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Investigating the nexus of energy consumption, economic growth and carbon emissions in selected african countries

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A B S T R A C T

The study is focused on Sustainable Development Goals (SDGs) 7, 8, and 13. At the nexus of energy consumption, economic growth, and carbon emissions, we investigated the interactive effect of energy consumption and economic growth on carbon emissions for seventeen selected African countries using static panel estimation techniques using annual data from 2000 to 2017. The result shows that an increase in energy consumption positively affects economic growth and negatively affects carbon emissions. However, the impact of energy consumption on economic growth is greater than its adverse environmental effect. We found that economic growth (due to the energy transition in Africa) reduces or dampens the negative effect of energy usage on the environment (indirectly, mitigating carbon emissions). A notable implication of our finding is that the transition to renewable energy is moderating the adverse effects of increasing energy consumption and economic growth on the environment. So, in applying the energy intensity theory to sub-Saharan Africa, a modification is proposed: carbon emissions are directly proportional to the amount of fossil fuel energy consumed per unit of output. We recommend the prioritization of economic growth and productive use of energy towards effectively reducing the negative impact of energy consumption on the environment. Future studies could consider increasing the number of countries, and, if data is available, an artificial intelligence experiment could be undertaken to check the reliability of previous results. We also suggest that future studies consider investigating the persistence of emissions using energy and growth as key independent and moderating variables.

Credit authors statement

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1. Introduction

Energy is critical to sustainable economic growth because it is used in many industrial, commercial and consumer activities [1,2]. Energy consumption is fundamental to the operation of every modern economy and serves as the physical engine for economic development and industrial innovation [3]. According to Ref. [4]; energy sources are in two primary categories - renewable and non-renewable. Renewable energy resources like solar, wind, water (hydro) and biomass are self-replenishing after use. Although their supply is non-exhaustible, they are unavailable at certain times, yielding intermittent electricity generation.

The combustion of fossil fuels – like coal, natural gas, and derivatives of crude oil - generates energy. However, heat-trapping gases - like carbon dioxide - are created and emitted when hydrocarbons are used to generate power, contributing to climate change and affecting human health [5]. Although energy is vital for economic development, studies have demonstrated that energy consumption directly affects the environment and climatic conditions [6,7]. For environmental sustainability, energy consequences such as rising carbon concentration, greenhouse effects, and global warming call for sustainable management and progress toward cleaner energy [8]. According to the World Economic Development (WED), in 2008 Sub-Saharan Africa (SSA) recorded 5.08 % growth in Gross Domestic Product (GDP) and a 2.5 % increase in per capita GDP. However, this was on the back of a 6 % increase in energy consumption coupled with a 20 % surge in carbon

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(CO_2) emissions [9]. The situation calls for further inquiry into the nexus of energy consumption, economic growth, and carbon emissions in African countries amidst the emerging transition to net zero.

[10–14]; and [15] considered the causality between energy consumption and economic growth without measuring the exact effect. Thus, the magnitude of change in one variable can solely cause the other [16]. studied 17 African economies using the Toda-Yamamoto test. The results confirmed a one-way causal relationship between energy consumption and economic growth in Ghana, Ivory Coast, Algeria, and Egypt. Both Gabon and Zambia showed bi-directional causality between energy consumption and economic growth. There is no causal link between both variables in Benin, Congo DR, Kenya, Senegal, South Africa, Sudan, Togo, Tunisia, and Zimbabwe. Research covering other geographical regions has yielded mixed outcomes, similar to prior investigations [13,17].

Meanwhile, [18]; and [19] argue that energy use, economic growth, population growth, and international trade greatly influence greenhouse gas emissions in China and developed economies. [20–25]; and [26] examined the relationship between energy consumption and emissions using causality tests. A cursory glance into these studies shows a plethora of knowledge produced in terms of the causality amongst energy consumption, economic growth, and carbon emissions. However, knowledge of the magnitude of change each variable can cause is lacking – a knowledge gap. Hence, this study offers additional information and insight into the extent to which energy consumption affects economic growth and carbon emissions.

Given this background, within the context of Africa's increasing population, we examine the combined effect of energy consumption and economic growth on carbon emissions in Africa – energy consumption being the moderating variable. Specifically, the study addresses three interrelated issues: (a) examine how energy consumption affects economic growth in selected African countries; (b) analyze the individual effect of energy consumption on carbon emissions in selected African countries; and (c) investigate whether economic growth and energy usage interactions aggravate or weaken carbon emissions in selected African countries. The relevance of this study is due to the nature of the demographic and energy transitions occurring in Africa. Specifically, the rate of population increase has implications for the interactive effect of energy consumption and economic development on carbon emissions. Furthermore, the rate of population growth and its interaction with economic growth could dampen or hasten the rate of decarbonization [27], but many studies have ignored this.

In this study, we uniquely adapted the methods in Refs. [28,29]. The Feasible Generalized Least Squares (FGLS) approach was used with a fixed and random effect model. FGLS helped to address issues of heteroscedasticity and serial correlation that may come along with fixed and random effects models. The unique approach is applied to address the research questions within the theoretical framework.

A notable implication of this study's finding is that the transition to cleaner energy technologies is moderating the adverse effects of increasing energy consumption and economic growth on the environment. So, in applying the energy intensity theory to Africa, a modification is proposed – carbon emissions are directly proportional to the amount of fossil fuel energy consumed per unit of output. Another noteworthy policy implication is the need for increased productive energy use in the selected countries at a higher rate than the increase in population. In this regard, it is essential to highlight the sociology of energy access and energy use. The results have policy implications for the ownership of efficient energy consumption appliances by low-income households and small businesses. Although the results show a growth-mitigated effect of energy consumption on the environment, policies to align the green agenda of African countries appear imperative. The results of the study have limited application only to the countries analyzed – due to the unavailability of data. Possibly, future studies could consider increasing the number of countries and, if data is available, an artificial intelligence experiment be undertaken to check the reliability of previous results. We further suggest that future studies consider investigating the persistence of emissions using energy and growth as key independent and moderating variables.

1.1. *Criteria for selecting countries*

The study was confined to a selected group of sub-Saharan African countries, primarily due to the availability of comprehensive and reliable data on critical variables. Among the numerous countries within the vast African continent, the following were chosen for examination: Angola, Benin, Botswana, Cameroon, Côte d'Ivoire, the Democratic Republic of the Congo, Gabon, Ghana, Kenya, Mauritius, Mozambique, Namibia, Niger, Nigeria, Senegal, South Africa, Sudan, Tanzania, and Togo. This subset was carefully selected to provide a representative cross-section of the region's diverse demographic, economic, and social characteristics - as they relate to energy consumption, access, and associated challenges. While the study acknowledges the significance of many other nations in Sub-Saharan Africa, the chosen group is reflective of the intricate interplay between demographic shifts, economic dynamics, and social aspects concerning energy usage. It is worth noting that the inclusion of these nations does not imply the exclusion of others; rather, it serves as a strategic starting point for analysis, given the available data infrastructure and the aim to explore common trends and challenges within the energy sector across a diverse range of contexts.

In the chosen Sub-Saharan African countries, a noticeable demographic trend is the substantial population growth combined with a youthful population structure, which directly influences the energy demand for residential, industrial, and commercial purposes. As the urbanization rate increases, energy demand becomes concentrated in urban areas, prompting the need for energy planning that focuses on cities. Economic development varies widely across these nations, impacting energy accessibility and affordability. Economic growth typically correlates with higher energy demand, particularly in energy-intensive sectors such as manufacturing and transportation. While some nations experience rapid economic expansion, others grapple with issues of poverty and limited energy access. Additionally, the presence of energy resources like oil, natural gas, and minerals in certain countries shapes energy strategies and export potential, shaping their economic landscapes.

On a social front, energy access inequalities persist, with rural regions facing challenges in accessing modern energy services, affecting healthcare, education, and economic opportunities. This unequal distribution extends to urban areas with better energy access. Many individuals encounter energy poverty, adversely affecting their quality of life due to inadequate access to electricity and clean cooking facilities. Environmental consciousness is growing, driving the adoption of sustainable energy solutions. Most of the countries selected are placing a heightened emphasis on integrating renewable energy sources and enhancing energy efficiency in response to mounting environmental challenges such as climate change and ecosystem degradation. This transition aligns with global efforts to mitigate the adverse environmental effects of energy consumption and to transition towards more environmentally friendly energy alternatives. A further comparison of the selected countries is in section 4.2.

The paper is organized as follows: section one introduces and gives the background to the study; section two discusses the relevant literature; section three covers the research methodology; section four discusses the empirical results; and the fifth section concludes the paper with relevant policy recommendations.

2. Literature review

A general review of relevant literature and the theoretical framework at the nexus of carbon emissions, energy consumption and economic growth is undertaken here to situate the study and adequately highlight its relevance.

2.1. Theoretical framework

2.1.1. Energy consumption theory

Energy consumption theory is a fundamental concept in the field of energy studies. It examines the patterns and trends of energy usage in various sectors of the economy and society. The theory is based on the understanding that energy is a finite resource and that its efficient use is crucial for sustainable development. The theory studies how individuals or organizations utilize energy and the variables that influence energy consumption patterns. It aims to explain why and how people use energy and the elements that influence this consumption. One of the theory's key assumptions is that individuals and organizations are rational actors who want to maximize their utility by using energy resources optimally [30].

One important factor influencing energy consumption is population growth. As the population increases, so does the demand for energy to meet basic needs such as cooking, heating, transportation, and electricity. A growing population in developing countries may lead to increased energy consumption as more people require energy services [31,32].

Economic factors, technology, cultural and societal norms, individual attitudes and beliefs, and government rules and regulations influence energy use. As economies grow, industries expand, and production processes become more energy-intensive. For instance, the manufacturing sector requires significant amounts of energy for processes such as production, transportation, and logistics. As a result, economic growth often leads to increased energy consumption. According to Ref. [33]; economic variables such as energy costs have a significant influence on energy consumption patterns. For example, when energy prices are high, consumers and companies may choose to use less energy or invest in energy-saving devices. In conclusion, the theory of energy consumption offers a framework for comprehending the many variables that affect consumption trends.

2.1.2. Energy intensity theory

Energy intensity theory is a concept that examines the relationship between energy use and economic activity. It seeks to understand how efficiently energy is used in different sectors of the economy and how this relates to overall productivity and growth. The theory suggests that as economies develop, they tend to become more energy efficient, meaning that less energy is needed to produce the same level of output. This is due to improvements in technology and industrial processes. However, energy intensity can vary across different countries and industries, depending on factors such as resource availability, policy frameworks, and market conditions.

According to Ref. [34]; energy intensity is the amount of energy utilized per unit of Gross Domestic Product (GDP). It measures the efficiency with which an economy uses energy [35]. presented the notion of energy intensity theory, which claims that there is a link between energy use and economic growth. Energy use normally increases as economies expand because it becomes more and more necessary to power economic activity. This is a result of the increased demand for energy in industries including manufacturing, transportation, and infrastructure construction. This issue is emphasized in Ref. [36]; who also drew attention to the expanding need for energy to support the increase in economic activity. This suggests that as economies develop, they tend to become more energy efficient, meaning that less energy is required to produce the same level of output. This efficiency improvement is attributed to advancements in technology and industrial processes.

However, the relationship between energy consumption and economic growth is not necessarily linear. The pace of energy consumption tends to slow down compared to the rate of GDP growth as economies advance and become more efficient. The diminishing energy intensity of economic expansion is the name given to this process. It implies that as economies develop, they discover ways to increase production and productivity while using less energy. Energy intensity theory emphasizes energy efficiency and the switch to cleaner energy sources towards decoupling economic growth from increasing energy use. To reduce the environmental effect associated with economic growth, governments and policymakers prioritize energy efficiency initiatives and promote sustainable energy practices.

However, technological advancements can lessen energy intensity by increasing energy usage effectiveness. Energy policies that support energy efficiency can also help to reduce energy intensity [34]. According to Ref. [35]; lowering energy intensity can aid in decreasing the harmful effects of energy production and use on the environment, such as air pollution and greenhouse gas emissions. The energy intensity hypothesis offers a framework for comprehending the connection between energy consumption and economic growth.

2.2. Economic growth and energy consumption

[11–14]; and Sarwar et al. (2018) studied the connection between energy use and economic growth employing trade openness, foreign direct investment, government expenditure, population growth, domestic credit to the private sector, and gross fixed capital formation as control variables. The influence was neglected in prior research, which verified the strong relationship between energy consumption and economic development. This new study set out to fill this gap.

[10] also assessed the dynamic causal relationships between energy consumption and economic growth in Saudi Arabia. Johansen's multivariate cointegration approach reveals a long-term relationship between energy use and economic growth. A two-way causal relationship starts with energy consumption and moves in the opposite direction to economic growth and carbon emissions. The relationship between short-term economic growth, energy usage, and carbon emissions is one-way causal.

[15] investigated whether there exists a causal link amongst carbon emissions, energy usage, and economic development in Pakistan. The bi-variate long-term associations between the variables have been evaluated using the Johansen-Julius cointegration, Autoregressive Distributed Lag (ARDL), and (Vector Error Correction Model) (VECM) tests. According to research, economic growth, energy consumption, and carbon emissions are all causally related in the short and long term.

[37] examined the relationship between energy consumption and economic growth using a dataset spanning over eighty decades in Italy using wavelet analysis. The findings suggest that there is no long-term relationship between energy consumption and economic development whilst a short-term relationship seems significant. Therefore, the influence of energy consumption on economic growth can only be detected significantly in the short run. This bidirectional causality is consistently observed across all frequency bands.

[38] also looks into the link between energy usage, carbon dioxide emissions, and economic growth for the South Caucasus region and Turkey between 1992 and 2013 using a panel Vector Autoregressive Model (VAR) approach with a 3-variable regression. According to empirical findings, CO2 emissions have a negative and statistically significant relationship to energy usage.

[16] studied 17 African economies using the Toda-Yamamoto test in multiple-country analysis. The results confirmed the one-way causal relationship between energy consumption and economic growth in Ghana, the Ivory Coast, Algeria, Egypt, and Egypt. While in Cameroon, Morocco, and Nigeria, energy consumption and economic growth are correlated in one way. Both Gabon and Zambia have seen bidirectional causality. There is no causal connection between Benin, Congo RP, Kenya, Senegal, South Africa, Sudan, Togo, Tunisia, and Zimbabwe. More recent researchers have also revealed mixed outcomes, similar to prior investigations [13,17]; Sarwar et al., 2017).

Furthermore, focusing on 15 West African countries, for the period 1995–2014 [39], used Panel Dynamic Ordinary Least Squares (PDOLS) to assess the effect of renewable energy on economic growth. Findings of the study suggest that the use of renewable energy inhibits economic growth in the 15 countries. The result is explained by the source of the renewable energy used in West Africa, primarily wood biomass. Most of the wood biomass fuels utilized in West Africa are dirty and extremely harmful after combustion. Meanwhile, West Africa countries also use clean renewable energies which have no negative environment effect. Given that the transition to renewable energy consumption can impede economic growth by decreasing productivity, it becomes pertinent to further explore their interactive linkage with the environment.

2.3. Carbon emission and energy consumption

[20] examined how energy consumption changed Malaysia's carbon emissions between 1970 and 1980. The results showed a long-term positive link between energy usage and carbon emissions, refuting the Environmental Kuznets Curve (EKC) theory. In a study of Pakistan [21], found evidence of an inverse relationship between energy use and carbon emissions. Although [22] examined the impact of renewable energy consumption on carbon emissions in Pakistan and discovered that energy has a significant negative effect on emissions, highlighting that higher consumption of renewable energy causes a decrease in emissions. These studies employed population growth, trade openness and other variables as control variables in their analyses.

In multiple-country case analyses [23], found a causal link between energy usage and carbon emissions in European countries [24]. used data from Gulf Cooperation Council (GCC) countries to show varying evidence of energy use and carbon emissions. In this regard [40], examined the role of green and blue economic factors in Saudi Arabia's sustainable growth – with their linkage to other GCC countries. The study recommends reforms in some key industries – fishery and marine tourism. Meanwhile [25], evaluated the relationship between the energy economy and emissions for the G-7 countries. The bootstrap ARDL limits test with structural breakdowns was applied to examine the relationship's causality. According to the study's results, economic growth, energy consumption, and carbon emissions in France, the United States, Italy, the United Kingdom, and Canada are unrelated. Germany and Japan, however, have shown a cointegration between economic growth and carbon emissions.

[26] examined differences in electricity consumption, the use of energy resources, and carbon emissions within the European Union from 2008 to 2016. Carbon emissions were also segmented based on the Kaya identity, used to determine the primary sources of inequality. The analyses showed that inequality is caused by differences in GDP due to variance in energy consumption, while carbon emissions show a stable degree of disparity. In Africa [41], used the Gregory and Hansen (1996a) model to analyze the causal dynamics amongst energy use, real GDP, and CO_2 emissions in the presence of regime shifts within six countries. Results show long-term relationships among energy use, real GDP, and CO2 emissions in the countries considered, proving that structural changes have an impact on both the economy and the environment. Therefore, it is essential to incorporate energy and environmental regulations into national plans to achieve sustainable development.

[42] investigated the relationship between CO2 emissions, energy consumption, and GDP in Russia. The study analyzed annual data from 1970 to 2017 using various time-series analyses such as stationarity, structural breaks, and cointegration tests. Additionally, they introduced a new D2C algorithm and conducted a Machine Learning experiment. By comparing the results from both approaches, the study drew the conclusion that economic growth leads to an increase in energy consumption and CO2 emissions. Finally, they performed robustness checks to ensure the validity of their findings using the new D2C algorithm. Essentially, their study demonstrated the presence of causal links in sub-permanent states among these variables.

[43] examined the relationship between CO2 emissions, economic growth in Italy. The study employed innovative algorithms and analyzed yearly data from 1960 to 2017. Specifically, they developed three different models: the batch gradient descent (BGD), the stochastic gradient descent (SGD), and the multilayer perceptron (MLP). The study found that, despite the period of low economic growth in Italy, the results indicate that CO2 emissions increased according to the predictive model. This finding contradicts the prevailing literature, as the algorithm reveals a correlation between low growth and higher CO2 emissions, diverging from the expected trend based on observed statistical data.

[44] conducted a study on the relationship between CO2 emissions, energy consumption, and GDP in Russia using annual data from 1990 to 2020. The study employed various time-series analyses, including stationarity, structural breaks, cointegration, and causality tests. Additionally, the researchers performed Machine Learning experiments as robustness checks. Both approaches highlighted a bidirectional causal relationship between energy use and CO2 emissions, indicating that changes in one variable can influence the other. Also, the study found a unidirectional link from CO2 emissions to real GDP, suggesting that changes in CO2 emissions can impact economic growth. Furthermore, the "neutrality hypothesis" prevails in the energy use-GDP relationship, indicating that energy conservation measures should not have an adverse effect on the country's economic growth trajectory. Given the current geopolitical scenario, these findings have important policy implications that can be derived from their study.

[45] critically analyzed the impact of fossil fuel dependency and polluting emissions from the transport sector on the performance of logistics operations within the framework of Green Supply Chain Management (GSCM). The study gathered macro-level time-series data for 27 European Union (EU) countries over the period 2007–2018. For the study to explore the dynamic interactions among various Logistics Performance Indexes (LPI), demand for oil products, and carbon dioxide (CO2) emissions from fuel combustion in the transport sector, the researchers utilized a new Artificial Neural Networks (ANNs) algorithm within a multivariate framework. The findings of the study revealed a significant influence of oil product consumption and CO2 emissions on the transport logistics indexes. However, an interesting feedback relationship was discovered for environmental pollution, indicating that supply chain performance does not significantly drive oil consumption. The study presented policy recommendations aimed at guiding the logistics sector towards a more sustainable path in the European region. By critically assessing the dynamic interplay between fossil fuel dependence, polluting emissions, and logistics performance, this study contributes to the growing field of GSCM and provides valuable insights for policymakers and industry stakeholders. Notably, African countries have unique demographic transition which is affecting their energy access, urbanization, and economic development, as well as, the rate and nature of energy transition and decarbonization. Herein is this study's scientific value and novelty.

3. Data, methodology and empirical analysis

This section describes the data, variables, and methods used to accomplish the study's aims. Choosing an objectivist epistemology - which has a perspective that meaningful reality exists and can be uncovered - the study used the positivist research philosophy and quantitative research approach. This approach provides objective analyses and reduces value judgment, making the result reliable, replicable, and valid.

3.1. Theoretical model specification

This study employed the energy consumption theory as the basic foundation for the empirical analysis. According to the theory, the cost of employing energy resources in manufacturing and service operations can be offset by the total beneficial effects on the economy. So, as energy is consumed in the production of goods and services, it adds up to the country's gross domestic product (GDP). This allows us to model GDP as a function of energy consumption together with other factors: $Y = f$ *(EC …)*, where: Y = Economic Growth and EC represents energy consumption.

3.2. Data description and apriori expectations

The research used panel data collected annually from 2000 to 2017. The dataset is from the World Development Indicators (WDI) of the World Bank. The study was limited to a few Sub-Saharan African nations largely based on data availability of critical variables. Angola, Benin, Botswana, Cameroon, Côte d'Ivoire, the Democratic Republic of the Congo, Gabon, Ghana, Guinea, Kenya, Mauritius, Mozambique, Namibia, Niger, Nigeria, Senegal, South Africa, Sudan, Tanzania, and Togo are a few of them. Overall, data for 19 nations covered 18 years. The variables used in the study are in Table 1.

3.3. Estimation techniques

This paper employed two static panel estimating techniques - Random Effects (RE) and Fixed Effects (FE) as in Refs. [28,29,46] - to analyze data. Towards ensuring the robustness and reliability of the estimation, as well as eliminate heteroscedasticity and serial correlation, the Feasible Generalized Least Squares (FGLS) was used - with a fixed and random effect model. FGLS helped to address issues of heteroscedasticity and serial correlation that may come along with fixed and random effects models. The Fixed and Random Effect models are more efficient when dealing with panel data that possess more within-individual or within-time variation. This helps to isolate the causal effect of specific policies. Additionally, we employed fixed and random effects models to address endogeneity issues by accounting for time-invariant unobserved factors related to the explanatory variables. These models use individual or time-specific features to reduce the bias caused by endogeneity.

The primary difference between fixed and random effect models is determined by the function of dummy variables. The fixed-effect model is used when the estimated parameter (dummy variable) is a component of the intercept. In contrast, the random-effect model is used when it is a component of the error term.

The Hausman test examines fixed and random effect models, assuming that individual effects are unrelated to any model regressor (Hausman, 1978). When a particular effect violates the Gauss-Markov requirements by correlating with other regressors, the random effect is no longer the Best Linear Unbiased Estimator (BLUE). This is because the error term in a random effect model contains individual effects. As a result, when the null hypothesis is rejected, the fixed-effect model beats the random model. A fixed effect model is still BLUE since the intercept contains individual effects, and the correlation between the intercept and the regressor breaks no Gauss-Markov requirement. Stata 17 was employed in analysing the data.

3.4. Empirical model specification

The empirical model follows the works of [18,19,47–50]. The functional form of the empirical model is Y = f(EC, TO,FDI,GE,POP,DCPS,GFCF) where:

Y represents Economic Growth.
EC is Energy Consumption,
TO is Trade Openness,
FDI is Foreign Direct Investment,
GE is Government Expenditure,
POP represent Population Growth,
DCPS is Domestic Credit to the Private Sector, and.
GFCF is Gross Fixed Capital Formation.

Trade openness, foreign direct investment, government expenditure, population growth, domestic credit to the private sector, and gross fixed capital formation served as control variables in this analysis. These control variables were used relying on [48–50].

In a model form, the empirical relationships are:

$$Y_{i,t} = \beta_0 + \beta_1 EC_{i,t} + \beta_2 TO_{i,t} + \beta_3 FDI_{i,t} + \beta_4 GE_{i,t} + \beta_5 POP_{i,t} + \beta_6 DCPS_{i,t} + \beta_7 \mathrm{GFCF}_{i,t} + \varepsilon_t \tag{1}$$

$$Carbon\ Emission_{i,t} = \beta_0 + \beta_1 EC_{i,t} + \beta_2 TO_{i,t} + \beta_3 FDI_{i,t} + \beta_4 GE_{i,t} + \beta_5 POP_{i,t} + \beta_6 DCPS_{i,t} + \beta_7 \mathrm{GFCF}_{i,t} + \varepsilon_t \tag{2}$$

$$Carbon\ Emission_{i,t} = \beta_0 + \beta_1 EC_{i,t} + \beta_2 Growth_{i,t} + \beta_3 (EC * Growth)_{i,t} + \beta_4 TO_{i,t} + \beta_5 FDI_{i,t} + \beta_6 GE_{i,t} + \beta_7 POP_{i,t} + \beta_8 DCPS_{i,t} + \beta_9 \mathrm{GFCF}_{i,t} + \varepsilon_t \tag{3}$$

Country and time are denoted by subscripts *t* and *i*, respectively.

4. Results and discussions

4.1. Descriptive statistics

The descriptive statistics for the factors considered in this study are in Table 2.

The average Real Gross Domestic Product (RGDP) of the 19 African nations studied between 2000 and 2017 was $500Million. With a low value of $15.2Million and a high value of $428Million, the yearly range across the countries under examination was $948.6Million. One of the dependent variables considered in this study is energy consumption, which has an average value of 162.061 kg of oil equivalent per person, with the highest value in the region being 642.084 kg and the lowest value being 54.298 kg.

The extent to which the emission measured by Carbon dioxide emissions in kilo tons deviates from the mean is 88,550.16 kilo tons within the region with an average value of 31,902.98 kilo tons and with 670 kilo tons and 447,930 kilo tons as the minimum and maximum values, respectively. The average level of foreign direct investment is

Table 1
Variables, data source and expected signs.

Variable	Description	Source	Expected sign	Units of Measure
RGDP	Real Gross Domestic Product	WDI		Real Gross Domestic Product (RGDP) in US dollars
CO2 Emissions	Carbon dioxide emissions	WDI		kilo tons
EC	Energy consumption	WDI	Positive/negative	kilogram of oil equivalent per person
TO	Trade openness	WDI	Positive/negative	The sum of imports and exports as a % of GDP
FDI	Foreign Direct Investment	WDI	Positive/negative	The net inflow of investment as a % of GDP
GE	Government expenditure	WDI	Positive	Government final consumption as a % of GDP
POP	Population growth rate	WDI	Positive	the annual growth rate of the population
DCPS	Domestic credit to the private sector	WDI	Positive	Domestic credit to the private sector as a % GDP
GFCF	Gross fixed capital formation	WDI	Positive	Gross fixed capital formation as a % GDP

Source: Authors' compilation, 2022

Table 2
Summary statistics.

Variable	Observation	Mean	Standard Deviation	Minimum	Maximum
Real GDP	342	5.00E+08	9.48E+08	1.52E+07	4.28E+09
Log Real GDP	342	18.98502	1.296561	16.53697	22.17806
Energy consumption	342	162.061	107.4402	54.2975	642.0836
CO_2 emissions	342	31902.98	88550.16	670	447930
Foreign Direct Investment	342	3.767597	5.175017	−6.05721	41.8096
Government Expenditure	342	14.06553	4.99646	0.951747	28.31945
Population growth	342	2.511579	0.774712	0.068723	3.907245
Domestic Credit to Private Sector	342	27.30421	32.69208	0.491388	160.1248
Gross Fixed Capital Formation	342	22.27392	6.761066	6.66279	43.0513
Trade Openness	342	70.31632	26.46792	19.1008	152.547

Source: Authors' computation, 2022

3.768%, with a deviation of 5.175% and comparable values of 41.81 and −6.057 for maximum and lowest.

Government consumption spending has an average value of 14.066, with the greatest and lowest values being 28.319 and 0.9512, respectively. The region's deviation from the mean as a proportion of GDP is 4.996. A proxy for labour force growth, the population growth rate (POP) averaged 2.512% and deviated 0.775% from the mean. The population growth of these countries under investigation ranges from 0.069 to 3.907%.

Domestic credit to the private sector (DCPS), a metric of financial development, ranged from 0.403 to 160.125 in the SSA nations under study. The regional standard deviation is 32.692, while the mean value of domestic private credit is 27.304.

Investment was proxied using gross fixed capital formation. The average GDP per capita in African nations is 22.274, with a standard deviation of 6.761. There have been temperatures as high as 43.051 and as low as 6.663 in the area. Trade Openness in the region spans from 19.101 to 152.547 at its best and lowest peaks, respectively. Trade openness has a standard deviation from the mean of 26.468 and a mean value of 70.316.

4.1.1. *Correlation analysis*

The correlation matrix (Table 3) reports the likelihood of multicollinearity of variables. Domestic lending to the private sector and real GDP are positively correlated, as shown in Table 3; thus, an increase in one will lead to an increase in the other. Trade openness, foreign direct investment, government spending, population growth, and gross fixed capital creation as a proportion of GDP are all adversely connected with real GDP. Since the correlation coefficients are less than 0.8, the correlation table demonstrates no multicollinearity between the variables.

4.2. *Comparative analyses*

Here, we comparatively examine how energy usage or consumption and carbon emissions differed among geographical, social, and economic groups in the 19 African nations studied between 2000 and 2017.

4.2.1. *Real GDP - based on regional groupings*

Fig. 1 displays the mean real GDP for the 19 African nations included in the research from 2000 to 2017. A bar graph shows how energy usage varies by region. The chart demonstrates that East African countries (EAC) consume the most energy, with an average consumption of 224.657 kg of oil equivalent, followed by Central and West African nations. The graph indicates that Eastern African countries use more energy compared to other regions in the continent.

4.2.2. *Energy use - based on economic groupings*

Fig. 2 displays the trend in energy consumption for the African countries evaluated by economic category. The Southern African Development Community (SADC) uses the most energy, followed by the Economic Community of West African States (ECOWAS).

4.2.3. *Carbon emissions - based on regional groupings*

Fig. 3 shows carbon dioxide emissions across the region. The Southern African region has the maximum level emissions average of 36.994 metric tons per capita, followed by the East African countries and the West African countries, which have a mean value of 26.068 and 25.013 metric tons per capita, respectively. This result is not surprising since South Africa, a major economy within the southern region, uses coal primarily in its power generation mix.

4.2.4. *Carbon emissions - based on income groupings*

Fig. 4 shows that countries within the Upper middle income pollute more than countries within the lower middle income. The lower middle income countries also pollutes more than the low-income countries on the average among countries used for the study. Upper Middle and Lower Middle-Income countries pollute as much as three times the lower-income countries' pollution level.

4.3. *Empirical estimation and discussions*

The static panel estimate findings are provided and analyzed in this part within the context of the literature. Table 3 shows how energy consumption affects economic growth. The effect of energy usage on

Table 3
Correlation analysis.

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
RGDP (1)	1								
CO_2 Emissions (2)	0.491*	1							
Energy consumption (3)	0.046	−0.117*	1						
Trade Openness (4)	−0.268*	0.181*	−0.138*	1					
Foreign Direct Investment (5)	−0.126*	−0.113*	0.262	0.319*	1				
Government Expenditure (6)	−0.122*	0.369*	−0.129*	0.502*	0.290*	1			
Population Growth (7)	−0.196*	−0.529*	0.263*	−0.327*	0.103	−0.234*	1		
Domestic Credit to Private Sector (8)	0.467*	0.827*	−0.092	0.206*	−0.061	0.429*	−0.692*	1	
Gross Fixed Capital Formation (9)	−0.124*	0.024	−0.202*	0.231*	0.305*	0.273*	0.158*	−0.061	1

* indicating the 0.05 alpha level of significance.
Source: Authors' computation, 2022 based on WDI data

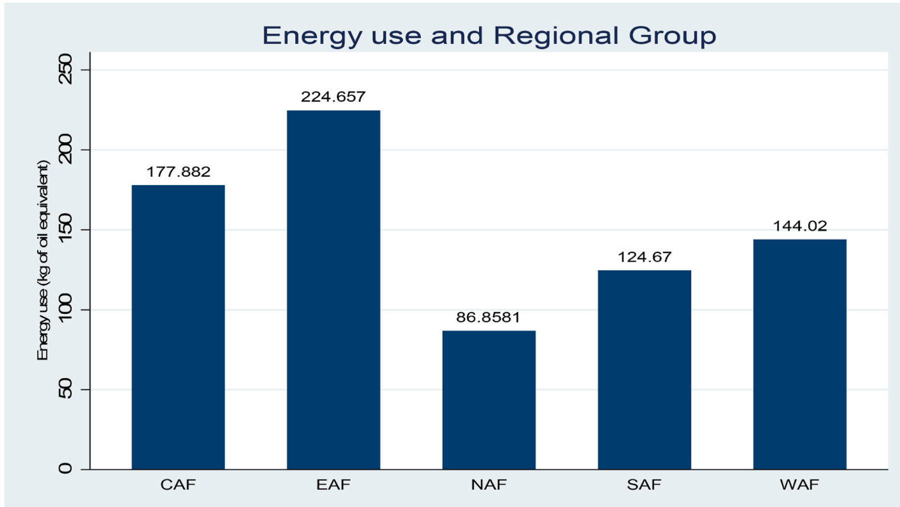

Fig. 1. Energy consumption by regional groupings.
Source: Authors' construction, 2022 based on WDI data

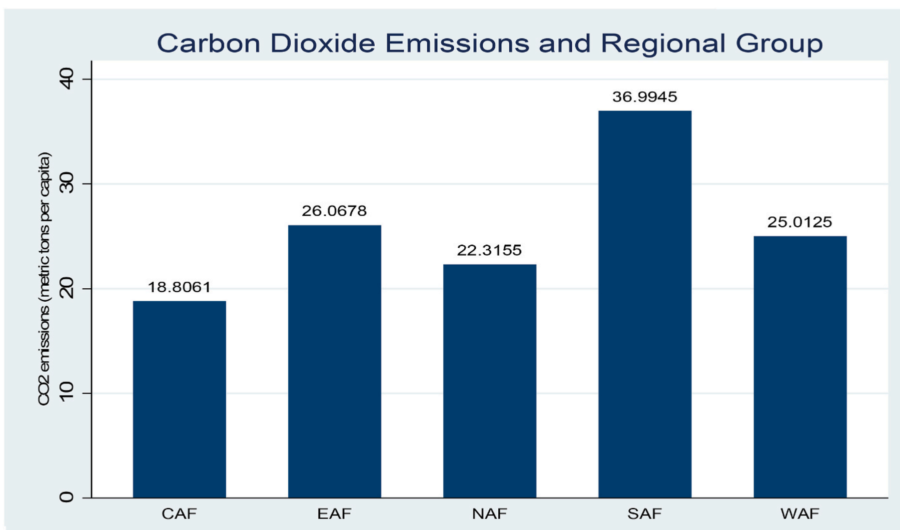

Fig. 2. Energy consumption.
Source: Authors' construction, 2022 based on WDI data

carbon dioxide emissions in a few African countries is presented in Table 4.

Table 4 shows the effect of energy consumption on growth in some selected African countries. The Random-effect model's result was interpreted for the first objective of this study - as chosen by the Hausman test.

From the result, a 1-kg rise in energy consumption will lead to a 0.002% rise in real GDP. At a 1 % alpha level, the outcome is substantial. This proves a link between rising energy consumption and accelerating economic growth – confirming the results of [51,52]; and [53].

At the 5 % alpha level, the coefficient of determination for Trade Openness (TO) is 0.003, and it is significant. Every percentage point increase in TO leads to an increase in real GDP of 0.003 %. The findings of this paper contrast the results of [54–56]; who discovered that trade openness had a negative consequence on economic development.

Foreign Direct Investment (FDI) also positively impacts the economy's growth. FDI is statistically significant at 1 % and has a positive coefficient of 0.019. To put it another way, a 1 % increase in FDIC as a proportion of GDP would translate into a 0.019 % increase in real GDP. Based on the above results, we may conclude that FDI is an important factor in the economic growth and development discussion. The results of [54,57,58] are similar to this, although [55,59] yielded different outcomes.

Government spending, domestic loans to the private sector, and gross fixed capital formation positively affect economic development, demonstrating that an increase in any of these factors will improve economic growth in the chosen African countries. In contrast, an increase in population had a negative effect on economic growth. This outcome is probably due to inadequate resources and infrastructure that constrain economic activities, leading to unemployment, poverty, and environmental degradation.

Table 5 shows the effect of energy consumption on carbon emissions in some selected African countries. The Random-effect model's result was interpreted for this objective as chosen by the Hausman test.

This shows that every 1 kg of oil equivalent increase in energy consumption or use will decrease carbon emissions by 0.001 kilo tonne, with a significance level of 10%. This demonstrates that an increase in energy consumption has a decreasing effect on carbon emissions for the

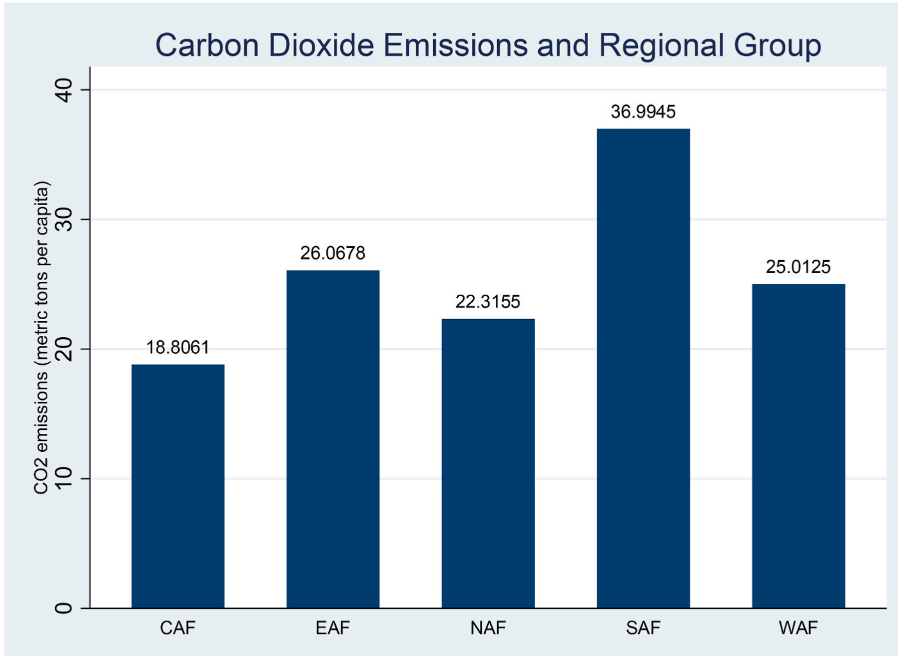

Fig. 3. Carbon dioxide emissions.
Source: Authors' construction, 2022 - based on WDI data

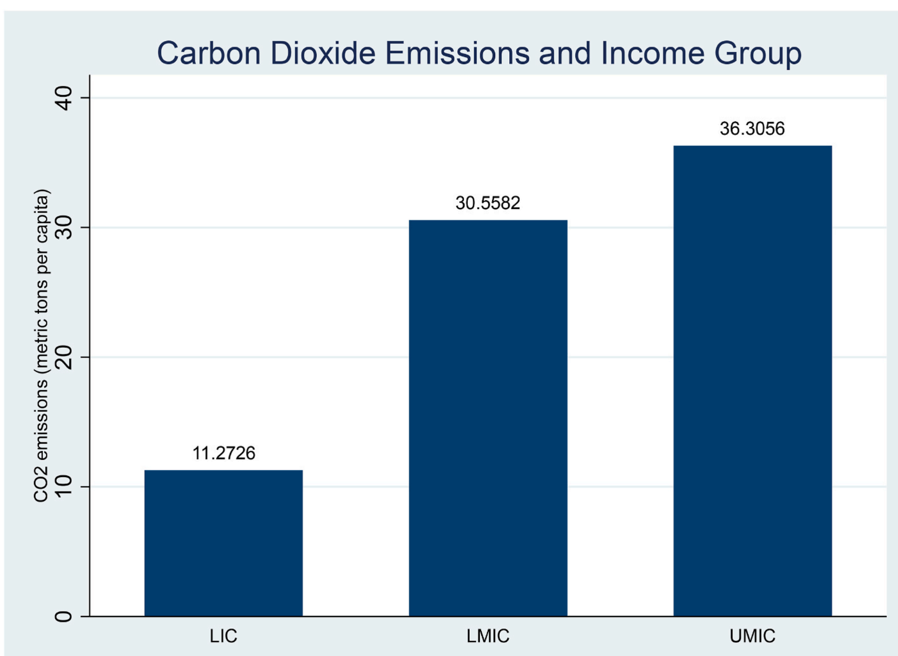

Fig. 4. Carbon Emissions - based on Income groups.
Source: Authors' Construction, 2022 based on WDI data

selected African countries. This finding indicates that increasing energy consumption has a decreasing effect on carbon emissions. A tenable explanation is that the selected African countries are transitioning towards more sustainable and low-carbon energy sources. Arguably, the decrease in carbon emissions is due to increased energy efficiency measures. This finding does not align completely with the energy intensity theory, which posits that carbon emissions are directly proportional to the energy consumed per unit of output. Empirically, this finding differs from the results obtained by Refs. [18,60]; and [19] – increase in energy consumption has a positive influence on carbon emissions.

There is a positive relationship between trade openness (TO) and credit to the private sector and carbon emissions, which shows that an increase in any of these variables would increase carbon emissions. Whilst FDI, population growth negatively impacts these countries' emissions.

The outcome from Table 6 demonstrates the interactive effect of energy usage and economic growth on carbon emissions in selected

Table 4
Effect of energy consumption on economic growth.

VARIABLES	FIXED	RANDOM
Energy Consumption	0.00217***	0.00202***
	(0.00067)	(0.00065)
Trade Openness	0.00340**	0.00313**
	(0.00158)	(0.00157)
Foreign Direct Investment	0.0192***	0.0190***
	(0.00459)	(0.00458)
Government Expenditure	0.0193**	0.0178**
	(0.00874)	(0.00871)
Population growth	−0.317***	−0.307***
	(0.0892)	(0.0878)
Domestic Credit to Private Sector	0.00563**	0.00572**
	(0.00267)	(0.00259)
Gross Fixed Capital Formation	−0.00568	−0.00537
	(0.00398)	(0.00397)
constant	18.82***	18.85***
	(0.281)	(0.411)
Number of observations	342	342
Number of groups	19	19
Wald chi2(7)		62.58
Prob > chi2		0.0000
F(7,316)	9.15	62.58
Prob > F	0.000	0.000
sigma_u	1.346176	1.320745
sigma_e	0.295081	0.295081
Rho	0.954154	0.952457
Hausman Specification		
chi2(7)	8.87	
Prob > chi2	0.2623	

Note: Robust Standard errors are in parentheses, while significance levels of 10 %, 5 %, and 1 % are indicated by *p < 0.1, **p < 0.05, and ***p < 0.01, respectively.
Source: Authors' computation, 2022 based on WDI data

Table 5
Effect of energy consumption or use on carbon emission.

VARIABLES	FIXED	RANDOM
Energy Consumption	−0.00113**	−0.000991*
	(0.00052)	(0.00052)
Trade Openness	0.00197	0.00213*
	(0.00123)	(0.00124)
Foreign Direct Investment	−0.00837**	−0.00845**
	(0.00359)	(0.00362)
Government Expenditure	−0.00851	−0.0084
	(0.00683)	(0.00689)
Population growth	−0.474***	−0.481***
	(0.0699)	(0.0699)
Domestic Credit to Private Sector	0.0127***	0.0142***
	(0.0021)	(0.00207)
Gross Fixed Capital Formation	−0.00087	−0.00145
	(0.00313)	(0.00316)
Constant	2.283***	2.237***
	(0.22)	(0.348)
Number of observations	342	342
Number of groups		19
Wald chi2(7)		141.29
Prob > chi2		0.000
F (7,316)	17.72	
Prob > F	0.000	
Sigma u	1.4312025	1.160588
Sigma e	.23043293	0.230433
Rho	.97473193	0.962074
Hausman Specification		
chi2(7)	5.6	
Prob > chi2	0.5875	

Note: Robust Standard errors are in parentheses, while significance levels of 10 %, 5 %, and 1 % are indicated by *p < 0.1, **p < 0.05, and ***p < 0.01, respectively.
Source: Authors' computation, 2022 based on WDI data

Table 6
The combined effect of energy usage and economic growth on carbon emissions.

Variables	Fixed	Random
Energy Consumption	0.00965*	0.00879
	(0.00546)	(0.00549)
Log of real GDP	0.139**	0.137**
	(0.0642)	(0.0642)
Energy Consumption*Real GDP	−0.000581**	−0.000529*
	(0.000290)	(0.000292)
Trade Openness	0.00133	0.00150
	(0.00125)	(0.00126)
Foreign Direct Investment	−0.00903**	−0.00924**
	(0.00367)	(0.00368)
Government Expenditure	−0.0110	−0.0108
	(0.00689)	(0.00692)
Population growth	−0.497***	−0.497***
	(0.0737)	(0.0734)
Domestic Credit to Private Sector	0.0124***	0.0136***
	(0.00209)	(0.00206)
Gross Fixed Capital Formation	0.000593	0.00000910
	(0.00319)	(0.00321)
Constant	−0.208	−0.220
	(1.179)	(1.213)
Number of observations	342	342
Number of groups	19	19
Wald chi2(9)		146.70
Prob > chi2		0.0000
F(9,314)	14.58	
Prob > F	0.0000	
sigma_u	1.4388098	1.2509975
sigma_e	.2292317	.2292317
Rho	.2292317	.96751418
Hausman Specification chi2(8)	14.03	
Prob > chi2	0.0811	

Note: Robust Standard errors are in parentheses, while significance levels of 10 %, 5 %, and 1 % are indicated by *p < 0.1, **p < 0.05, and ***p < 0.01, respectively.
Source: Authors' computation, 2022 based on WDI data

African countries. The Fixed-effect model's result was interpreted for this objective as chosen by the Hausman test.

From the result, a kilogram rise in energy consumption will increase carbon emission by 0.009 kilo tons with a significance level of 10%. This demonstrated that an increase in energy consumption increases carbon emissions in selected African countries. This result contradicts the earlier finding in Table 5, where we do not control for growth in the model. This is different from the results obtained by Refs. [18,60]; and [19] - that an increase in energy consumption reduces carbon emissions.

The result also showed that a percent increase in real GDP would increase carbon emission by 0.139 kilo tons at a 5 % alpha level of significance. This implies that any attempt to improve growth will likely come with some level of carbon emissions. The finding of this study is in tandem with [20,25,61,62]; and [63]. However, the results differ from the findings of [64,65] – they posit no relationship between economic growth and carbon emissions.

However, when energy consumption interacts with economic growth (or real GDP), allowing growth to moderate the relationship between energy consumption and carbon emissions, the overall result implies that economic growth minimizes the negative impact of energy consumption on carbon emissions. Specifically, finding the moderating role of real GDP from equation (3) gives $\frac{\Delta Carbon\ Emission_{i,t}}{\Delta EC_{i,t}} = \beta_1 + \beta_3 Y_{i,t} = 0.00965 + (-0.000581)(\overline{Y})$. Placing the mean value of the log of real GDP of 18.98502 from the descriptive statistics gives $\frac{\Delta Carbon\ Emission_{i,t}}{\Delta EC_{i,t}} = 0.00965 + (-0.000581)(18.98502) = -0.10065$. This shows that with an average log GDP of 18.98502, every 1 kg of oil equivalent increase in energy consumption will decrease carbon emissions by 0.10065 kilo tons with a significant level of 5%. This demonstrated that growth reduces the impact of energy consumption on carbon emissions. This reaffirms the findings of [60,66]; and [18].

5. Conclusion and recommendations

The result of the study shows that a rise in energy consumption has a positive effect on economic growth in the selected countries. This demonstrated that energy consumption plays a crucial role in driving economic growth and development. As energy is an essential input in the production process, higher energy consumption leads to increased economic output and expansion, especially in developing countries that consume less energy than the minimum required for growth.

However, the study's findings on the relationship between energy usage and carbon emissions were worth mentioning. Despite the favourable impact on economic growth, the study found that increased energy use has a negative association with carbon emissions. Moreover, the study found that the impact of energy consumption on economic growth appears to be stronger compared to its effect on the environment (measured by carbon emissions). This suggests that the positive contribution of energy consumption to economic growth outweighs its negative impact on the environment, at least within the context of the selected countries. It implies that nations may be adopting more energy-efficient technology or cleaner energy sources, lowering their carbon footprint despite their levels of energy use.

The study also looked at how energy use and economic growth interact to affect carbon emissions. Surprisingly, the findings show that economic growth works as a mitigating factor, lowering the impact of energy use on carbon emissions. This implies that when economies develop, they become better positioned to embrace cleaner technology and execute policies that mitigate the environmental repercussions of growing energy use.

Finally, the result obtained here adequately addresses the issues of interest: (a) examine how energy consumption affects economic growth in selected African countries; (b) analyze the individual effect of energy consumption on carbon emissions in selected African countries; and (c) investigate whether economic growth and energy usage interactions aggravate or weaken carbon emissions in selected African countries. One of the notable implications of this study's finding is that the transition to cleaner energy technologies is moderating the adverse effects of increasing energy consumption and economic growth on the environment. So, in applying the energy intensity theory to Africa, a modification is proposed: carbon emissions are directly proportional to the amount of fossil fuel energy consumed per unit of output.

Therefore, the study recommends increasing energy access and use in the selected countries at a rate that surpasses the increase in population. In this regard, it is essential to highlight the distinction between energy access and energy use (consumption through an appliance). Policy interventions are needed to increase the acquisition and ownership of efficient energy consumption appliances by low-income households and small businesses. More so, public orientation and awareness programmes are required to drive the productive use of energy, especially in rural areas. The study further recommends that since growth efficiently reduces the negative impact of energy consumption on the environment, policies should be focused on improving economic growth and the productive use of energy. Although our results show a growth-mitigated effect of energy consumption on the environment, policies to drive renewable energy utilization are needed. The result obtained here somewhat justifies the need for an African agenda for a green recovery in the post-COVID-19 era posited by Ref. [67].

The study was limited to 19 Sub-Saharan African nations, largely based on data availability of critical variables. This limitation could hinder the generalization of the results for the sub-Saharan African region. Hence future studies could consider increasing the number of countries, and, if data is available, an artificial intelligence experiment could be undertaken to check the reliability of previous results. We also suggest that future studies consider investigating the persistence of emissions with energy and growth as key independent and moderating variables.

CRediT authorship contribution statement

Obindah Gershon: Conceptualization, Methodology, Supervision, Writing - review & editing. **Joseph Kwasi Asafo:** Conceptualization, Methodology, Data curation, Formal analysis, Software, Writing - original draft, Writing - review & editing. **Abel Nyarko-Asomani:** Literature Review, Data curation, Writing - review & editing. **Eric Fentim Koranteng:** Literature Review, Data curation, Software, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Abbreviations

ARDL	Auto-Regressive Distributed Lag
BLUE	Best Linear Unbiased Estimator
CO_2	Carbon Dioxide
DCPS	Domestic Credit to the Private Sector
EAC	East African Countries
ECOWAS	Economic Community of West African States
EKC	Environmental Kuznets Curve
EC	Energy Consumption
FDI	Foreign Direct Investment
FE	Fixed Effect (model)
GCC	Gulf Cooperation Council
GDP	Gross Domestic Product
GFCF	Gross Fixed Capital Formation
OECD	Organisation for Economic Co-Operation and Development
PDOLS	Panel Dynamic Ordinary Least Squares
POP	Population Growth Rate
RE	Random Effect (mode)
RGDP	Real Gross Domestic Product

SDGs	Sustainable Development Goals
SSA	Sub-Saharan Africa
SADC	Southern African Development Community
TO	Trade Openness
VAR	Vector Autoregressive Model
VECM	Vector Error Correction Model
WDI	World Development Indicators
WED	World Economic Development

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