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Article

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DEVELOPMENT ECONOMICS | RESEARCH ARTICLE

The dynamic linkage between renewable energy consumption and environmental sustainability in Sub-Saharan African countries: Heterogeneous macro-panel data analysis

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Abstract: Environmental sustainability is a pivotal facet of sustainable development, captivating the attention of development researchers. Within this context, energy consumption emerges as a pivotal determinant influencing environmental sustainability variations among countries. This study delves into the linkages between renewable



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PUBLIC INTEREST STATEMENT

Despite commendable efforts, the pace of progress toward sustainable development remains insufficient, with persisting issues like negative environmental impacts, climatic catastrophes, biodiversity loss, pollution, and social tensions. Turning our attention to Sub-Saharan Africa, we recognize it as a diverse continent blessed with abundant natural and human resources, holding immense potential for fostering inclusive growth and eradicating poverty. However, the looming threat of climate change poses significant challenges, potentially impacting millions in this region. Meaningful climate and development solutions are imperative, and this statement underscores the pivotal role of energy consumption. While energy is a catalyst for economic growth, its excessive use contributes to environmental degradation. Our research investigates the dynamic linkage between renewable energy consumption and environmental sustainability in Sub-Saharan African countries from 2000 to 2020. Our overarching goal is to provide evidence-based insights crucial for well-informed and effective policymaking. Through our research, we aspire to contribute to driving sustainable development in Sub-Saharan Africa, aligning with global agendas, and fostering a resilient, equitable, and environmentally conscious future for the region. We believe that by understanding the intricate dynamics between renewable energy consumption and environmental sustainability, we can pave the way for informed decisions that positively impact the region's trajectory.

energy consumption and environmental sustainability within 30 Sub-Saharan African countries, utilising panel data from 2000 to 2020. It contributes to the expanding literature on this subject by considering the impacts of institutional and political factors while addressing challenges related to cross-sectional dependence, heterogeneity, and serial correlation through robust estimation. To this end, the Augmented Mean Group Model was used in the empirical estimation. The study reveals a noteworthy 67.32% mean score for renewable energy consumption in the total final energy consumption across the sampled countries, a positive deviation from the global average of 11.2%. Empirical results signify a positive and statistically significant long-term relationship between renewable energy consumption and environmental sustainability. Nevertheless, the inclusion of a policy dummy variable indicates a significant increase in greenhouse gas emissions post the Millennium Development Goals period. Granger non-causality test results reveal a bidirectional causality between renewable energy consumption and environmental sustainability. Thus, subsidies and tax exemptions for renewable energy production and consumption, as well as supporting sustainable development goals with appropriate environmental investment, are among the policy options that Sub-Saharan African countries and policymakers could pursue to achieve environmental sustainability and sustainable development goals.

Subjects: Ecological Economics; Economics

Keywords: energy consumption; environmental sustainability; augmented mean group; Granger causality; Sub-Saharan Africa

1. Introduction

The interconnectedness of nature, society, and the economy underscores the compelling need for sustainable development (Cavagnaro & Curiel, 2017). This imperative has ascended to the forefront of the international policy agenda, particularly following the introduction of the Global Goals. Notably, the recent COP26 summit witnessed nations making substantial commitments to collaborative action on pressing global challenges. These commitments encompass a broad spectrum, ranging from the reduction of methane emissions and the prevention of forest loss to the alignment of the financial sector with the ambitious net-zero target by 2050. Furthermore, countries pledged to expedite the phase-out of coal, transition away from internal combustion engines, and cease foreign financing for fossil fuels (WRI, 2022).

Notwithstanding global endeavors to attain sustainable development, progress towards this goal is not unfolding at the necessary pace or magnitude. Negative footprints, climatic catastrophes, catastrophic biodiversity loss, pollution, inequality, and persistent or exacerbated social tensions persist, alongside substantial and ongoing unsustainable behaviors (Kopnina, 2020).

Sub-Saharan Africa (SSA) stands as a diverse continent blessed with abundant natural and human resources, presenting the potential for inclusive growth and poverty eradication. The region is charting a novel development trajectory by harnessing the capabilities of its resources and people. However, despite these strides, climate change is anticipated to exacerbate poverty in SSA, potentially affecting 39.7 million people, unless meaningful climate and development solutions are enacted before 2050 (Jafino et al., 2020).

Energy consumption stands as a pivotal catalyst for economic growth, serving as a primary input in the industrial sector for the production of goods and services. Additionally, it constitutes a substantial portion of household consumption. However, despite its critical role, heightened energy consumption contributes to the accumulation of waste and emissions, emerging as significant contributors to

pollution. Consequently, sustained economic expansion raises profound environmental challenges, a connection that has predominantly been explored in light of the environmental Kuznets curve hypothesis (Al-Mulali et al., 2014; Dogan & Inglesi-Lotz, 2020; Phong et al., 2018).

Sustainable Development Goals (SDGs) number 7 explicitly underscores targets for affordable and clean energy. Consequently, incorporating renewable energy sources or those with minimal environmental impact emerges as a crucial imperative in economic development (Adebayo et al., 2021; Dong et al., 2017; Güney & Kantar, 2020; Khan et al., 2023; Pattiruhu, 2020). The consumption of renewable energy not only contributes to green economic growth but also mitigates pollution from the combustion of fossil fuels, thereby reducing carbon emissions (Akram et al., 2023; Khan et al., 2022, 2023). Moreover, these sources are environmentally friendly and renewable, ensuring sustained utilization without the fear of resource depletion (Adebayo et al., 2023).

Therefore, the acceleration of renewable energy expansion is imperative to ensure a climate-friendly energy transition, aligning with the climate action objectives outlined in SDG-13. While the impact of renewable energy consumption on greenhouse gas emissions is generally positive, it is essential to recognize that the overall reduction depends on various factors. These factors include the scale of renewable energy deployment, the transition away from fossil fuels, and the implementation of supportive policies and regulations (Adebayo & Ullah, 2023). In this latter aspect, evidence-based policymaking is crucial for informed and effective decision-making in this direction. The literature on the relationship between renewable energy consumption and environmental sustainability is vast and continually growing, supporting this process. However, it presents some critical gaps.

The present study delves into the dynamic relationship between renewable energy consumption and environmental sustainability in Sub-Saharan African countries from 2000 to 2020, contributing to the existing literature in four key aspects. Firstly, it considers the pivotal role of institutional and political factors, often overlooked in previous studies despite their significance for developing countries like those in SSA (see, e.g. Adebayo et al., 2021; Behboudi et al., 2017; Güney, 2021; Hu et al., 2023; Liu et al., 2023; Pattiruhu, 2020; Ullah et al., 2023; among others).

Secondly, while the empirical literature frequently employs models such as dynamic ordinary least squares, fixed effect, and random effect (see, e.g. Adebayo et al., 2021, Mahjabeen et al., 2020; Vasylieva et al., 2019, among others), these models may lack robustness in the presence of cross-sectional dependence and heterogeneity issues. To address this concern, the present study adopts the Augmented Mean Group (AMG) model.

Thirdly, the AMG estimators do not inherently provide the direction of causality among variables, a critical aspect for policy recommendations (Dumitrescu & Hurlin, 2012). Therefore, this paper incorporates the Granger non-causality test in panel data models to enhance the investigation of the link between renewable energy consumption and environmental sustainability and explore potential causality, a facet often overlooked in prior studies (see, e.g. Behboudi et al., 2017, Güney & Kantar, 2020; Lassoued, 2021; Pattiruhu, 2020; Vasylieva et al., 2019; among others).

Fourthly, this study controls for the potential effects of key variables like economic growth, population growth, institutional quality, and policy dummy factors often neglected in prior research on this topic.

This paper is structured as follows: Section 1 outlines the methodology employed, Section 2 delves into the empirical results, and Section 3 provides conclusions along with recommendations.

2. Methodology

2.1. Theoretical framework and empirical model

The theoretical framework employed in this study closely adheres to the specification outlined by Pattiruhu (2020). It elucidates the relationship between renewable energy consumption and environmental sustainability, relying on a variant of the Solow growth model specified as follows:

$$GHGE_{it} = \alpha_{it} + \beta_1 REC_{it} + \beta_2 Z_{it} + \epsilon_{it} \quad (1)$$

where $GHGE_{it}$ represents greenhouse gas emission (a measure of environmental sustainability) for country i at year t , REC_{it} stands for renewable energy consumption, Z_{it} denotes a vector of control variables for environmental sustainability, α_{it} is the constant, β_1 and β_2 show the slope coefficients, and ϵ_{it} is the error term.

The empirical model adopted in this study links renewable energy consumption and environmental sustainability, including other factors that affect environmental sustainability, as follows:

$$GHGE_{it} = f(REC_{it}, GDP_{it}, PG_{it}, IQ_{it}, PD) \quad (2)$$

where the vector of control variables includes the gross domestic product, GDP , as a measure of economic growth, population growth (PG), institutional quality (IQ_{it}), and a policy dummy (PD).

Equation (2) can be rewritten as:

$$GHGE_{it} = \alpha_{it} + \beta_1 REC_{it} + \beta_2 GDP_{it} + \beta_3 PG_{it} + \beta_4 IQ_{it} + \beta_5 PD + \epsilon_{it} \quad (3)$$

In this study, the dependent variable is environmental sustainability, quantified by total greenhouse gas emissions in kilotons (kt) of CO₂ equivalent. Renewable energy consumption is represented as the percentage of renewable energy in total final energy consumption. Economic growth is measured as the annual GDP growth rate, denoting the annual percentage growth of GDP at market prices based on constant local currency. Population growth is expressed as the exponential growth rate of the midyear population from year $t-1$ to t , presented as a percentage. The institutional quality is gauged through an index incorporating six indicators: voice and accountability (VA), government effectiveness (GE), control of corruption (CC), political stability and absence of violence/terrorism (PSAV), regulatory quality (RQ), and the rule of law (RL). The policy dummy variable assumes the value 0 from 2000 to 2015, corresponding to the Millennium Development Goals period, and 1 from 2016 to 2020, aligning with the implementation period of the SDGs. The interconnectedness between SDGs and environmental sustainability is emphasized, stressing the significance of adopting sustainable practices across various sectors, including energy.

The data for all variables were sourced from the World Development Indicators dataset, publicly accessible at <https://data.worldbank.org/>, with the exception of institutional quality data, which was retrieved from the World Governance Indicators dataset, available at <https://databank.worldbank.org/source/worldwide-governance-indicators>.

The dataset spans from 2000 to 2020, influencing the sample size, which encompasses 30 Sub-Saharan African countries: Angola, Benin, Botswana, Burkina Faso, Burundi, Cape Verde, Cameroon, Central African Republic, Chad, Comoros, Congo, Democratic Republic of Congo, Ethiopia, Gambia, Ghana, Ivory Coast, Kenya, Madagascar, Malawi, Mali, Mozambique, Namibia, Niger, Nigeria, Senegal, South Africa, Sudan, Tanzania, Togo, and Zambia. The study's conclusions are representative of the entire SSA region as it includes a sufficiently diverse set of countries from the Eastern, Western, Central, and Southern parts of the region.

2.2. Empirical strategy

Prior to conducting panel long-run estimates, the study conducted assessments for cross-sectional dependence, slope homogeneity, unit root presence in each series within the panel, and panel co-integration. The examination of cross-sectional dependence and slope homogeneity holds significant importance, as these factors influence the selection of robust empirical models in panel data analysis. Moreover, testing for unit roots in each series within a panel is essential to prevent the risk of spurious regression. Furthermore, mandatory testing for co-integration among variables is imperative for the subsequent discussion of long-run relationships.

2.2.1. Cross-sectional dependence test

Cross-sectional dependence, where all units in the same cross-section are correlated, has the potential to impact panel data. This phenomenon is often ascribed to unobserved common factors, spatial effects, and spillover effects from socioeconomic interactions (Chudik & Pesaran, 2015; Pesaran, 2004). Consequently, in the context of panel data analysis, it is recommended to test for cross-sectional dependence due to its capacity to yield inconsistent estimates and provide misleading information (Bilgili & Ulucak, 2018; Pesaran, 2004).

In this study, the Cross-Sectional Dependence (CD) test proposed by Pesaran (2004) was used to identify this potential issue. The empirical literature also mentions the Breusch and Pagan (1980) Lagrange Multiplier (LM) test. However, it may be inconsistent and unsuitable when the number of cross-sectional units exceeds the number of time periods. In the case of this study, there are 30 cross-sectional units/countries and 21 time periods/years.

Thus, Pesaran (2004) introduced the CD test to adjust the bias in the LM test as follows:

$$CD = \sqrt{\frac{2T}{N(N-1)}} \sum_{i=1}^{N-1} \sum_{j=i+1}^N \frac{(T-k)\hat{\rho}_{ij}^2 - E[(T-k)\hat{\rho}_{ij}^2]}{\text{Var}[(T-k)\hat{\rho}_{ij}^2]} \quad (4)$$

Where N is the sample size, T denotes the time period, k denotes the identity matrix, and $\hat{\rho}_{ij}$ denotes the pairwise correlation coefficient derived from Ordinary Least Squares estimation for each cross-section dimension, i , given $j = i + 1$. Accordingly, the CD statistic is tested against the null hypothesis of no cross-sectional dependence.

2.2.2. Slope homogeneity test

Homogeneous panel data models operate under the assumption that all individuals/countries share identical model parameters. Conversely, heterogeneous models allow for individual variations in any or all of the model parameters. Given this consideration, when dealing with heterogeneous panel data, reliance on slope homogeneity may yield results that are unreliable and untrustworthy. Therefore, to scrutinize the phenomenon of slope homogeneity as outlined in equations (5), (6), and (7), this study employed the Swamy test method proposed by Pesaran and Yamagata (2008) as follows:

$$\bar{V} = \sqrt{N} \left[\frac{N^{-1} \bar{S} k}{\sqrt{2k}} \right] \quad (5)$$

$$\bar{V}_{adj} = \sqrt{N} \left[\frac{N^{-1} \bar{S} k}{\sqrt{\frac{2k(T-k-1)}{T-1}}} \right] \quad (6)$$

$$S = \sum_{i=1}^N \left(\hat{\beta}_i - \tilde{\beta}_{WFE} \right)' \frac{X_i' M_i X_i}{\delta^2} \left(\hat{\beta}_i - \tilde{\beta}_{WFE} \right) \quad (7)$$

\bar{S} , \bar{S}_{adj} and S are the standardized dispersion, the biased-adjusted statistics and the Swamy statistic (based on the dispersion of individual slope estimates), respectively. $\hat{\beta}_i$ stands for the pooled Ordinary Least Squares regression coefficients for each country i ranging from 1 to N , and $\tilde{\beta}_{WFE}$ denotes the weighted fixed effect pooled estimator. Additionally, M_i , δ^2 and k are, respectively, the identity matrix, the estimate of σ_i^2 and the number of independent variables. Accordingly, the Swamy statistic value is tested against the null hypothesis of slope homogeneity.

2.2.3. Panel unit root test

Cross-sectional dependence invalidates first-generation panel unit root tests such as Levin-Lin Chu, Im-Pesaran-Shin, augmented Dickey-Fuller, and Phillips-Perron (Pesaran, 2007). Consequently, in this investigation, Pesaran's (2007) second-generation panel unit root tests, specifically the cross-sectional augmented Dickey-Fuller (CADF) and the cross-sectional augmented Im-Pesaran-Shin (CIPS), which are robust in the presence of cross-sectional dependence, were employed. The formula for calculating the CADF statistic is as follows:

$$\Delta y_{i,t} = \alpha_i + \beta_i y_{i,t-1} + \gamma_i \bar{y}_{t-1} + \delta_i \Delta \bar{y}_{i,t} + \epsilon_{it} \quad (8)$$

Where \bar{y}_{t-1} and $\Delta \bar{y}_{i,t}$ are the cross-sectional averages of lagged levels and the first differences of individual series, respectively. This can be explicitly stated as follows:

$$\bar{y}_{t-1} = \frac{1}{N} \sum_{i=1}^N y_{i,t-1} \quad (9)$$

$$\Delta \bar{y}_{i,t} = \frac{1}{N} \sum_{i=1}^N \Delta y_{i,t} \quad (10)$$

The CADF statistic can be computed by averaging the CADFi as follows:

$$CIPS = \frac{1}{N} \sum_{i=1}^N CADFi \quad (11)$$

CADFi, however, is the t-statistic for the CADF regression as defined by equation (8).

Accordingly, the variables are stationary if the absolute values of CIPS and CADF statistics are greater than the critical values at a 5 percent significant level.

2.2.4. Panel co-integration test

This study employed Westerlund (2007) panel co-integration test, which is robust in the presence of cross-sectional dependence. It is based on the following error-correction model:

$$\Delta y_{i,t} = \delta_i' d_t + \rho_i (y_{i,t-1} - \beta_i' X_{i,t-1}) + \sum_{j=1}^k \varphi_{ij} y_{i,t-j} + \sum_{j=1}^k \varphi_{ij} X_{i,t-j} + \mu_{i,t} \quad (12)$$

where ρ_i is the adjustment term that controls how quickly the system returns to equilibrium.

The test is built on the least-squares estimates of ρ_i with the null hypothesis assuming no co-integration. Accordingly, the groups mean statistics can be computed as follows:

$$G\tau = \frac{1}{N} \sum_{i=1}^N \frac{\rho_i}{\text{Se}(\hat{\rho}_i)} \quad (13)$$

$$G\alpha = \frac{1}{N} \sum_{i=1}^N \frac{T\rho_i}{\rho'_i(1)} \quad (14)$$

It can be concluded that co-integration exists in at least one cross-sectional unit of the panel when $G\tau$ and $G\alpha$ statistics reject the null hypothesis.

In the meanwhile, the following formulas are used to extract the panel statistics:

$$P\tau = \frac{\hat{\rho}_i}{\text{Se}(\hat{\rho}_i)} \quad (15)$$

$$P\alpha = T\hat{\rho} \quad (16)$$

It is possible to infer that co-integration exists in the whole panel if the null hypothesis is rejected.

2.2.5. Panel long-run estimates

Conventional panel regression techniques could be inconsistent and biased in the presence of cross-sectional dependency (Paramati et al., 2017; Pesaran & Smith, 1995). To derive panel-specific slope coefficients, the MG approach utilizes the Ordinary Least Squares technique on each panel, followed by averaging the panel-specific coefficients.

However, the MG estimator lacks insights into potential common factors within the panel data. The Common Correlated Effects Mean Group estimator, robust to cross-sectional dependence and slope homogeneity, was initially developed by Pesaran (2006). It incorporates common unobserved effects(f_t) and the averages of both independent and dependent variables.

$$y_{it} = \alpha_i + \beta_i X_{it} + \gamma_i \bar{y}_{it} + \delta_i \bar{X}_{it} + c_i f_t + \varepsilon_{it} \quad (17)$$

Where y_{it} and X_{it} are variables; β_i represents the country-specific slope; f_t denotes the unobserved common factor with heterogeneous factor; α_i and ε_{it} are the intercept and error terms, respectively.

Furthermore, the Common Correlated Effects Mean Group and AMG estimator, developed by Eberhardt and Bond (2009), exhibits robustness even in the presence of cross-sectional dependence and slope heterogeneity. The common dynamic effect parameter in equation (17) specifies the unobservable common factors (f_t) captured by the AMG estimator. To illustrate, consider the first-difference Ordinary Least Squares equation (18) for the AMG estimator:

$$\Delta y_{it} = \alpha_i + \beta_i \Delta X_{it} + \sum_{t=1}^T \theta_t D_t + \varphi_i f_t + \varepsilon_{it} \quad (18)$$

Δ stands for the first-difference operator, β_i for country-specific coefficients and θ_t for time-specific coefficients.

Then, using the across-panel averaged group-specific parameters, the AMG estimator is obtained:

$$AMG = \frac{1}{N} \sum_{i=1}^N \tilde{\beta}_i \quad (19)$$

In equation (19), $\tilde{\beta}_i$ is the estimator of β_i in equation (18).

This study used the AMG approach to investigate the long-run parameters because its performance in Monte Carlo simulation is unbiased and efficient for different number of observations (N) and time settings (T).

2.2.6. Causality test

The determination of causality among variables, a crucial factor in shaping policy recommendations, is not delineated by the AMG and Common Correlated Effects Mean Group estimators. In response, this study employs Dumitrescu and Hurlin's (2012) Granger non-causality test within a panel data framework to scrutinize the connection between renewable energy consumption and environmental sustainability, shedding light on potential causal relationships. This test is favored due to its suitability for Monte Carlo simulations, even in the presence of cross-section dependencies. The underlying vector autoregressive model on which the test is based renders it suitable for a balanced and heterogeneous panel.

The panel linear model where a pair-up of the variables asy_{it} and X_{it} is presented as:

$$y_{it} = \sum_{r=1}^R \beta_i^{(k)} y_{it-r} + \sum_{r=1}^R \gamma_i^{(k)} x_{it-r} + \varepsilon_{it} \quad (20)$$

where, k denotes the lag length, $\beta_i^{(k)}$ is the autoregressive parameter, and $\gamma_i^{(k)}$ is the regression coefficient that adjusts within the group with a normal, independent and identically distributed error term (ε_{it}) for each cross-section (i) at the time (t). Given that the null hypothesis of non-causality and the alternative hypothesis are, respectively, H_0 and H_1 , the expression is given as:

$$H_0 = \gamma_i = 0, \forall i = 1, 2N \quad (21)$$

$$H_1 = \gamma_i = 0, \forall i = 1, 2N1; \gamma_i \neq 0, \forall i = N1 + 1, N1 + 2N \quad (22)$$

As $\gamma_i = (\gamma_i^1 \dots \gamma_i^k)$, $N1 = N$ indicates that the causality of any member of the panel, but $N1 = 0$, points out causality within cross-sections as the value $N1/N$ is reasonably less than one.

3. Results and discussion

This section presents and discusses the empirical results of the study, utilizing STATA 15 software for data analysis. The following sub-sections delve into both descriptive and econometric results.

3.1. Descriptive statistics

This section provides essential descriptive statistics to offer insights into the nature of the data employed for the empirical analysis. All data statistics are derived from observations within the study sample, spanning the period 2000–2020 and encompassing 30 SSA countries.

Table 1 presents descriptive statistics, revealing fluctuations in our independent variable of interest. The mean score for renewable energy consumption (REC) stands at 67.32 percent of total final energy consumption from renewable sources. This result is notably positive when compared to the global average of 11.2 percent for renewable energy's share of total final energy consumption (C2ES, 2019). However, it is imperative to build upon and fortify this outcome to align with the overarching global objective of achieving net-zero emissions by 2050.

Moreover, the overall, between, and within standard deviations of REC are 22.74, 22.56, and 4.91, respectively. This suggests that the variability in the renewable energy share of total final energy consumption is more pronounced among countries (with a between standard deviation of 22.56) than over time within a single country (with a within standard deviation of 4.91). In other words,

Table 1. Statistical description of the variables in the selected Sub-Saharan African countries

Variable	Observation	Panel characteristics	Mean	Std. deviation	Minimum	Maximum
GHGE	N = 630 n = 30 T =21	Overall	57923.20	92100.61	320.00	525050.00
		Between		92484.23	444.97	470379.10
		Within		14182.94	68325.90	121318.40
REC	N = 630 n = 30 T =21	Overall	67.32	22.74	9.78	98.34
		Between		22.55	11.50	96.65
		Within		4.91	49.03	85.26
PG	N = 630 n = 30 T =21	Overall	2.63	0.62	0.26	3.91
		Between		0.59	1.33	3.77
		Within		0.21	1.35	3.46
GDP	N = 630 n = 30 T =21	Overall	4.18	4.50	-36.39	33.63
		Between		1.61	1.23	8.80
		Within		4.21	-33.45	31.64
VA	N = 630 n = 30 T =21	Overall	-0.47	0.69	-1.85	0.97
		Between		0.68	-1.71	0.84
		Within		0.20	-1.18	0.20
GE	N = 630 n = 30 T =21	Overall	-0.77	0.56	-1.89	0.66
		Between		0.54	-1.63	0.45
		Within		0.16	-1.29	0.02
CC	N = 630 n = 30 T =21	Overall	-0.64	0.61	-1.57	1.24
		Between		0.60	-1.43	0.89
		Within		0.17	-1.16	-0.09
PSNV	N = 630 n = 30 T =21	Overall	-0.61	0.93	-2.70	1.22
		Between		0.87	-2.13	1.03
		Within		0.37	-2.08	0.58
RQ	N = 630 n = 30 T =21	Overall	-0.64	0.53	-1.84	0.90
		Between		0.52	-1.48	0.67
		Within		0.14	-1.10	-0.16
RL	N = 630 n = 30 T =21	Overall	-0.67	0.59	-1.85	0.67
		Between		0.58	-1.67	0.53
		Within		0.17	-1.13	-0.07

Note: GHG= Greenhouse Gas Emission; REC= Renewable Energy Consumption; PG= Population Growth; GDP= Gross Domestic Product; VA= Voice and Accountability; GE= Government Effectiveness; CC= Control of Corruption; PSNV= Political Stability and Absence of Violence; RQ,= Regulatory Quality and RL= Rule of Law. Source: Authors' calculations.

temporal variations are relatively small compared to cross-sectional variations, aligning with the pattern observed in most variables considered in this study. Additionally, the results reveal an overall maximum REC score of 98.34 and an overall minimum REC score of 9.78. Among the sampled countries, the Democratic Republic of Congo exhibits the highest renewable energy consumption in total final energy, while South Africa has the lowest. These findings underscore significant disparities in renewable energy consumption among the countries in the region, necessitating prompt efforts to address these gaps.

The correlation matrix in Table 2 dispels concerns of collinearity or multi-collinearity. The highest correlation coefficient between REC and all other explanatory variables is less than 0.8, the threshold for high correlation. This indicates that neither collinearity nor multi-collinearity poses an issue in our data.

Table 2. Correlation among variables

Variable	GHGE	REC	PG	GDP	VA	GE	CC	PSNV	RQ	RL	PD
GHGE	1.00										
REC	-0.21	1.00									
PG	-0.26	0.54	1.00								
GDP	-0.02	0.11	0.21	1.00							
VA	0.09	-0.62	-0.41	0.05	1.00						
GE	0.21	-0.65	-0.41	0.08	0.81	1.00					
CC	0.01	-0.69	-0.52	0.03	0.83	0.86	1.00				
PSNV	-0.19	-0.55	-0.23	0.05	0.75	0.68	0.73	1.00			
RQ	0.17	-0.63	-0.39	0.03	0.82	0.91	0.84	0.69	1.00		
RL	0.02	-0.63	-0.38	0.05	0.87	0.89	0.91	0.80	0.85	1.00	
PD	0.06	-0.08	-0.04	-0.21	0.20	-0.02	-0.01	-0.09	-0.04	0.01	1.00

Note: GHG= Greenhouse Gas Emission; REC= Renewable Energy Consumption; PG= Population Growth; GDP= Gross Domestic Product; VA= Voice and Accountability; GE= Government Effectiveness; CC= Control of Corruption; PSNV= Political Stability and Absence of Violence; RQ= Regulatory Quality; RL= Rule of Law and PD=Policy Dummy. Source: Authors' calculations.

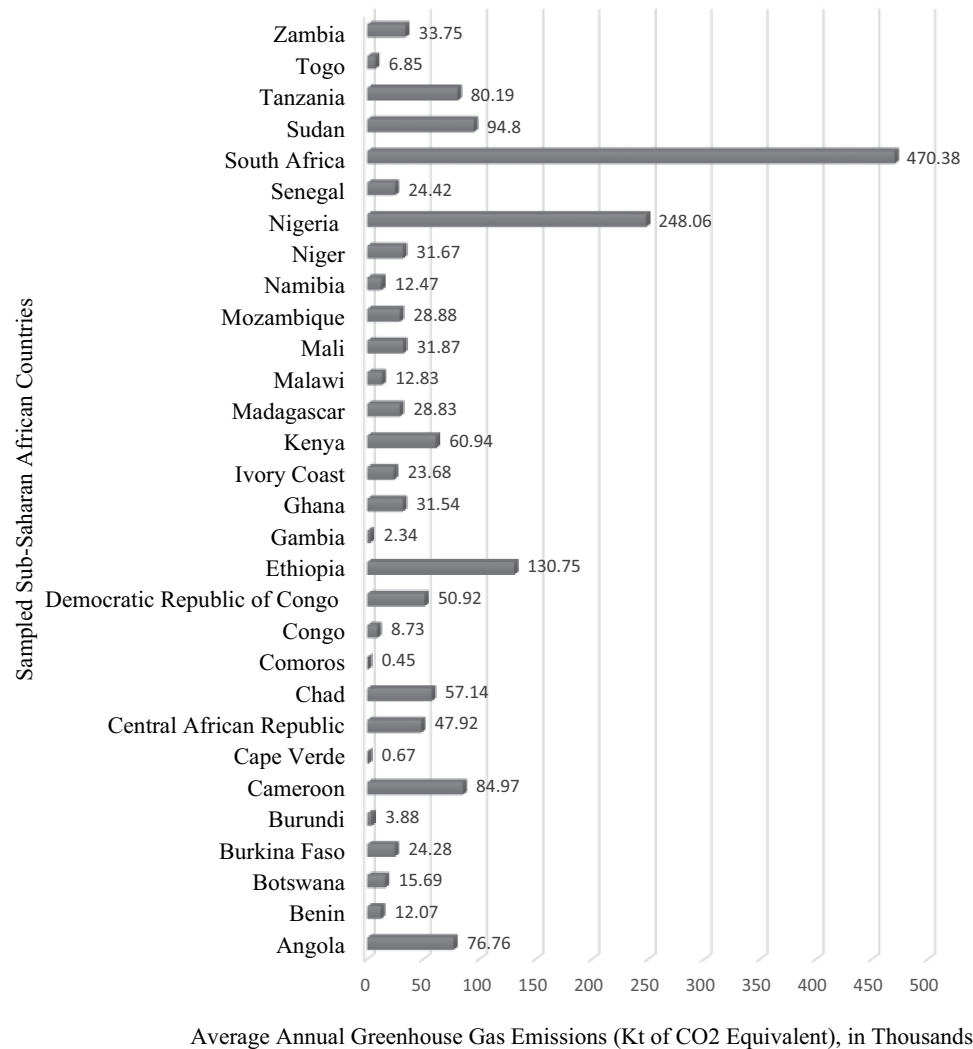
Figures 1 to 4 visually illustrate the annual average trends of GHGE and REC by country and region. Figure 1 highlights that the three highest average annual greenhouse gas emissions in the study period at the country level are 470,379.00 kt for South Africa, the highest emitter, followed by Nigeria at 248,055.00 kt, and Ethiopia at 130,747.00 kt. Conversely, the three lowest average annual greenhouse gas emissions are 444.97 kt in Comoros, the lowest emitter, followed by Cape Verde at 671.58 kt and Gambia at 2,337.16 kt. The results reveal substantial variations in greenhouse gas emissions among the sampled countries in the region, attributed to differences in key economic sectors, energy consumption patterns, investments in emission reduction technologies, among other factors. For instance, as reported by the Government of South Africa (2020), the strategic economic sectors in the country, including mining, transport, energy, manufacturing, and agriculture, are highly susceptible to emissions.

Moreover, Figure 2 illustrates that the three highest values for average annual renewable energy consumption during the study period are attributed to the Democratic Republic of Congo (96.65%), Ethiopia (92.99%), and Burundi (92.47%). Conversely, the three lowest values for average annual renewable energy consumption are found in South Africa (11.50%), Cape Verde (26.55%), and Botswana (30.13%). Notably, the Democratic Republic of Congo boasts the highest average annual renewable energy consumption as a percentage of total energy consumption, while South Africa records the lowest. These disparities stem from variations in energy development strategies pursued by different countries. For example, in South Africa, coal-fired power plants generate approximately 42,000 MW, constituting around 85 percent of the country's electricity production (ITA, 2022b). In contrast, in the Democratic Republic of Congo, hydroelectricity accounts for 96 percent of domestic energy production, with a significant portion generated by the Inga I and Inga II dams in the Kongo Central province (ITA, 2022a).

The descriptive statistics raised concerns about potential regional specificities. Consequently, we generated four regional dummies for the sampled SSA countries to examine whether there were any regional variations in average annual greenhouse gas emissions and average annual renewable energy consumption during the analyzed period.

As depicted in Figure 3, the highest average annual greenhouse gas emissions were observed in Southern Africa (95,665.60 kt), while the lowest were in Central Africa (38,432.90 kt). Furthermore, Figure 4 illustrates that Central Africa recorded the highest

Figure 1. Average annual greenhouse gas emissions by country: source: authors' calculations.



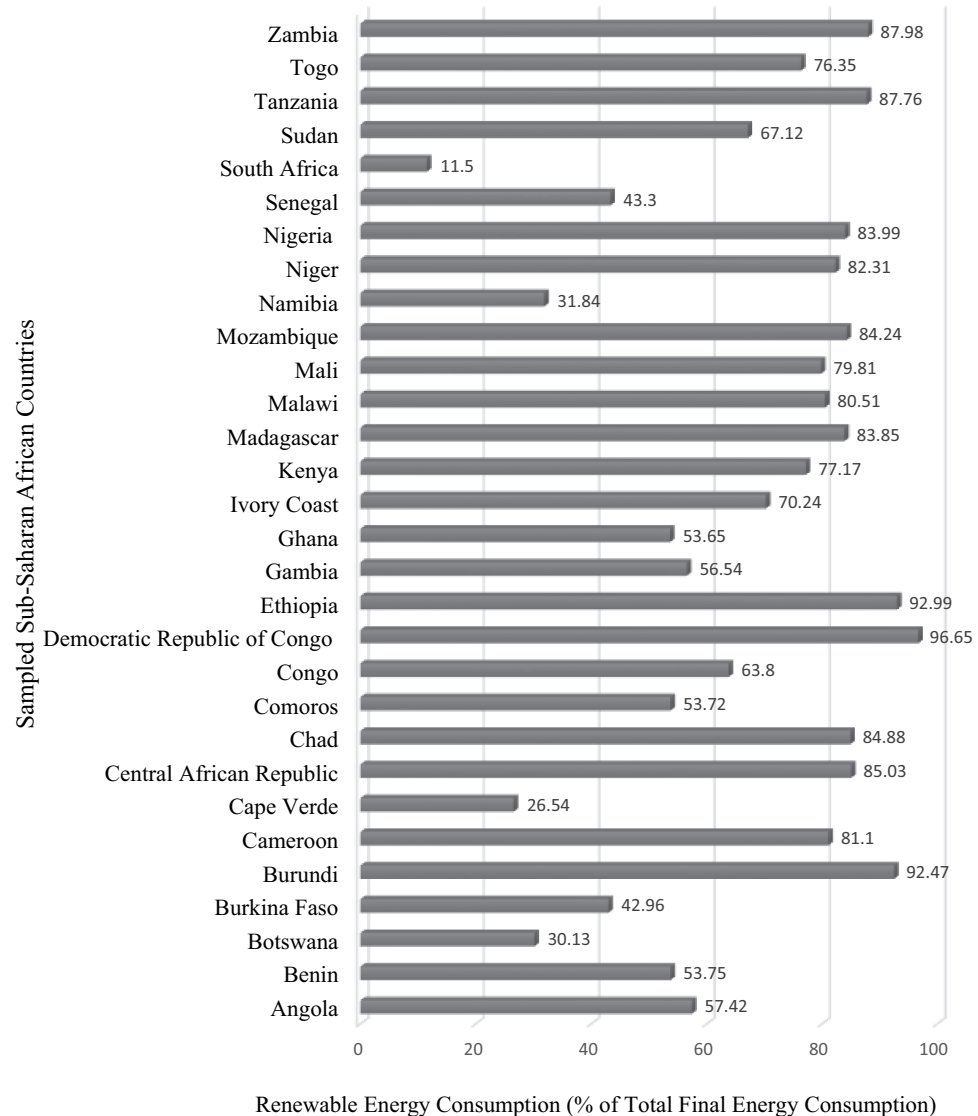
average annual renewable energy consumption as a percentage of total energy consumption (78.64%), while the lowest percentage share was in Southern Africa (54.37%).

Generally, the findings from Figures 3 and 4 bear significant implications for the empirical analysis of the dynamic linkage between renewable energy consumption and greenhouse gas emissions in SSA countries. Specifically, regions with the highest renewable energy consumption tend to exhibit lower greenhouse gas emissions, and conversely.

3.2. Econometric results

This study rejected the null hypothesis of no cross-sectional dependence at a 1 percent significance level, as indicated by the results from Pesaran's (2004) CD test (Table 3). In essence, the panel data exhibits compelling evidence of cross-sectional dependence. This outcome is attributed to the impact of specific unobserved common factors, spatial effects, and spillover effects arising from socioeconomic interactions. These elements introduce inconsistencies in the estimates, prompting the study to take them into account in subsequent stages of the analysis.

Figure 2. Average renewable energy consumption by country: source: authors' calculations.



The utilized data also exhibit slope heterogeneity, as revealed by the Pesaran and Yamagata (2008) test across all six equations. Notably, all test statistics attain significance at the 1 percent level (Table 4).

Owing to slope heterogeneity and cross-sectional dependence in the data, the first-generation unit root tests for stationarity in the variables were deemed unsuitable for this study. Consequently, CIPS and CADF test statistics, representing second-generation unit root tests, were adopted. As depicted in Table 5, certain variables demonstrate stationarity at the level, while others exhibit stationarity at the first difference. In other words, they are integrated at orders 0 and 1, respectively, commonly denoted as $I(0)$ and $I(1)$. The subsequent analysis delves into whether these variables manifest co-integration or the long-run linear interdependence of their trajectories.

Finally, the study identified a potential long-run relationship among the variables using the Westerlund (2007) co-integration test. The results in Table 6 confirm the presence of co-integration among all variables in the six equations. Subsequently, the study estimated the long-

Figure 3. Average annual greenhouse gas emission by region.

source: authors' calculations.

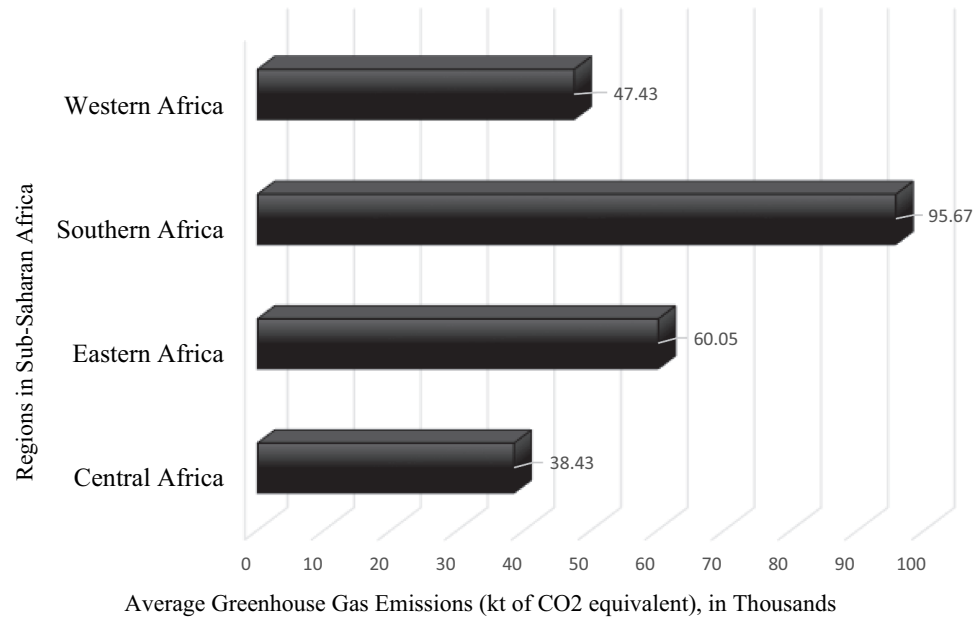
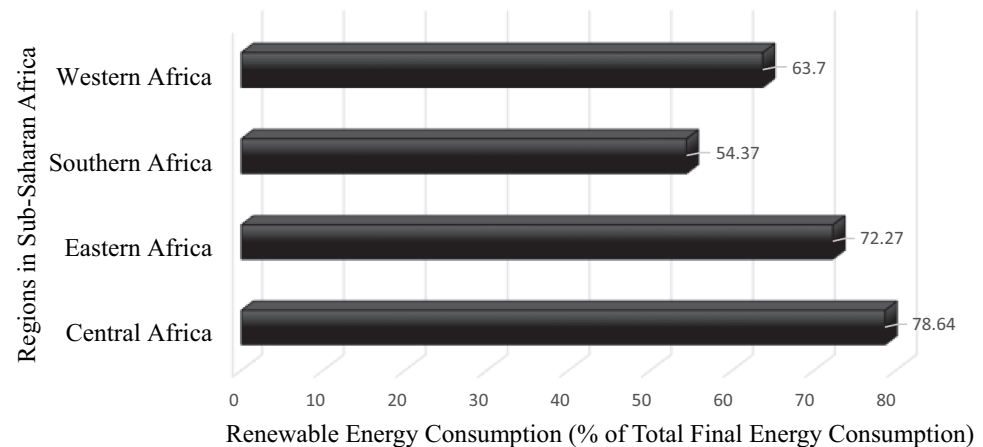


Figure 4. Average annual renewable energy consumption by region.

source: authors' calculations.



run coefficients of the heterogeneous panel data using the augmented mean group (AMG) estimator. This was done after addressing cross-sectional dependence, slope heterogeneity, confirming the variables' stationarity, and verifying co-integration properties. Six separate equations were estimated using the AMG estimator, each incorporating one of the six indicators of institutional quality.

Wald test statistics in all six equations displayed significant probability values, underlining the robustness of the model and the long-run association among the variables. These estimates were further explored to examine long-term coefficients, detailed in Table 7.

Table 7 reveals that renewable energy consumption (REC) has a negative and statistically significant impact on greenhouse gas emissions (GHGE) in Sub-Saharan African countries. This suggests that renewable energy consumption contributes positively to environmental sustainability in the region, aligning with findings from previous studies (see, e.g. Adebayo, 2022; Adebayo

Table 3. Pesaran (2004) cross-sectional dependence test results

Variable	CD-test	p-value	Correlation (mean ρ)	Absolute correlation
GHGE	67.27 ***	0.000	0.704	0.795
REC	38.52***	0.000	0.403	0.537
GDP	15.90***	0.000	0.166	0.250
PG	4.45***	0.000	0.047	0.485
PD	95.58***	0.000	1.000	1.000

Note: GHG= Greenhouse Gas Emission; REC= Renewable Energy Consumption; GDP= Gross Domestic Product; PG= Population Growth; and PD=Policy Dummy. ***indicates significance at 1% level. Source: Authors' calculations.

Table 4. Pesaran and Yamagata (2008) slope homogeneity test results

Model/Equations	Statistics	Values	P-value
Model-1 (IQ=VA)	Delta	15.188***	0.000
	adj.	18.601***	0.000
Model-2 (IQ=GE)	Delta	14.836***	0.000
	adj.	18.170***	0.000
Model-3 (IQ=CC)	Delta	15.383***	0.000
	adj.	18.841***	0.000
Model-4 (IQ=PSNV)	Delta	15.880***	0.000
	adj.	19.448***	0.000
Model-5 (IQ=RQ)	Delta	15.774***	0.000
	adj.	19.319***	0.000
Model-6 (IQ=RL)	Delta	15.234***	0.000
	adj.	18.657***	0.000

Note: IQ= Institutional Quality; VA= Voice and Accountability; GE= Government Effectiveness; CC= Control of Corruption; PSNV= Political Stability and Absence of Violence; RQ,= Regulatory Quality; and RL= Rule of Law. ***indicates significance at a 1% level. Source: Authors' calculations.

Table 5. Pesaran (2007) second-generation panel unit-root test results

Variable	CIPS test Statistic		CADF test Statistic		Order
	Level	First difference	Level	First difference	
GHGE	-2.580 ***	-	-2.208***	-	I(0)
REC	-1.962	-3.879***	-1.848	-2.975***	I(1)
PG	-3.265***	-	-2.190***	-	I(0)
GDP	-3.793	-	-2.257***	-	I(0)
VA	-1.857	-4.456***	-1.559	-2.837	I(1)
GE	-2.389***	-	-2.677***	-	I(0)
CC	-1.926	-4.969***	-1.659	-2.139***	I(1)
PSNV	-2.877***	-	-2.174***	-	I(0)
RQ	-2.010	-5.012***	-1.207	-2.247***	I(1)
RL	-1.908	-4.983***	-1.604	-2.181***	I(1)

Note: GHG= Greenhouse Gas Emission; REC= Renewable Energy Consumption; PG= Population Growth; GDP= Gross Domestic Product; VA= Voice and Accountability; GE= Government Effectiveness; CC= Control of Corruption; PSNV= Political Stability and Absence of Violence; RQ,= Regulatory Quality and RL= Rule of Law. ***indicates significance at a 1% level. Source: Authors' calculations.

Table 6. Westerlund (2007) co-integration test results

Ho: No co-integration
 Ha: Some panels are co-integrated

Co-integrating vector: Panel specific
 Panel means: Included
 Time trend: Not included
 AR parameter: Panel specific
 Number of panels = 30
 Number of periods = 21

	Model-1 (IQ=VA)		Model-2 (IQ=GE)		Model-3 (IQ=CC)	
	Statistic	P-value	Statistic	P-value	Statistic	P-value
Variance ratio	2.620***	0.004	3.522 ***	0.000	3.178***	0.001
	Model-4 (IQ=PSNV)		Model-5 (IQ=RQ)		Model-6 (IQ=RL)	
	Statistic	P-value	Statistic	P-value	Statistic	P-value
Variance ratio	2.481***	0.007	2.909***	0.002	3.121***	0.001

Note: IQ= Institutional Quality; VA= Voice and Accountability; GE= Government Effectiveness; CC= Control of Corruption; PSNV= Political Stability and Absence of Violence; RQ= Regulatory Quality; and RL= Rule of Law. ***indicates significance at 1% level. Source: Authors' calculations.

et al., 2021; Behboudi et al., 2017; Güney & Kantar, 2020; Lassoued, 2021; Mahjabeen et al., 2020; Pattiruhu, 2020; Vasylieva et al., 2019, among others). Additionally, alongside renewable energy consumption, enhancing non-renewable energy efficiency is crucial for environmental sustainability (Ozkan et al., 2023). While Sub-Saharan African countries display encouraging patterns in renewable energy consumption, ongoing efforts are vital to advance green transitions as environmental challenges demand international cooperation.

Furthermore, the policy dummy (PD) variable exhibits a positive and statistically significant impact on greenhouse gas emissions in Sub-Saharan African countries. This effect is particularly pronounced when accounting for aspects of institutional quality such as government effectiveness (GE), regulatory quality (RQ), and the rule of law (RL). The implication is that greenhouse gas emissions have significantly increased after 2015 or during the SDGs period compared to the Millennium Development Goals period in Sub-Saharan African countries. Thus, environmental sustainability has been negatively affected during the SDGs period. Recognizing environmental sustainability as a complex issue, the study acknowledges ongoing global efforts and collaboration. While progress has been made in some areas during the SDGs period, challenges and setbacks underscore the imperative for accelerated, coordinated action at local, national, and international levels to achieve the goals outlined in the SDGs.

Finally, the study conducted a causality test between the independent variable and the dependent variable using the Dumitrescu and Hurlin (2012) panel Granger non-causality test approach. Results in Table 8 reveal bidirectional causality between renewable energy consumption and greenhouse gas emissions (environmental sustainability) in SSA. This implies that historical information on renewable energy consumption can significantly explain the future dynamics of greenhouse gas emissions (environmental sustainability) in the panel countries. Moreover, bidirectional causality suggests that either being environmentally sustainable is a cause of renewable energy consumption or renewable energy consumption is a cause of environmental sustainability.

Table 7. Heterogeneous parameter estimates using the augmented mean group estimator (Eberhardt & Bond, 2009; Eberhardt & teal, 2010) results

Variables	Model-1 (IQ=VA)		Model-2 (IQ=GE)		Model-3 (IQ=CC)	
	Coefficients	P-value	Coefficients	P-value	Coefficients	P-value
REC	−0.007***	0.001	−0.007***	0.002	−0.007***	0.001
PG	0.032	0.649	0.054	0.392	0.026	0.702
GDP	0.001	0.136	0.001	0.316	0.001	0.069
IQ	−0.025	0.363	0.021	0.331	−0.013	0.659
PD	0.012	0.399	0.379***	0.000	0.011	0.407
__00000R_c	0.759***	0.000	0.850***	0.000	0.859***	0.000
__000007_t	0.006	0.065	0.002	0.512	0.002	0.477
_cons	10.139***	0.000	10.235***	0.000	10.172***	0.000
Wald chi2(5)	14.700**	0.012	57.070***	0.000	14.740**	0.012
Variables	Model-4 (IQ=PSNV)		Model-5 (IQ=RQ)		Model-6 (IQ=RL)	
	Coefficients	P-value	Coefficients	P-value	Coefficients	P-value
REC	−0.008***	0.001	−0.008***	0.002	−0.008***	0.002
PG	0.008	0.13	0.044	0.502	0.066	0.350
GDP	0.001	0.230	0.001	0.305	0.001	0.289
IQ	−0.013	0.315	−0.011	0.661	−0.003	0.933
PD	0.006	0.621	0.375***	0.000	0.336***	0.000
__00000R_c	0.921***	0.000	0.859***	0.000	0.775***	0.000
__000007_t	0.003	0.322	0.003	0.227	0.004**	0.043
_cons	10.270***	0.000	10.201***	0.000	10.201***	0.000
Wald chi2(5)	14.46**	0.013	51.820***	0.000	55.700***	0.000

Number of obs = 630
 Number of groups = 30
 Observation per group: Minimum = 21
 Average = 21.0
 Maximum = 21

Note: REC= Renewable Energy Consumption; PG= Population Growth; GDP= Gross Domestic Product; IQ=Institutional Quality; PD=Policy Dummy; VA= Voice and Accountability; GE= Government Effectiveness; CC= Control of Corruption; PSNV= Political Stability and Absence of Violence; RQ= Regulatory Quality and RL= Rule of Law. ***, **indicates significance at 1% and 5% levels. Source: Authors' calculations.

Table 8. Dumitrescu and Hurlin (2012) panel granger non-causality test

Null Hypothesis	W-Stat.	Prob.	Direction of causality
REC does not Granger-cause GHGE	10.2768***	0.0000	with feedback
GHGE does not Granger-cause REC	12.2979***	0.0000	

***, **indicates significance at 1% and 5% levels. Source: Authors' calculations.

4. Conclusions

The introduction of the SDGs has propelled environmental sustainability and greenhouse gas emission reduction to the forefront of the global policy agenda. Consequently, the adverse impacts of energy use have garnered significant attention and are recognized as a critical policy concern. The overarching objective of global climate policy has been to promote renewable energy consumption. Acknowledging the often overlooked institutional and political factors in the literature, this study contributes to the existing knowledge on the relationship between renewable energy consumption and environmental sustainability. By doing so, it aims to mitigate bias in regression

estimates arising from omitted variables in earlier research. The empirical estimation of the model also accounts for issues of cross-sectional dependence, slope heterogeneity, and co-integration.

This study investigates the dynamic linkages between renewable energy consumption and environmental sustainability in 30 Sub-Saharan African countries, utilizing annual data spanning from 2000 to 2020 and employing an augmented mean group (AMG) estimator. Additionally, Dumitrescu and Hurlin's (2012) Granger non-causality test is applied, given that the AMG estimator does not provide information on the direction of causality among variables crucial for policy recommendations.

The empirical results reveal a significant negative impact of renewable energy consumption on greenhouse gas emissions in Sub-Saharan African countries, indicating that renewable energy consumption positively influences environmental sustainability in the region. Furthermore, a bi-directional causality is identified between renewable energy consumption and greenhouse gas emissions. The policy dummy variable also indicates a positive and statistically significant impact on greenhouse gas emissions, especially when accounting for aspects of institutional quality. This suggests an increase in greenhouse gas emissions after 2015, or during the SDGs period, in Sub-Saharan African countries, negatively affecting environmental sustainability.

Based on these findings, the study puts forth policy recommendations for promoting the positive impact of renewable energy consumption on environmental sustainability in the region. Policymakers in Sub-Saharan African countries are urged to develop energy policies encouraging renewable energy consumption, potentially through subsidies and tax incentives. Diversification and development of renewable energy sources should be prioritized to meet increasing energy demands in an environmentally sustainable manner. High-emitting countries, particularly in Southern Africa, such as South Africa, are encouraged to invest in renewable energy production and consumption to mitigate greenhouse gas emissions. Additionally, the worsening environmental sustainability situation during the post- Millennium Development Goals period suggests that SDGs policies should be complemented with substantial investments in environmentally friendly technologies to curb the effects of greenhouse gas emissions. Governments in Sub-Saharan African countries should engage in effective environmental advocacy strategies and collaborate internationally to attract global climate finances for emissions reduction.

While this study provides valuable insights, it is not without limitations. Relying solely on historical data for renewable energy consumption, the study acknowledges the need to consider other factors, including energy efficiency, land use, technological advancements, and global cooperation, for a more comprehensive understanding of the dynamics shaping future greenhouse gas emissions. Additionally, generating micro-level evidence could further enrich the literature on this topic.

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Disclosure statement

No potential conflict of interest was reported by the author(s).

Data availability statement

All the data used for this study is openly available in the World Development Indicators data set, at <https://data.worldbank.org/>, except for the data on institutional quality, which is from the World Governance Indicators data set available at <https://datatabank.worldbank.org/source/worldwide-governance-indicators/>.

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