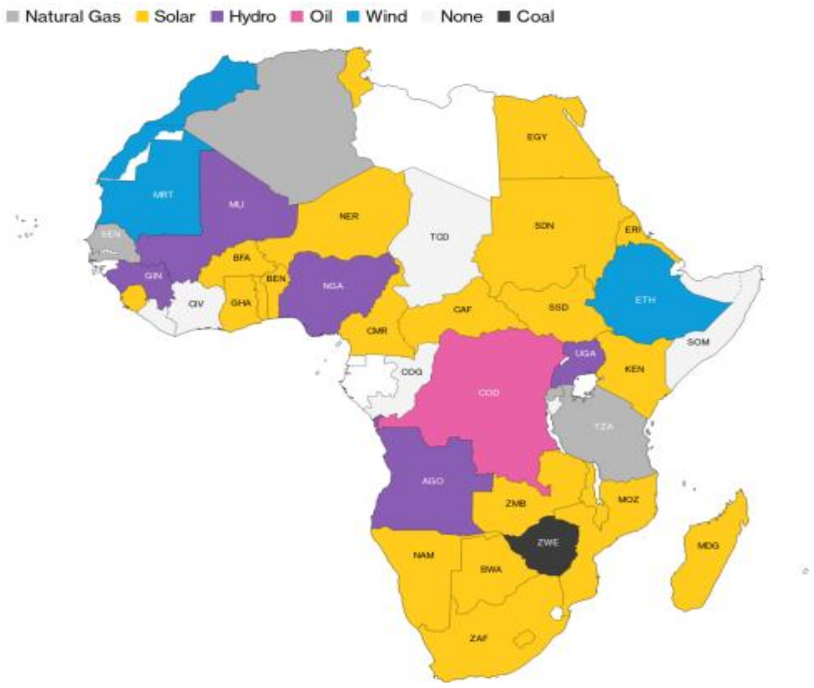

Figure 1: Distribution of renewable energy resources in African countries (2023)
Source: Bloomberg NEF (2024)

Angola, Nigeria and Mozambique, where fossil fuel subsidies and infrastructure investments are still prominent. Therefore, while strong solar radiation, favorable wind regimes and rich hydropower potential across the continent offer low-carbon production opportunities, including green hydrogen (Hamukoshi et al., 2022), fossil fuel-heavy policies are slowing down the pace of energy transition in some countries.

In Africa, solar energy will be the preferred renewable energy source in 21 countries by 2023, with new capacity investments. This increase has been achieved thanks to decreasing costs, the spread of small-scale PV systems and policy support. Wind energy, on the other hand, has been prominent in Mauritania, Ethiopia and Morocco, while it has been limited in other countries. Hydroelectric investments have increased in Angola, Guinea, Mali, Nigeria and Uganda, but these countries have also made large investments in fossil fuel power plants.

Despite its huge renewable energy potential, however, Africa is still unable to fully utilise these resources due to infrastructure, technical capacity and policy gaps. As a result, more than 600 million people still lack access to reliable and affordable electricity, while 780 million continue to use traditional biomass for cooking (Focus, 2021). Africa's dependence on non-renewable energy, combined with rapid population growth, has slowed economic growth, damaged livelihoods and deepened environmental degradation by increasing CO_2 emissions. Current renewable energy policies and investments are inadequate to curb rising emissions. In addition, the risks of extreme weather events, temperature increases and water scarcity triggered by climate change necessitate planning of renewable projects with an approach that will make Africa's energy infrastructure more resilient and that also takes into account climate adaptation. Therefore, Africa must resolutely support renewable energy by developing a comprehensive strategy that accelerates renewable energy investments and includes population management (Obonyo, 2021).

Another policy needed to reduce the effects of climate change is reduction of energy intensity. The role of energy intensity should also be taken into account when determining the level of CO_2 emissions, because it is a key indicator in assessing the impact of the low-carbon transition and reveals the extent to which economies are dependent on energy (Jiao et al., 2024). It is also used to measure the energy efficiency of national economies and is calculated as the amount of energy consumed per unit of gross domestic product. While lower energy intensity means less energy use, higher energy intensity is associated with increased costs and CO_2 emissions (Martínez et al., 2019). High energy intensity indicates that energy is used inefficiently and the environmental burden per unit becomes heavier. As economies grow, energy demand generally increases, which brings with it the risk of increasing CO_2 emissions (Dunyo et al., 2024). In fact, intensive energy use directly paves the way for escalating environmental pollution (Shahbaz et al., 2015; Danish et al., 2020). Therefore, examining the dynamics of energy intensity in Africa in detail is critical to realising the continent's green growth potential and curbing CO_2 emissions. In addition, research shows that Africa's population growth also drives up the continent's CO_2 emissions (Adusah-Poku, 2016). Kaya and Yokobori (1997) confirm that economic growth, population, and energy intensity affect emissions.

This study investigates the impact of renewable energy consumption and energy intensity on environmental sustainability in a panel of 24 African countries over the period 1990–2021. To ensure econometric validity in a multi-country setting, the empirical design priorities panel methods that explicitly accommodate cross-sectional dependence and long-run co-movement among variables. Accordingly, long-run parameters are estimated using the common correlated effects (CCE), augmented mean group (AMG), and mean group (MG) estimators. When a cointegration relationship exists, these approaches facilitate statistically sound long-run inference by allowing for heterogeneous slope coefficients and by mitigating biases that can arise from unobserved common factors and cross-sectional dependence.

A further motivation for adopting CCE, AMG, and MG is that such estimators remain underutilised in the empirical literature, particularly in studies focused on African economies. This methodological gap implies that existing evidence for the region may be limited in scope and, in some cases, open to debate due to estimator choice. By applying AMG, CCE, and MG within a cointegration-consistent framework, this study contributes to the literature in two main ways: it helps address the methodological shortfall in African-focused empirical research, and supports more robust long-run conclusions for the region. In addition, simultaneous quantile regression (SQREG) and generalised method of moments (GMM) methods were used to verify the robustness of the basic findings. Using different estimation techniques together increases the reliability of the results and strengthens the empirical contribution of the study.

Beyond renewable energy and energy intensity, the analysis also incorporates economic growth and population as additional drivers of environmental outcomes, given their central role in sustainability debates. Energy intensity is commonly interpreted as an economy-wide proxy for energy efficiency;

higher energy intensity typically reflects less efficient production structures and is often associated with stronger reliance on fossil fuels, thereby worsening environmental indicators. The main reason why energy intensity increases environmental degradation is that it means more energy is used to produce one unit of output. This increase in energy demand creates higher CO_2 emissions, greater carbon intensity, and therefore more pronounced environmental pressure, especially in economies where energy supply is based on fossil fuels (Shahbaz et al., 2015; Danish et al., 2020; Namahoro et al., 2021).

Furthermore, high energy intensity often points to low energy efficiency, technological deficiencies, and a carbon-intensive production structure. Therefore, the increase in energy intensity brings not only increased energy consumption but also a structural deepening of environmental degradation (Amin and Dogan, 2021; Li et al., 2024). Renewable energy expansion, by contrast, is widely viewed as a key mechanism for reducing carbon emissions. The environmental consequences of economic growth may be ambiguous: environmental pressure can intensify in early development stages, while cleaner technologies and stronger environmental regulation may become more feasible after a certain income threshold. Population growth can further amplify environmental stress by increasing the demand for energy and natural resources. Examining these channels jointly is therefore essential for informing sustainable development strategies. Importantly, the African context remains relatively underrepresented in the environmental sustainability literature, and evidence on the region has been comparatively scarce in recent years, underscoring the need for more comprehensive, methodologically robust analyses.

The main hypotheses of this research are as follows: (1) Renewable energy use is expected to reduce CO_2 emissions in Africa, and this effect is assumed to be strong. (2) Energy intensity is expected to have a negative impact on environmental degradation. (3) The association between economic growth and environmental degradation is assumed to be nonlinear; in particular, the effects of environmentally friendly policies are expected to become more pronounced once a certain income level is reached in developing African economies. (4) Population growth is assumed to exacerbate environmental degradation and to intensify environmental sustainability challenges by increasing pressure on natural resources in Africa.

The remainder of the paper is organised as follows. Section 2 reviews the relevant empirical literature on the variables examined in the analysis. Section 3 presents the dataset and outlines the econometric methodology. Section 4 reports the empirical results and discusses their implications. Finally, Section 5 concludes, and derives policy recommendations.

2. Literature review

2.1 Energy intensity and CO_2

While energy is critical to the functioning of modern societies, energy intensity, which refers to how efficiently energy is used, causes serious environmental problems, especially in economies dependent on fossil fuels (Shahbaz et al., 2015). Numerous scientific studies show that this relationship is consistent on a global scale. Analyses conducted on different continents and countries confirm that high energy intensity is directly linked to increased CO_2 emissions and environmental pollution. In a study conducted specifically for Africa, Namahoro et al. (2021) showed that energy intensity increased CO_2 emissions in a sample of 50 countries during the period 1980–2018. Li et al. (2024), with data covering 38 countries for the period 2002–2020, showed that increasing energy intensity parallel to economic development increased carbon emissions and decreased environmental quality; Zhou et al. (2025) confirmed the same trend for 41 high-polluting countries in the period 1990-2021. Amin and Doğan (2021) on China (1980–2016), Doğan and Shah (2022) on the United Arab Emirates (1992–2017), and Shokoohi et al. (2022) on Iran, Iraq, and Türkiye (1971-2015) identified energy intensity as one of the main drivers of environmental degradation. Marra et al. (2024) used first-difference PVAR analysis in a study conducted with panel data from 34 OECD countries for the period 1994–2019 and found that decreases in energy intensity not only reduced CO_2 emissions but also triggered technological and structural transformations. Ma and Stern (2008) found that energy intensity in China decreased significantly from the late 1970s to 2000, but this decline slowed down after 2000 and started to increase in 2003. The study reveals that this long-term decline is mainly due to technological progress, while certain changes in sectoral structure additionally shape energy intensity. Danish et al. (2020) examined the role of economic policy uncertainty in the relationship between energy intensity and CO_2 emissions using annual US data for the period 1985–2017. Empirical findings show that an increase in energy intensity increases pollution in a statistically significant way. Doğan and Karay (2019), who analysed the 1971-2015 data for Türkiye, showed that a 1% increase in energy intensity increases fuel-related CO_2 emissions by approximately 0.96% in the long term; therefore, high energy intensity significantly increases emissions. Mahmood and Ahmad (2018) emphasised that countries with higher energy intensity bear additional costs in terms of environmental pollution.

Andersson and Karpestam (2013) examined the short- and long-term determinants of energy intensity, carbon intensity, and scale effects using 1973-2007 data from eight developed and two developing countries; the findings revealed that climate policies are more effective, especially in the long term. Salahuddin and colleagues (2020) examined 34 Sub-Saharan African countries for the period 1984-2016 and showed that renewable energy reduces CO_2 emissions and energy intensity, while fossil fuel consumption leads to deterioration in both indicators. Li et al. (2024) analysed 38-country panel data for the period 2002–2020 and found that increasing energy intensity accompanying economic growth increased carbon emissions.

2.2 Renewable energy and CO_2

The relationship between renewable energy consumption and CO_2 emissions has become an increasingly important research area in environmental economics. A significant portion of current empirical studies demonstrates that increased use of renewable energy contributes to a reduction in carbon emissions and improved environmental quality by decreasing dependence on fossil fuels.

A broad strand of the empirical literature documents that expanding renewable energy use is associated with improved environmental outcomes, whereas reliance on fossil fuels tends to worsen emission-related indicators. For instance, using a sample of 34 Sub-Saharan African countries over 1984–2016, Salahuddin et al. (2020) reported that renewable energy deployment reduces both CO_2 emissions and energy intensity, while fossil fuel consumption increases these measures of environmental pressure. Consistent with this evidence, Rahman and Alam (2022) quantified the mitigation effect by showing that a one-unit increase in renewable energy can lower carbon intensity by 0.003 units. The effectiveness of policy intervention is also emphasised in the literature: Andersson and Karpestam (2013), drawing on data from eight developed and two developing economies for 1973–2007, found that climate policies are particularly effective especially over the long run in reducing both energy intensity and carbon intensity. Evidence from South Asia similarly underscores the emissions-reducing role of renewables; Mehmood (2022) showed that, for India, Pakistan, Sri Lanka, and Bangladesh, a 1% increase in renewable energy consumption was associated with an approximately 13% decline in CO_2 emissions.

Methodologically diverse studies reinforce the same direction of association. Based on wavelet co-coherence for nine major African oil-producing countries during 2000–2019, Abban et al. (2022) identified a counter-directional co-movement between renewable energy use and CO_2 emissions, indicating a mitigation pattern. For Indonesia (1965–2022), Idroes et al. (2025) found that economic growth raised CO_2 emissions in the long run, whereas renewable energy consumption reduced both emissions and the ecological footprint. Along similar lines, Haciimamoglu et al. (2025), using data from 17 countries characterised by high wealth inequality over 1995–2021, concluded that renewable energy consumption exerted an emissions-abating effect. Yao et al. (2019) also provided cross-country support: analysing 17 developed and developing economies for 1990–2014, they showed that renewable energy consumption significantly lowers carbon emissions.

The literature further points to dynamic interlinkages among growth, energy use, and emissions. Using Pakistani data, Mirza and Kanwal (2017) documented bidirectional causality among economic growth, energy consumption, and CO_2 emissions, implying that increasing the share of renewable sources in the energy mix can potentially support growth while easing emissions pressures. For Asian economies over 1975–2020, Ali et al. (2023) found that non-renewable energy consumption increased CO_2 emissions in the long run, whereas renewable energy use significantly reduced emissions. A country-specific study for India (1990–2019) by Onakpojeruo et al. (2025) similarly highlighted the substantial contribution of non-renewable energy use to CO_2 emissions and stressed the urgency of strategies aimed at curbing this effect. For Sub-Saharan Africa, Adeniran et al. (2025) applied fixed effects and quantile fixed effects models to a panel of 45 countries for 1980–2020 and showed that renewable energy consistently reduced CO_2 emissions across estimation approaches. Evidence from advanced economies is also aligned: Borgi et al. (2024), using G7 data, reported that renewable energy use (together with eco-innovation) significantly lowered CO_2 emissions. Finally, nonlinearities and growth channels are also discussed in related work: Akpolat and Bakırtaş (2024), based on eight developing countries over 1990–2021, identified an inverted-U relationship between renewable energy consumption and fossil fuel use/CO_2 emissions, while Abid et al. (2020), using Pakistan's 1990–2017 data within an FMOLS and Gregory–Hansen cointegration framework, found that non-renewable energy consumption increases CO_2 emissions whereas renewable energy use supports economic growth.

2.3 Economic growth – population and CO_2

Although the literature on the relationship between economic growth and CO_2 emissions is rapidly expanding, studies that address the linkage specifically

specifically for African countries are relatively limited. Although there are numerous studies examining climate change and global warming, the number of studies examining the interaction between economic growth and CO_2 emissions under the unique conditions of Africa is still small. Azam et al. (2016) found a positive relationship between economic growth and CO_2 emissions in China, Japan and the USA by examining high-emission economies. Bengochea-Morancho et al. (2001) found that the relationship between economic growth and CO_2 emissions varied across countries in the 1981–1995 period, emphasising that policy design should be specific to national conditions. Acaravcı and Öztürk (2010) showed that there was long-term cointegration between CO_2, energy consumption and growth in only seven countries with ARDL bounds tests for 19 EU countries. Farhani and Ben Rejeb (2012) examined 15 MENA countries with data from 1973–2008; in the case of Israel, energy consumption exhibited a long-run cointegrated relationship with both GDP and CO_2 emissions. Magazzino (2015) conducted a causality test in Israel covering the period 1971–2006, showing that real GDP is the main driver of both energy consumption and CO_2 emissions. Zardoub's (2024) empirical analysis based on data from 2002-2019 confirmed that economic growth in BRIC countries increased CO_2 emissions in both the short and long terms. Xuan (2025) analysed the dynamics between innovation, renewable energy consumption, foreign direct investment and CO_2 emissions in Vietnam with annual data for the years 2000–2023 using the autoregressive distributed lag (ARDL) model, revealing that economic growth increased environmental pollution in a statistically significant way. Haciimamoglu et al. (2025), in a study conducted for 17 countries with high wealth inequality using 1995-2021 data, confirmed the environmental Kuznets curve hypothesis by showing that economic growth initially increases CO_2 emissions and decreases them after a certain threshold. Khan et al. (2020) analysed Pakistan's 1965–2015 data, to show that economic growth and energy consumption increased national CO_2 emissions in the short and long terms. Alakbarov et al. (2024), in their EKC-based analysis covering G20 countries, found that economic growth increases environmental degradation, especially in developed member countries.

Demographic dynamics play a critical role in determining human behavior patterns and have a significant impact on CO_2 emissions (Wang and Li, 2021). Using robust panel cointegration and causality techniques on comprehensive panel data covering the period 1993 Q1–2018 Q4, Pickson et al. (2024) demonstrated that the impact of population-related factors on CO_2 emissions varied significantly according to the country's income level. According to the results, while the aging population increased emissions in upper-middle- and lower-middle-income economies, it played a reducing role in high-income countries. Population density, on the other hand, had a limiting effect on CO_2 emissions in high- and lower-middle-income groups and an increasing effect in low-income groups. The findings emphasised the necessity of considering demographic structure together with income level in the design of environmental policies. Lawal (2019), analysing time series data for the period 1975–2016, showed that the effect of population growth on CO_2 emissions in Nigeria is only marginal. Pebra and Busneti (2025) showed that both GDP and population growth positively and statistically significantly increased CO_2 emissions in the six ASEAN countries they examined for the period 2012–2022. Martinez et al. (2007) examined the effect of population growth on CO_2 emissions in EU countries with data for 1975–1999. The results showed that population growth increased emissions more than proportionally in new member states; on the other hand, the population-emission elasticity remainee below one in old member states and lost statistical significance when dynamic time series features were properly included in the model. Behera and Vishnu (2011) found that urbanisation, population growth, service and industrial sectors, and per capita GDP in India had negative environmental impacts.

3. Analysis

This section provides a detailed account of the dataset and the econometric framework employed, covering cross-sectional dependence diagnostics as well as unit-root and cointegration tests for the variables of interest. It also outlines the panel estimators and causality procedures used in the estimation stage, with the overall methodological sequence summarised schematically in Figure 5.

3.1 Data

In the study, 1990–2021 data were used to examine the effects of renewable energy and energy intensity on environmental quality in 24 African countries (Angola, Benin, Botswana, Cameroon, Congo, Democratic Republic of the Congo (DRC), Equator, Gabon, Ghana, Kenya, Mairitus, Nabimbya, Niger, Nigeria, Rwanda, Senegal, South Africa, Sudan, Tanzania, Togo, Uganda, Zambia, Zimbawe, and Mozambique). Theanalysis is limited to 2021 because of the difficulties in accessing data from African countries. In the study, CO_2 emissions were used as the dependent variable, and energy intensity (EI), renewable energy (RE), economic growth (GDP), and population (POP) variables were used as independent variables. The energy intensity variable was taken from *Our World in Data* (OWD), and all other variables were taken from the *World Bank Indica-*

tors (WDIs) Table 1 provides a detailed summary of variable definitions and related data sources.

Descriptive statistics include basic measures such as mean, median, mode, range, variance and standard deviation. These indicators help in understanding the central tendencies, level of variability and general distribution of the data. The results of descriptive statistics are given in Table 2.

Table 1: Description of variables

Variable	*Description*	*Unit of measurement*	*Source*
CO_2	Carbon emissions	Carbon intensity of GDP (kg CO_2e per constant 2015 USD of GDP)	WDI
EI	Energy intensity	Energy intensity per capita	OWD
RE	Renewable energy consumption	Renewable energy consumption (% of total final energy consumption)	WDI
GDP	Economic growth	Per capita GDP 2015 constant	WDI
POP	Population	Population, total	WDI

Table 2: Summary statistics

	CO_2	*EI*	*RE*	*GDP*	*POP*
Mean	0.4097823	0.6256641	66.89883	2301.603	50.51946
Maximum	4.036944	2.96	98.3	13048.07	52.76197
Minimum	0.0675531	0.11	3.7	188.6583	47.0204
Std. dev.	0.3522953	0.5395056	25.86707	2444.452	0.9384944
Skewness	4.105421	2.329701	-0.941739	1.753461	-0.149151
Kurtosis	30.30515	8.008738	2.748943	5.538349	4.454691
Jarque-Bera	26015.65	1497.520	115.5366	599.7348	70.56356
Observations	768	768	768	768	768

Data from the WDI and OWD indicators, consisting of CO_2, RE, EI, GDP and POP variables for 24 African countries, cover the period 1990–2021; these are shown in Figure 2.

Figure 3 shows that African countries have exhibited different trends in renewable energy use during the period 1990–2021. Renewable energy consumption of the sample is highest in the DRC, Uganda, Tanzania, and Mozambique, and lowest in South Africa and Mauritius. These trends reveal the progress African countries have made with the various strategies they have adopted in the clean energy transition process.

Figure 4 shows the energy intensity trends of African countries over 1990–2021. The data shows that South Africa has the highest energy intensity, followed by Gabon. This is noteworthy because South Africa, which ranked last in renewable energy consumption in the previous graph, also stands out with the highest energy intensity. In contrast, the DRC, Uganda, Tanzania and Mozambique, which lead in renewable energy use, have the lowest energy intensities, demonstrating the positive relationship between clean energy penetration and energy efficiency across the continent.

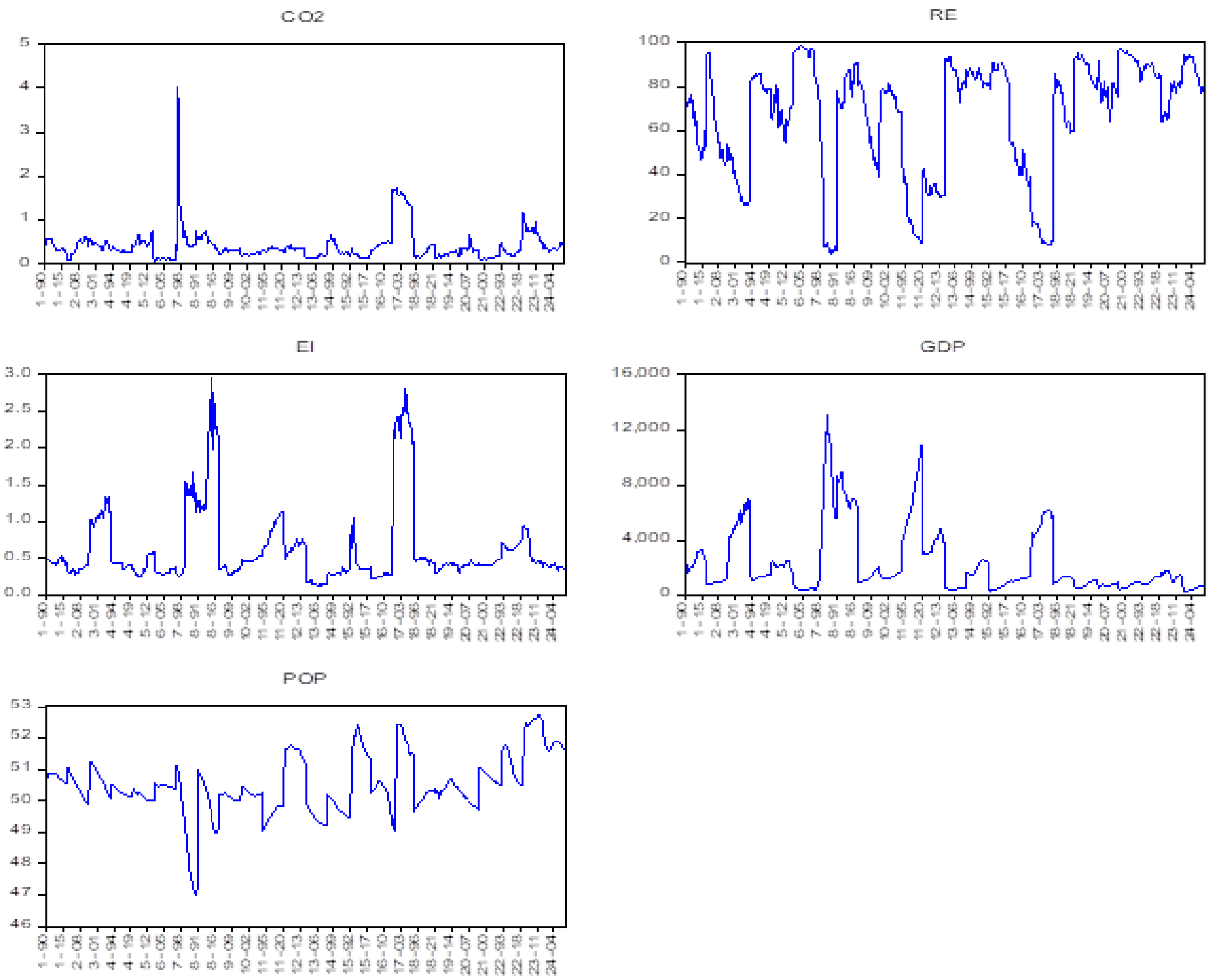

Figure 2: Evolution of variables

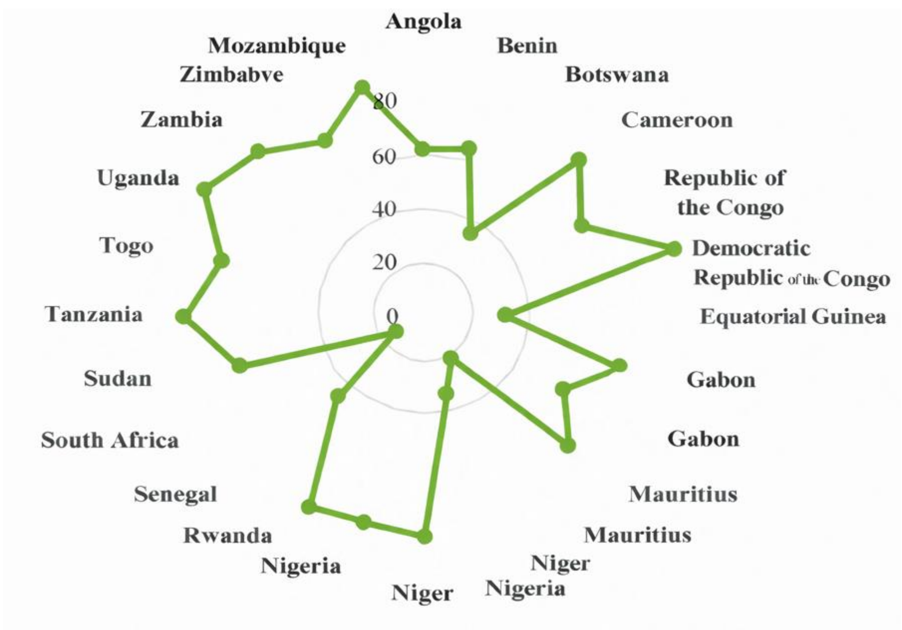

Figure 3: Renewable energy in African countries

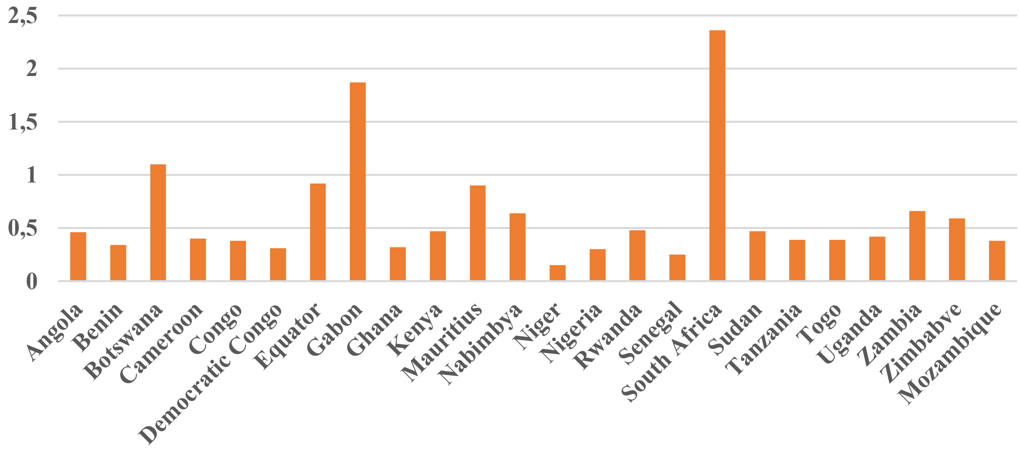

Figure 4: Energy intensity in African countries

Table 3: Correlation matrix

	CO_2	*EI*	*RE*	*GDP*	*POP*
CO_2	1				
EI	0.5344	1			
RE	-0.4431	-0.5194	1		
GDP	0.3100	0.7225	-0.7111	1	
POP	0.2030	-0.0003	0.1597	-0.2823	1

Table 4: Multicollinearity test results

	VIF	*1/VIF*
EI	2.31	0.43297
RE	2.03	0.49254
GDP	3.59	0.27850
POP	1.20	0.83060
Mean VIF	2.28	

Table 3 summarises the correlations between the variables. A positive correlation was found between CO_2 and EI, indicating that emissions increase as EI increases. In contrast, RE is negatively correlated with both CO_2 and EI, indicating that clean energy use reduces both emissions and EI.

The mean variance inflation factor (VIF) indicates that multicollinearity is not a concern in the model, as all values remain well below the conventional threshold of 5.

3.2 Mathematical model

The mathematical model used in the study is given in Equation 1.

$$CO_2it = f(EIit, REit, GDPit, POPit) \quad (1)$$

where i = cross-section; t = time; CO_2it = carbon dioxide emissions to represent environmental quality; REit = renewable energy; GDPit = economic growth; and POPit = total population. The transformed version of the model is given in Equation 2.

$$CO2_{it=}\beta_0 + \beta_1 EI_{it} + \beta_2 RE_{it} + \beta_3 GDP_{it} + \beta_4 POP_{it} + \mathcal{E}_{it} \quad (2)$$

In this model, the parameters β1 to β4 are elasticity coefficients. They measure the effect of a 1 unit increase in the independent variables on CO_2. The main focus of the study is to estimate these parameters, which express the effects of EI, RE, GDP and POP variables on CO_2. In the model, β0 represents the constant term, while Ɛit represents the error term.

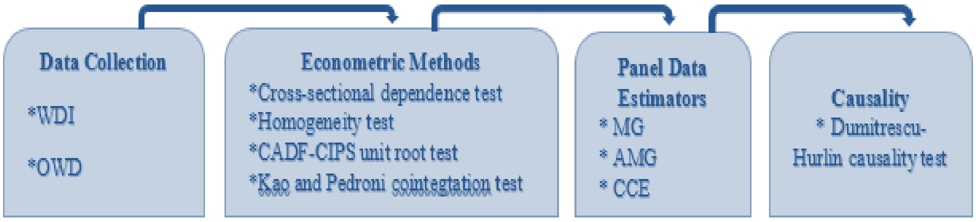

Figure 5: Methodological flowchart

3.3 Econometric methodology

3.3.1 Cross-sectional dependence tests

The statistics for the cross-sectional dependence relationship between units, analysed through four different tests (Breusch and Pagan (1980) LM, Pesaran (2004) CDLM and CD, and Pesaran (2008) LMAdj) are presented in Equations 3–6.

$$LM = T \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \tilde{\rho}_{ij}^2 \quad (3)$$

$$CD_{LM} = \left(\frac{1}{N(N-1)}\right)^{\frac{1}{2}} \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \left(T\tilde{\rho}_{ij}^2 - 1\right) \quad (4)$$

$$CD = \left[\frac{2T}{N(N-1)}\right]^{\frac{1}{2}} \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \tilde{\rho}_{ij}(T-k)\tilde{\rho}_{ij}^2 \quad (5)$$

$$LM_{Adj} = \left[\frac{2T}{N(N-1)}\right]^{\frac{1}{2}} \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \tilde{\rho}_{ij}(T-k)\tilde{\rho}_{ij}^2 - \mu T_{ij}/(vT_{ij}^2)^{\frac{1}{2}} \quad (6)$$

3.3.2 Homogeneity slope test

Determining whether the slope parameters are identical across countries is a crucial preliminary inference. When slope coefficients are presumed to be equal, simple, conventional tests are usually sufficient. If, however, the slopes differ, this signals heterogeneity and calls for more advanced testing procedures. Slope homogeneity can be assessed with the SH statistic introduced by Pesaran and Yamagata (2008), which rests on Swamy's (1970) random coefficients approach. The rigorous asymptotic properties of these statistics are presented in Equations 7 and 8.

$$\tilde{\Delta} = \sqrt{N}\,\frac{N^{-1}\tilde{S}-k}{\sqrt{2k}} \quad (7)$$

$$\tilde{\Delta}_{Adj} = \sqrt{N}\,\frac{N^{-1}\tilde{S}-k}{v_{ar}(t,k)} \quad (8)$$

3.3.3 Pesaran CIPS unit root test

The Pesaran (2007) CIPS panel unit-root framework explicitly accommodates cross-sectional dependence by augmenting each unit's regression with cross-sectional averages of the lagged level terms and first differences. In practice, this approach is implemented through the cross-sectionally augmented Dickey–Fuller (CADF) specification, which can be expressed as in Equation 9.

$$Y_{it} = (1-\emptyset)_i + \emptyset_i Y_{i,t-1} + \varepsilon_{it}\,(i = 1, \dots\dots, N; t = 1, \dots\dots, T) \quad (9)$$

where $\varepsilon_{it=}Y_i f_t + U_{it}$ = the error term εit; f_t = the unobservable joint effect of each country; and Uit = individual error term. By writing them into Equation 9, Equation 10 is obtained.

$$\Delta Y_{it} = \alpha_i + \beta_i Y_{i,-1} + Y_i f_t + U_{it} \quad (10)$$

First, the CADF test values for each cross-sectional unit are found using Equation 10; then, the CIPS statistics are obtained by taking the simple arithmetic average of these values. The relevant formulations are given in Equations 11 and 12.

$$CADF_i = \frac{\Delta Y_i' M_Z Y_{i,-1}}{\hat{\sigma}_i \sqrt{Y_{i,-1}' M_Z Y_{i,-1}}} \quad (11)$$

$$CIPS = \frac{\sum_{i=1}^{N} CADF_i}{N} \quad (12)$$

3.3.4 Panel cointegration test

The most important cointegration tests based on the Engle and Granger (1987) approach, the Kao and Chiang (2000) test and the Pedroni (1999, 2001, 2004) tests used for heterogeneous panel data, evaluate the long-term relationship between variables by also considering whether it is spurious or not. These tests examine whether the regression residuals of the integrated series of the first degree are I(0) or I(1) based on the unit root results. If the residuals are I(0), that is, if stationarity is achieved, it is concluded that there is cointegration between the variables; otherwise, there is a possibility of spurious relationship. While Pedroni statistics are of ADF and PP type in both homogeneous/panel and heterogeneous/group versions, Kao's test appears as an ADF test with homogeneous coefficients and constant intercept assumption. In both tests, the analysis is performed under the intercept but trendless model and using the lag and the leaders determined according to the Schwarz information criterion.

3.3.5 Common correlated effects

Augmented Mean Group (AMG) estimator proposed by Eberhardt and Teal (2010) and Bond and Eberhardt (2009), Average Group (MG) estimator developed by Pesaran and Smith (1995) and Common Correlated Effects (CCE) estimator presented by Pesaran (2006) are widely used in panel data analysis to reliably reveal long-run relationships. These methods not only make long-run coefficient estimates accurate in the presence of cross-sectional dependence and cointegration between series, but also increase the consistency of the results by controlling the risk of multicollinearity.

3.3.6 Causality test

To explore the direction of predictive relationships among the variables, the Dumitrescu and Hurlin (2012) panel Granger-causality framework is applied. This procedure is suitable for panels where countries may differ in slope parameters and where cross-sectional dependence may be present. The test is implemented with appropriate lag lengths and evaluates whether past values of one variable contain incremental predictive content for another variable, beyond its own history. The analysis is applied with the lagged values of variables expressing unit roots. The test statistics can be given as follows in Equations 13 and 14 (asymptotic and semi-asymptotic):

$$\tilde{Z}_{N,T}^{HNC} = (N/2K)^{\frac{1}{2}}(W_{N,T}^{HNC} - K) \quad (13)$$

$$\tilde{Z}_{N}^{HCN} = [(N)^{\frac{1}{2}}(W_{N,T}^{HNC} - N^{-1}\sum_{i=1}^{N} E(W_{i,T})]/ [N^{-1}\sum_{i=1}^{N} Var(W_{i,T})]^{\frac{1}{2}} \quad (14)$$

4. Results and discussion

The results shown in Table 5 are obtained through cross-sectional dependence tests developed by Pesaran (2004), and Breusch and Pagan (1980). The findings indicate that cross-sectional dependence exists, rejecting the null hypothesis of no cross-sectional independence across African countries, regions and income levels at the 1% level of significance. All variables are significant at the 1% level of significance for all tests (LM, CDLM, CD and LMAdj).

As a different a priori examination, the homogeneity test of Pesaran and Yamagata (2008), which is based on the homogeneity of the slopes of the countries, was applied. The results of this test are presented in Table 6. The results lead us to reject the null hypothesis of slope homogeneity, indicating that the slope parameters vary across cross-sectional units.

To determine the stationarity properties and the order of integration of the variables, the Pesaran (2007) CIPS panel unit-root procedure is used. The corresponding unit-root outcomes are reported in Table 7. The unit-root results indicate that each series becomes stationary after taking the first difference, implying that the variables share a common integration order of one, they are integrated of order I(1). Given this integration structure, we proceed with residual-based panel cointegration procedures specifically the Kao and Pedroni tests to assess whether a stable long-run equilibrium relationship exists among the variables.

Table 5: Cross-sectional dependency test results

Test	*CO_2*	*EI*	*RE*	*GDP*	*POP*
LM	2347.061 (0.000)***	2707.465 (0.000)***	3613.007 (0.000)***	4581.278 (0.000)***	4881.230 (0.000)***
CD_{LM}	88.150 (0.000)***	103.490 (0.000)***	142.032 (0.000)***	183.244 (0.000)***	196.011 (0.000)***
LM_{Adj}	87.763 (0.000)***	103.102 (0.000)***	141.645 (0.000)***	182.857 (0.000)***	195.624 (0.000)***
CD	-1.737 (0.082)*	8.3089 (0.000)***	32.212 (0.000)***	41.6391 (0.000)***	21.695 (0.000)***

Note: P-Values in parentheses. *** p<0.01, ** p<0.05, * p<0.10.

Table 6: Homogeneity test results

	$\tilde{\Delta}$	$\tilde{\Delta}_{Adj}$
Test Statistic	32.331	35.868
P-Value	0.000***	0.000***

Note: *** p<0.01, ** p<0.05, * p<0.10.

Table 7: Results of panel unit root tests

Variables	*CADF*		*CIPS*	
	I(0)	*I(1)*	*I(0)*	*I(1)*
CO_2	0.671	-10.629***	-2.375	-5.418***
EI	2.073	-7.953***	-1.998	-5.525***
RE	0.502	-8.349***	-2.206	-5.321***
GDP	-1.380	-6.204***	-2.200	-4.548***
POP	-0.023	-4.556***	-0.898	-2.799***

Note: *** p<0.01, ** p<0.05, * p<0.10. Critical values are -2.580, -2.650, -2.780. The significance of the test statistics of the variables at both the level and the first differences was compared with the critical values in the Pesaran (2007) study.

Table 8: Cointegration tests

H_0: No cointegration; H_1: All panels are cointegrated		
Test	*Statistic*	*p-value*
Kao test for cointegration		
Modified Dickey–Fuller t	-9.3262	0.000***
Dickey–Fuller t	-8.0119	0.000***
Augmented Dickey–Fuller t	-11.9559	0.000***
Unadjusted modified Dickey–Fuller t	-14.7991	0.000***
Unadjusted Dickey–Fuller t	-9.3569	0.000***
Pedroni test for cointegration		
Modified Phillips–Perron t	1.8202	0.034**
Phillips–Perron t	-4.3015	0.000***
Augmented Dickey–Fuller t	-3.8210	0.000***

Note: *** p<0.01, ** p<0.05, * p<0.10.

To determine the long-term impacts of EI, RE, GDP, and POP on CO_2, Table 9 presents panel long-term estimates derived from MG, AMG, and CCE estimators. The use of these alternative estimators allows for robustness checking of coefficient signs and magnitudes while accounting for slope heterogeneity and cross-sectional dependence between countries. The results show that there is a statistically significant relationship between EI, RE, GDP and POP variables and CO_2 in all tests. According to the AMG test, a one-unit increase in EI increases CO_2 by 0.404, while a one-unit increase in RE and GDP decreases CO_2 by -0.010 and -0.0002, respectively. According to the MG test, a one-unit increase in EI increases CO_2 by 0.395, and a one-unit increase in POP increases CO_2 by 0.086. A one-unit increase in GDP and RE decreases CO_2 by -0.00021 and -0.01062, respectively. According to the CCE test, a one-unit increase in EI increases CO_2 by 0.40489, and a one-unit increase in POP increases CO_2 by 0.09474. A one unit increase in GDP and RE decreases it by -0.00020 and -0.01089, respectively.

Table 9: Long-term estimates of MG, AMG, and CCE for the panel

Test	*Variables*	*Coefficient*	*Std. error*	*z*	*P>z*
AMG estimator	EI	0.40489	0.10485	3.86	0.000***
	RE	-0.01089	0.00192	-5.67	0.000***
	GDP	-0.00020	0.00003	-6.13	0.000***
	POP	0.09474	0.03936	2.41	0.016**
	CONS	-3.42657	2.00053	-1.71	0.087*
MG estimator	EI	0.39550	0.10693	3.70	0.000***
	RE	-0.01062	0.00207	-5.11	0.000***
	GDP	-0.00021	0.00003	-6.37	0.000***
	POP	0.08645	0.03909	2.21	0.027**
	CONS	-2.98022	1.98930	-1.50	0.134
CCE estimator	EI	0.40489	0.10485	3.86	0.000***
	RE	-0.01089	0.00192	-5.67	0.000***
	GDP	-0.00020	0.00003	-6.13	0.000***
	POP	0.09474	0.03936	2.41	0.016**
	CONS	-3.42657	2.00053	-1.71	0.087*

Note: *** p<0.01, ** p<0.05, * p<0.10.

The positive and relatively high coefficient of energy intensity indicates that this variable has a strong impact on CO_2 emissions, not only statistically but also economically. This finding reveals that increased energy use in production significantly increases carbon emissions, and that energy intensity is one of the key structural determinants of environmental degradation. Therefore, reducing energy intensity is a critical policy area not only for increasing technical efficiency but also for low-carbon and sustainable growth. This result demonstrates that technological transformation and the use of clean energy, which increase energy efficiency, are central to environmental improvement.

In Africa, the reduction of CO_2 emissions due to economic growth can be explained by the fact that growth does not always come from polluting sectors. If growth is driven not by heavy industry and fossil fuel use, but by the services sector, increased productivity, technological innovation, and renewable energy investments, then emissions can decrease while GDP increases. Therefore, the key issue is not growth itself, but how it occurs. For this reason, a negative GDP coefficient demonstrates that economic growth can coexist with a cleaner and less energy-intensive structure.

These results are parallel to the following studies: Namahoro et al. (2021) found that increases in energy intensity increase CO_2, while increases in renewable energy and economic growth decrease it. The underlying reason why increases in GDP reduce CO_2 supports the view that a clean environment will be achieved through economic growth, as assumed by the Environmental Kuznets Curve (EKC) hypothesis. This result supports the study of Mongo et al. (2021), while it contradicts the study of Chen and Zhang (2025). Shahbaz et al. (2015) and Shahbaz et al. (2016) concluded that economic growth and energy intensity increase CO_2 emissions. Contrary to these studies, Hatzigeorgiou et al. (2008) showed that energy intensity was the main factor responsible for the decrease in CO_2 emissions in Greece. A one-unit increase in POP increases CO_2 by 0.094. In the literature, the finding that the effect of population on emission increase is significant is found in most of the studies that include this factor (Patino et al., 2021; Hatzigeorgiou et al., 2008; Martín-Vide et al., 2007; Wang et al., 2005; Al Mamun et al., 2014).

The results of the dynamic GMM robustness test presented in Table 10 show that the model generally produces strong and consistent findings. Firstly, the positive and highly significant lagged dependent variable indicates that CO_2 emissions exhibit significant persistence and that past emission levels strongly influence the current period. This suggests that environmental degradation has a structural characteristic that does not easily disappear in the short term. When the independent variables are examined, it is seen that economic growth and the use of renewable energy have a positive effect on reducing CO_2 emissions. This finding suggests that economic development, under certain conditions, can contribute to environmental improvement through cleaner production techniques, technological progress, and energy transition. In contrast, energy intensity and population growth stand out as factors that increase CO_2 emissions. In particular, the positive coefficient of energy intensity shows that insufficient energy efficiency in production processes increases environmental pres-sure. Similarly, the increase in emissions due to population growth can be associated with increased energy demand, consumption pressure, and expansion in the volume of economic activity. In addition, the insignificant results of the Arellano-Bond AR(1) and AR(2) tests show that the serial correlation problem is not significant in the model and support the reliability of the estimation results. Overall, these findings demonstrate that the study's core conclusions are preserved under an alternative dynamic estimation approach, thus revealing that the empirical relationships obtained are robust and suitable for generating policy implications.

The SQREG results presented in Table 11 show that the determinants of CO_2 emissions exhibit a heterogeneous structure across the distribution. The GDP variable has a negative sign across all quantiles, indicating that economic growth is generally associated with reducing CO_2 emissions. However, this effect is stronger in the middle quantiles and becomes more limited towards the upper quantiles. The renewable energy variable is negative and statistically significant across all quantiles, which shows that the use of renewable energy is effective in reducing environmental degradation at both low and high emission levels. The energy intensity variable is positive and strongly significant across all quantiles; furthermore, the significant increase in the coefficient in the middle quantiles suggests that energy inefficiency has more destructive consequences, especially in areas with high CO_2 emission concentrations. The population variable is weak and insignificant in most cases in the lower quantiles, but strengthens in both magnitude and significance towards the upper quantiles. This finding indicates that population growth becomes a stronger factor increasing environmental pressure, especially at high emission levels. Overall, the quantile regression findings suggest that determinants of environmental degradation vary depending on the emission level, and therefore, differentiated policy designs based on emission intensity are more appropriate than a uniform policy approach.

Table 10: Robustness check results with GMM dynamic regression test

CO_2	*Coefficient*	*Robust std. err.*	*z*	*P>z*
CO_{2L1}	0.76058	0.01185	64.14	0.000***
GDP	-0.00007	2.34e-06	-30.97	0.000***
RE	-0.00669	0.00022	-29.13	0.000***
EI	0.13632	0.00634	21.48	0.000***
POP	0.03680	0.00534	6.88	0.000***
Arellano-Bond test		Ar(1) : -1.1179 Prob > |z| = 0.2636 AR(2) : -1.0179 Prob > |z| = 0.3087		

Note: *** p<0.01.

Table 11: Simultaneous quantile regression (SQREG) estimation results

Variable	*Quantile*								
	10th	*20th*	*30th*	*40th*	*50th*	*60th*	*70th*	*80th*	*90th*
GDP	-0.00003 (0.000)***	-0.00004 (0.000)***	-0.00005 (0.000)***	-0.00006 (0.000)***	-0.00007 (0.000)***	-0.00007 (0.000)***	-0.00003 (0.060)***	-0.00001 (0.029)***	-0.00001 (0.401)***
RE	-0.00469 (0.000)***	-0.00488 (0.000)***	-0.00537 (0.000)***	-0.00618 (0.000)***	-0.00688 (0.000)***	-0.0066 (0.000)***	-0.00591 (0.000)***	-0.00617 (0.000)***	-0.00647 (0.000)***
EI	0.22574 (0.000)***	0.24424 (0.000)***	0.27437 (0.000)***	0.3327 (0.000)***	0.44463 (0.000)***	0.44915 (0.000)***	0.35137 (0.000)***	0.35483 (0.000)***	0.33098 (0.000)***
POP	0.01004 (0.001)***	0.00524 (0.363)	0.00819 (0.233)	0.02569 (0.141)	0.04723 (0.002)***	0.04368 (0.006)***	0.08694 (0.000)***	0.09350 (0.000)***	0.11058 (0.000)***

Note: P-Values in parentheses. *** p<0.01.

Table 12: Dumitrescu-Hurlin panel causality test results

Null hypothesis	*W-Stat.*	*Zbar-Stat.*	*P-Value*
$CO_2 \nrightarrow$ GDP	3.0366	7.0550	0.000***
GDP $\nrightarrow CO_2$	2.8056	6.2549	0.000***
$CO_2 \nrightarrow$ RE	3.4687	8.5520	0.000***
RE$\nrightarrow CO_2$	3.2219	7.6968	0.000***
$CO_2 \nrightarrow$ EI	1.4569	1.5829	0.113
EI $\nrightarrow CO_2$	3.3625	8.1838	0.000***
$CO_2 \nrightarrow$ POP	2.9599	6.7894	0.000***
POP $\nrightarrow CO_2$	13.7352	44.1161	0.000***

Note: *** p<0.01, ** p<0.05, * p<0.10.

Table 12 reports the causality results for the 24 African countries and provides evidence of causal linkages among energy intensity, economic growth, renewable energy use, population, and CO_2 emissions. The findings indicate a one-way causal effect running from EI to CO_2 emissions. This pattern is consistent with the evidence reported by Agboola et al. (2021) for Saudi Arabia, where causality is found to run from energy consumption toward carbon emissions. From a policy perspective, the result implies that increases in energy intensity translate into higher emissions, highlighting the need for countries to strengthen energy-efficiency strategies; in particular, measures that reduce energy intensity can contribute materially to lowering CO_2 emissions and, by extension, carbon intensity. In addition, the analysis reveals bidirectional causality between RE consumption and CO_2 emissions, which aligns with the findings of Leitão (2021).

To summarize, the Dumitrescu-Hurlin Granger test confirms the AMG, MG and CCE results, showing that renewable energy, population, energy intensity and economic growth are strong predictors of future CO_2 emissions. This statistical relationship implies that population growth and energy intensity may have a negative impact on emissions over the study period, while also clearly indicating that Africa needs to continuously expand its renewable energy capacity to achieve its environmental goals.

5. Conclusions and policy implications

This paper investigated how energy density and renewable energy shape environmental pollution across 24 African economies over the 1990–2021 period, using CO_2 emissions as the indicator of environmental degradation. In addition to these key variables, the analysis also considered the roles of population dynamics and economic growth in explaining changes in CO_2 emissions. The empirical strategy was designed within a phased framework. First, it was tested whether the panel exhibits cross-sectional dependence and then it was assessed whether slope parameters are homogeneous across countries. Accounting for cross-sectional dependence in the unit-root stage, it was found that the variables are non-stationary in levels but become stationary after first differencing, implying an I(1) integration order. Given these properties, the Kao and Pedroni panel cointegration tests were used consistent with a heterogeneous panel structure under cross-sectional dependence to examine the existence of a long-run equilibrium relationship. Subsequently, the long-run cointegrating coefficients were estimated using the MG, AMG, and CCE estimators, which yielded broadly consistent results. Overall, the MG/AMG/CCE estimates indicated that higher energy intensity is associated with increased CO_2 emissions, whereas greater renewable energy use reduces CO_2 emissions. In addition, the results consistently suggested that GDP growth is linked to lower CO_2 emissions, while population growth exerts upward pressure on CO_2 emissions.

To test the robustness of the long-term findings obtained from the MG, AMG, and CCE estimators, dynamic GMM and SQREG estimations were additionally applied. The results indicated that the core empirical findings were largely preserved even under these alternative estimation methods. The GMM results confirmed that CO_2 emissions exhibited dynamic continuity and that, while renewable energy reduces emissions, energy intensity and population growth increased them. The SQREG findings, however, revealed that these relationships were not entirely homogeneous across the distribution, particularly noting that the effects of energy intensity and population became more pronounced in high-emission quantiles. In this context, the fact that the core results remain generally consistent across the MG, AMG, CCE, GMM, and SQREG estimators strengthened the robustness of the findings and demonstrated that the conclusions reached are not specific to a single econometric method.

5.1 Policy implications

As a policy implication, this evidence suggests that higher renewable energy and lower energy intensity tend to reduce CO_2. Therefore, considering that energy intensity plays a critical role in providing basic services and achieving development goals, and that energy is a major determinant of carbon emissions, policy makers should develop behavioral interventions and regulatory frameworks to transform energy consumption habits. Financial incentives to encourage the adoption of low-carbon energy technologies and educational campaigns to raise public awareness of energy efficiency will pave the way for consumer preferences to shift in favour of clean energy. Infrastructure investments that will ensure balanced, safe and accessible use of the rich renewable (solar, wind, hydro) and traditional energy resources on the African continent will both support equity in energy access and contribute to emission reduction. In addition to hydro and geothermal, there are additional renewable resources, such as biofuels, across the continent, and the uneven distribution of these resources necessitates cross-border energy trade. In order to ensure public participation in the process of reducing emissions and mitigating their effects, awareness should be raised about the causes, dimensions and social impacts of climate change and positive behaviours and technologies that limit greenhouse gas emissions and adapt to the climate should be encouraged.

The African continent is a strategic region in terms of global environmental policies with its rich natural resources, rapid population growth, urbanisation dynamics and developing economic structure. Despite having low greenhouse gas emissions, the continent is quite vulnerable to environmental risks due to its agriculture-based economy and inadequate infrastructure. On the other hand, thanks to its high renewable energy potential, it is possible to both increase access to energy and adopt low-carbon development models.

In conclusion, ensuring environmental sustainability in African economies requires policymakers to move beyond a narrow focus on expanding energy supply. Greater priority should also be given to restructuring energy systems in ways that improve efficiency, expand the use of cleaner energy sources, and promote more inclusive access to modern energy services. In this respect, scaling-up renewable energy investments, introducing structural reforms that reduce energy intensity, designing sustainable infrastructure policies that take population growth and urbanisation pressures into account, and strengthening cross-border energy cooperation should remain central policy priorities. Such a comprehensive approach would not only help reduce CO_2 emissions, but also improve energy access, support long-term economic development, and enhance the resilience of African countries to climate-related risks. At the same time, the effectiveness of these policies will depend on the extent to which they are supported by institutional capacity, regulatory coordination, and investment frameworks capable of sustaining the energy transition over time.

Given the substantial structural differences across African countries, environmental policies should be designed in line with country-specific priorities, resource endowments, and development conditions. In this context, expanding renewable energy investments, implementing efficiency-enhancing measures that lower energy intensity, strengthening rural energy access, and deepening regional energy cooperation emerge as key policy areas for both emission reduction and sustainable development. A differentiated policy approach is therefore essential to ensure that environmental strategies remain both effective and feasible across diverse national contexts. In particular, policies should be sufficiently flexible to address differences in energy infrastructure, levels of electrification, and dependence on conventional energy sources across the continent.

5.2 Study limitations and future directions

This study has some limitations. First, the empirical analysis is based on a relatively limited sample, covering only 24 African countries. Expanding the sample size by including more countries in future research could increase the external validity of the findings. Subsequent studies could achieve more comprehensive results by conducting comparative analyses among economies with varying levels of development. Moreover, the limited availability of long-term and comparable data for African countries may create some limitations in terms of data quality and measurement errors. This necessitates careful evaluation of the results, particularly regarding data compatibility and indicator consistency across countries. Additionally, instead of assessing environmental degradation through a single indicator, using alternative measures such as ecological footprint, load capacity factor, and broader greenhouse gas emission indicators could contribute to a more holistic examination of the relationship.

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