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Research article

Industrialization and environmental sustainability in Africa: The moderating effects of renewable and non-renewable energy consumption

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ABSTRACT

African countries have become interested in economic transformation through revamping their manufacturing sectors. However, the environmental effect of industrialization is an issue of great concern, with the need to maintain a sustainable environment in line with sustainable development goals. This study investigates the effect of industrialization on environmental sustainability in Africa, taking in to consideration the moderation effect of renewable energy and non-renewable energy consumption. Data was collected for 46 African countries from the Global Footprint Network, World Development Indicators of the World Bank and the Food and Agricultural Organization from 2000 to 2022. Robust panel fixed effects regression and generalized least squares methods were used to analyze the data. The empirical results showed that value added in manufacturing has a negative and significant effect on environmental sustainability. However, when interacted with renewable energy consumption, manufacturing exerted a positive effect on load capacity factor, indicating that the environment will be sustainable if manufacturing sector activities are powered by renewable energies. This suggests that renewable energy has the ability to propel industrial growth in Africa while sustaining the environment. The moderating effect of non-renewable energy and manufacturing is positive in the fixed effects regression and negative for the generalized least squares estimates. This suggest that fossil fuel consumption, particularly clean fossil fuels or natural gas can still drive African manufacturing without considerably harming the environment but continual use of it in to the long run will make the environment unsustainable. From the above results, this study recommends that for sustainable industrialization to take place, Africa should grow her manufacturing sector by extending the range of manufactured products from light to heavy manufactures while ensuring that renewable energy remains the major source of industrial energy supply.

1. Introduction

Rapid industrial development and economic transformation are a strategic objective of developing countries, especially African countries. Africa, with its great resource potentials and an increasing population has recognized the important role of industrialization

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in overcoming the socioeconomic challenges of the region [1]. Agenda 2063 of the African Union emphasizes the significant role that a robust manufacturing sector can play in enhancing Africa's socioeconomic development. This has gained momentum with the putting in place of the African Continental Free Trade Area (AfCFTA), which is out to create a unified market for goods and services across Africa, unlocking the potentials for manufacturing, accelerating industrialization, promoting sustainable and inclusive growth, reducing unemployment and poverty reduction for Africans [2,3]. The [4] adds that industrializing Africa will foster technological advancement, innovation, knowledge-sharing and diversification of African economies. Furthermore, a robust manufacturing sector can boost agricultural productivity through processing, value addition and contribution to food security. The benefits of a vibrant industrial sector for Africa cannot be overemphasized.

Though industrial development holds great potential for Africa's sustainable economic growth, its environmental effects cannot be neglected. Industrialization causes air pollution, water pollution, land degradation and climate change. Jayaram et al. [5] documented that about 30–40% of total emissions in Africa are associated with African manufacturing, which emits roughly 440 megatons of carbon dioxide equivalent ($MtCO_2e$). By 2050, this will almost double to around 830 $MtCO_2e$ within the next 20–30 years if African manufacturing follows the growth pattern of the developed world. According to Ref. [6], the typical affluent chemical oxygen demand of municipal wastewater treatment plants (WWTPs) usually exceeds 2000 mg/L in many African pond systems. Manufacturing leads to soil erosion, deforestation and loss of biodiversity. The empirical support of manufacturing's degradation effect on the environment is existent, with studies such as [7–19] supporting the fact that industrialization increases environmental degradation. With the environmental consequences of manufacturing being almost unavoidable, an important policy question for Africa is how to become industrialized while reducing environmental pollution—sustainable industrialization. This study argues that this is determined by the energy form that is driving industrial development, whether renewable or non-renewable.

Energy consumption has long been considered as one of the most important resources for industrial development and economic growth for any country [20]. From the beginning of the industrial revolution till today, non-renewable energy has been the dominant source of energy driving economic activities, accounting for about 87% of primary energy used globally [21]. China, India and Pakistan as well as African economies highly rely on non-renewable energy consumption for industrialization and economic growth [22] due to the necessity to reduce energy deficiency and because it is cheaper and easily accessible relative to renewable energies. However, the increased dependence on non-renewable energy threatens environmental sustainability especially through the release of carbon dioxide (CO_2) emissions and other greenhouse gas emissions [23,24]. This has generated interest in renewable energy, which has the ability to minimize environmental and ecological damage [25,26]. Empirically, the literature connecting renewable energy consumption to industrial development is scanty, with the works of [27–29] being amongst the few. Similarly, most studies have only investigated the relationship between non-renewable energy consumption and economic growth [30–34], studies focusing specifically on industrial growth being relatively scarce. This study provides insights in to the interactions between energy consumption (renewable and non-renewable) and value added in manufacturing and its implications on environmental sustainability.

Based on the above background and rationale, this study is out to provide answers to the following research questions;

1) What is the effect of value added in manufacturing on load capacity factor in Africa?
2) What is the moderation effect of renewable and nonrenewable energy consumption on the relationship between manufacturing and load capacity factor in Africa?

At this juncture, it is important to highlight the operational objectives of this paper which are linked directly to the research questions. These are to;

1) Analyze the effect of value added in manufacturing on load capacity factor in Africa
2) Investigate the moderation effect of renewable and nonrenewable energy consumption on the relationship between manufacturing and load capacity factor in Africa.

The remainder of this paper is structured as follows; section two dwells on the literature review while the materials and methods are discussed in section three. The fourth section presents and discusses the empirical results. The last section concludes and suggests policy implications.

2. Literature review

Most developing countries, including African countries have become interested in economic transformation through revamping their manufacturing sectors. However, the environmental effect of industrialization remains an issue of great concern, with the need to maintain a sustainable environment in line with sustainable development goals (SDGs). Fossil fuels consumption to power factories and other industrial facilities is increasing GHG emissions, leading to climate change. Due to the awareness of sustaining development, the use of renewable energy in the place of non-renewable energy for industrialization is increasingly favoured [35]. The effect of industrial processes on air, water and soil pollution, degradation of land and destruction of forests and other natural habitats are noticeable and have become a subject of empirical investigation [7,8,36]. Though literature in this domain is vast, the general consensus from these studies, regardless of the environmental indicator and estimation techniques used, is that industrialization harms the environment. A summary review of some recent empirical studies is presented on Table 1.

Employing the generalized estimating equation, generalized least squares, dynamic common correlated effect, mixed effect model, Driscoll-Kraay standard errors and the panel corrected standard error techniques with data from 1991 to 2019, [36] found that for 32

African countries, value added in manufacturing had detrimental effects on ecological footprint. The ability of these countries to develop and use environmentally friendly methods of production is limited alongside weak environmental policies and public health safety rules. Hence the growth of textiles, apparel and tanneries industries in Africa breeds water scarcity and landfills. Opoku & Aluko [17] found non-linear effects of manufacturing on ecological footprint for 37 African countries from 2000 to 2016 using panel quantile regression. The effect turns from positive in the 10th-13th quantile to negative in the 40th-90th quantile, suggesting that at some point, industrialization mitigates environmental degradation. However, this later effect is uncommon in the developing countries context and can be explained by Africa's low level of industrialization, as the manufacturing sector is yet to gain steam in the African continent. In another study by Ref. [8] for South Africa using the non-linear ARDL, economic growth and industrialization negatively impacted on the load capacity factor.

Evidence for Asian and other developed countries have also revealed that ecological footprint is negatively impacted by industrial development. For instance, Ref. [7] showed using the CS-ARDL model with data from 1990 to 2020 that industrial development increases resource footprint for Asian economies including Malaysia, Sri Lanka, Bangladesh, India, Indonesia, China and Malaysia. However, when financial development is moderated with technological innovation, the negative effect of industrialization on resource footprint is reduced. Another study by Ref. [16] using augmented mean group estimates in the 10 top newly industrialized economies of China, Indonesia, India, Brazil, Mexico, Malaysia, the Philippines, South Africa, Thailand and Turkey between showed that the industrialization process adversely affects ecological footprint. The study equally found financial development and total reserves to aggravate environmental pollution while renewable energy use and total natural resources rents mitigate it. Liao et al. [11] held that industrialization, foreign direct investment and economic growth increases ecological footprint in OECD countries within the period 1990–2019 while green innovations and transitions to clean energy reduces ecological footprint.

Some studies have concluded that industrialization increases CO_2 emissions [9,12,14,15,18,28,39]. For instance, Ref. [9], employs the non-linear autoregressive distributed lag model (NARDL) with a dataset from 1971 to 2019 for India to show that industrialization and economic growth increases CO_2 emissions while globalization negates it. With data from 1972 to 2021, using the CS-ARDL model, [14] found environmental degradation in the BRICS economies to worsen as industrialization takes steam. The result was not different for Argentina based on the ARDL bounds test for cointegration and Granger Causality within the same time period [12]. Population growth worsened the environment while education improved it. Raihan et al. [15] also reached similar conclusions for Bangladesh using a dataset from 1990 to 2019, based on the ARDL, DOLS techniques. Urbanization and economic growth have also been cited by the study as main drivers of environmental degradation. With data from 1990 to 2020 for Australia, using the ARDL bounds test for

Table 1
Summary empirical reviews on industrialization and environmental sustainability.

Author (s)	Country/Region	Period	Method	Environmental indicator	Findings
Samour et al. [37]	BRICS-T	1990–2018	Linear and non-linear ARDL	Load capacity factor	↑ IND→ ↓ LCF
Fang [38]	China	2005–2019	Generalized Method of Moments (GMM)	CO_2 emissions	↑ IND→ ↓ CO_2
Aladejare and Nyiputen [36]	African countries	1991–2019	Variety of estimation methods	Ecological footprint	↑ IND→ ↑ EF
Jin and Huang [8]	South Africa	1990–2019	NARDL, spectral Granger Causality	Load capacity factor (LCF)	↑ IND→ ↓ LCF
Li and Li [7]	Asia	1990–2022	Cross-Sectional ARDL model	Resource footprint	↑IND→ ↑ EF
Patel and Mehta [9]	India	1971–2019	NARDL	CO_2 emissions	↑ IND→ ↑ CO_2
Ali et al. [10]	Saudi Arabia	1991–2020	quantile-on-quantile (QQ) and quantile regression (QR)	Carbon emission intensity	↑ IND→ ↑ CO_2
Liao et al. [11]	OECD countries	1990–2019	Method of moments quantile regression	Ecological footprint	↑ IND → ↑ EF
Voumik and Ridwan [12]	Argentina	1972–2021	ARDL Bounds test, Granger Causality	CO_2 emissions	↑ IND→ ↑ CO_2
Raihan [13]	Phillipines	1990–2020	ARDL, DOLS, Granger Causality	CO2 emissions	↑ IND→ ↑ CO_2
Voumik and Sultana [14]	BRICS economies	1972–2021	Cross-Sectional ARDL model	CO_2 emissions	↑ IND→ ↑ CO_2
Raihan et al. [15]	Bangladesh	1990–2019	ARDL, DOLS	CO_2 emissions	↑ IND→ ↑ CO_2
Usman and Balsalobre-Lorente [16]	Newly industrialized economies	1990–2019	Augmented mean group	Ecological footprint	↑ IND→ ↑ EF
Opoku and Aluko [17]	African countries	2000–2016	Panel quantile regression	Ecological footprint	↑ IND→ ↑↓ EF
Nasir et al. [18]	Australia	1980–2014	Johansen cointegration and VECM	CO_2 emissions	↑ IND→ ↑ CO_2
Sikder et al. [19]	Developing countries	1995–2018	Panel ARDL, heterogeneous causality	CO_2 emissions	
Rahman and Alam [39]	Australia	1990–2020	ARDL Bounds test, Granger Causality	CO_2 emissions	↑ IND→ ↑ CO_2
Mentel et al. [28]	Europe and Central Asia	2000–2018	Two-step GMM	CO_2 emissions	↑ IND→ ↑ CO_2
Opoku and Boachie [40]	African countries	1980–2014	Pooled mean group estimation	CO_2 emissions, nitrous oxide, methane, GHG emissions	Insignificant effect
Wang et al. [41]	G7 countries	1990–2020	Cross-section ARDL	Ecological footprint	↑ IND→ ↑ EF
Li and Lin [24]	Low, middle, high income countries	1971–2010	Dynamic panel threshold regression models	Carbon dioxide emission	↑ *IND*→ ↑ CO_2

cointegration and error correction model, [39] realized that industrialization hurts the environment. Non-renewable energy also aggravated CO_2 emissions while the squared term of industrialization, renewable energy use and financial development improved the environment. To continue, [28] affirmed the positive effect of industrialization on CO_2 emissions in Central Asia and Europe with data from 2000 to 2018 based on system GMM technique.

Using the Johansen cointegration and error correction mechanism, [18] also confirmed that industrial development in Australia accelerates CO_2 emissions. Furthermore, economic growth, financial development, energy consumption and trade openness are fundamental drivers of environmental pollution. Contrary to ref [10], ref [17]concluded that industrial development in Saudi Arabia increases carbon emissions intensity for most quantiles using the quantile on quantile (QQ) and quantile regression (QR). An early study by Ref. [24] employing dynamic panel threshold regression with data from 1971 to 2010 for 73 countries indicated that for low/middle and high-income countries, CO_2 emissions rise due to industrialization. Samour et al. [37] established the link between human capital and consumption of renewable electricity on environmental sustainability with evidence from the BRICS-T countries. Using linear and non-linear ARDL with data from 1990 to 2018, the study showed that increased human capital and increasing the consumption of renewable electricity are environmentally sustainable while industrialization and economic growth reduces load capacity factor. Fang [38] however showed that industrial structure, green technological innovations and renewable energy investment reduces CO_2 emissions in 32 provinces of China. Economic complexity index accounts for worsening environmental conditions. From the above reviews, this paper first hypothesizes as follows;

Hypothesis 1. *Valued added in manufacturing does not have a negative significant effect on load capacity factor*

Renewable energy has recently been increasingly seen as a means to ensure environmental and ecological sustainability while advancing the economy [25]. From an empirical perspective, however, the literature connecting renewable energy consumption and industrial growth is scanty. Dey et al. [27] and Van Hoang [29] are amongst the few studies that have investigated this relationship. For instance, Ref. [29] found that renewable energy consumption does not just fuel industrial production for the United States, but the source of energy also matters. Biomass energy consumption showed a stronger effect on industrial production compared to hydro-electric energy and geothermal energy but requires time for its impacts on industrial production to be felt. The study established bidirectional causality between renewable energy consumption and industrialization. Dey et al. [27] disaggregated renewable energy in to different sources; biomass, solar, wind, bagasse, small hydropower (SHP) and waste and considered their effect on sustainable industrialization in India. Based on quantile regression, renewable energy sources, especially SHP and bagasse increased industrial production in India. The study observed bidirectional non-linear causality between biomass, waste heat and industrial production and unidirectional non-linear causality with other energy sources. Mentel et al. [28] examines the relationship between industrialization and CO_2 emissions in Central Asia and Europe, considering the moderation effect of renewable energy. Using the two-step GMM and data from 2000 to 2018, the study results revealed that industrial development worsens CO_2 emissions, while the moderation effect of renewable energy turns to be negative. Based on robust least squares and Granger Causality tests, [35] further found that for Pakistan, renewable energy consumption and industrialization positively affects economic growth. From the above studies on renewable energy consumption and industrialization, this study secondly hypotheses thus;

Hypothesis 2. T*he interaction between renewable energy consumption and valued added in manufacturing has no positive significant effect on load capacity factor*

The industrialization of Africa is heavily reliant on fossil fuels. Fossil fuels, such as coal, oil, and natural gas, are used to power factories, transportation, and other industrial activities. Empirically, studies specifically investigating the effect of non-renewable energy consumption on industrialization are scarce. A number of studies have rather investigated the effect of non-renewable energy consumption on economic growth [30–34] with all finding that consumption of non-renewable energy significantly propels economic growth. For instance, 30 found that the consumption of petroleum and natural gas are the major drivers of growth among oil producing economies in Africa. Baz et al. [31] holds that fossil fuels consumption positively affects economic growth and a unidirectional causality exist. Rath et al. [32] argued that fossil fuels consumption significantly affects total factor productivity with a feedback effect. Okoye et al. [34] found that fossil fuels significantly affect economic growth in Nigeria. Mendoza-Rivera et al. [42] uncovered that non-renewable energy consumption affects the economies of Canada and the US adversely while for Mexico, the effect is positive. Mexico is still developing and fossil fuels is their major energy source and driver of industrial development.

Hypothesis 3. *The interaction between non-renewable energy consumption and value added in manufacturing has no negative significant effect on load capacity factor*

From the empirical reviews, this study identifies missing gaps and highlight the contribution of the current study. First, while many studies have separately considered how industrialization and energy consumption affect environmental degradation, none has so far interacted energy consumption and industrialization to uncover their effect on environmental degradation. The effect of industrialization on load capacity depends on whether industrialization is driven more by consumption of renewable energy or non-renewable energy, as environmental conditions largely depend on the type of energy driving economic activities. Hence the need to understand these effects. Thus, a main contribution of this study is that, first to the best of our knowledge, it is the first to analyze how renewable and nonrenewable energy consumption moderate the effect of industrialization on environmental degradation. Moreover, a study such as this appears not to exist for Africa, which is strongly advocating for industrial development. It will therefore contribute to existing literature. Second, previous studies have mostly employed greenhouse gases (such as carbon dioxide, nitrogen oxide, sulfur dioxide, methane) and ecological footprint as indicators of environmental degradation. While ecological footprint is a better indicator of environmental degradation than atmospheric gas emissions, as it further incorporates other indicators such as cropland, grazing land, built-up land, fishing grounds and forests, it fails to account for biocapacity. This paper closes this gap by using the most comprehensive indicator of environmental sustainability—the load capacity factor which captures both biocapacity and ecological footprint, hence considering both the supply side and demand side of the ecological system. From a methodological perspective, the use of the panel generalized least squares and robust panel fixed effects estimators for analytical purposes in this paper takes care of cross-section dependence, heteroskedasticity and autocorrelation, hence guaranteeing the robustness of the results.

3. Materials and methods

3.1. Data

This study employs annual time series data for 23 years, spanning between 2000 and 2022 for 46 African countries, making up 1058 observations. The time period and number of countries selected was due to data availability. Some African countries were excluded from the analysis because observations were completely missing or largely incomplete for some variables within the period. The list of African countries included in this study is presented on Table 1A of the appendix. The data used was obtained from a number of internationally recognized sources, including the Global Footprint Network (GFN), World Bank's World Development Indicators (WDI) and the Food and Agricultural Organization (FAO). Table 2 presents the symbols of the variables, their units of measurement and corresponding sources of data.

3.2. Justification of variables

The selection of variables relevant for the econometric analysis of this study is informed from recent empirical studies.

3.2.1. Dependent variable

3.2.1.1. Load capacity factor (LCF). Load capacity factor (LCF) is used in this study as a measure of environmental sustainability. Of recent, environmentalists increasingly favour it as a measure of environmental degradation than greenhouse gases (such as carbon dioxide, nitrogen oxide, sulfur dioxide, methane) and ecological footprint which are often used, arguing that LCF is a more comprehensive measure as it considers both the supply and demand side of the ecological system. The other measures neglect the supply side [8,43–45]. While ecological footprint (EF), which encompasses six environmental indicators; cropland, grazing land, built-up land, fishing grounds, emissions of CO_2 and forests is a better measure of environmental degradation than atmospheric emissions [17,36], it neglects the productivity of ecological assets known as biocapacity. By considering both the EF and biocapacity, the LCF becomes superior to EF as a measure of environmental deterioration, as it assesses whether countries are surpassing their sustainability limit. Based on this indicator, the environment is sustainable if the LCF is 1 or higher and unsustainable if it is less than 1. The sustainability limit is 1 [43].

3.2.2. Independent and control variables

3.2.2.1. Manufacturing (valued added). Manufacturing, value added, defined as sum of gross output less value of intermediate factor inputs [46] is used in this study to measure industrial development. Li & Li [7], Opoku & Aluko [17] and Aladejare & Nyiputen [36] employed value added in manufacturing as the proxy for industrialization. Though other studies have used value added in industry, including construction [8,14,18], Ref. [17] argues that value added in industry underestimates the impact of the manufacturing sector, as it includes sectors like water, electricity, construction and mining which dampens manufacturing. Furthermore, target 9.2 of SDG 9 which focuses on promoting inclusive and sustainable industrialization aims at increasing the value added in manufacturing in GDP. Manufacturing is harmful to the environment through release of gases, heavy metals and toxic chemicals from manufacturing plants in to the atmosphere, land and water bodies, causing degradation of all types. Thus, this study expects that manufacturing, value added should negatively affect the load capacity factor.

3.2.2.2. Population. Population is captured in this study by urban population, defined by the 44 as the people living in urban areas as defined by national statistical offices. It has been argued that the effect of population on the environment can be positive, negative or

Table 2
Variables, units of measurement and sources of data.

Short name	Variable description	Definition and units of measurement	Source of data
LCF	Load capacity factor	Hectares	GFN
MAN	Total manufacturing	Current million US dollars	FAO
REC	Renewable energy consumption	Percent of total final energy consumption	World Bank World Bank
GHG	Total greenhouse gas emissions	Kiloton (kt) of CO_2 equivalent	World Bank
POP	Population, total	Total population, million people	
OPEN	Openness	Trade (percent of GDP)	World Bank
TNR	Total natural resources rents	Percent of GDP	World Bank
GDPPC	Per capita GDP	Current US dollars	World Bank

Source: Authors (2023).

both. Aladejare &Nyiputen [36] contends that while urbanization can increase the consumption of fossil fuels energy through an increase in the demand for housing, transportation and energy, it can also negate it when environmentally-friendly energy sources and transportation models are used. Ali et al. [10], Voumik & Sultana [14], Li & Lin [24] also document the negative environmental effects of urbanization. On the basis of the above works, population is expected to reduce environmental sustainability.

3.2.2.3. Renewable energy consumption. Renewable energy consumption is defined as the proportion of renewable energy in total final energy consumption [46]. Increased renewable energy consumption has been noted to reduce GHG emissions and pollution in general, thereby improving environmental sustainability. Though [8] found that renewable electricity consumption both increase and have a neutral effect on load capacity factor [14,16], cited that renewable energy consumption benefits the environment. A priori, this study expects renewable energy consumption to positively affect the load capacity factor.

3.2.2.4. Fossil fuels energy consumption. Fossil fuels energy consumption comprises energy from non-renewable sources such as coal, oil, petroleum, and natural gas products [46]. Rahman & Alam [39] holds that non-renewable energy is detrimental to the environment. This study uses GHG emissions as the proxy for fossil fuels energy consumption, due to the missing data for fossil fuels energy consumption for most of the countries studied. The expectation in this study is that an increase in GHG emissions should reduce environmental sustainability, owing to the direct link between non-renewable energy consumption and environmental degradation.

3.2.2.5. Total natural resources rents. Total natural resources rents (NRR) are defined as the total of mineral rents, forest rents, oil rents, coal rents (hard and soft) and natural gas rents [46]. These are revenues or rewards from the extraction of natural resources and incentivize their exploitation. Africa is abundantly rich in these resources which provide a great potential for industrialization. But their rapid exploitation brings environmental decadence. More importantly, natural resources degradation affects ecological footprint through destruction of cropland, grazing land, fishing grounds, built-up land and forest area [16,36,41]. Following from these studies, an increase in natural resource rents will reduce the load capacity factor.

3.2.2.6. Openness. Openness is captured by trade as a percentage of GDP, defined by Ref. [46] as the sum of exports and imports of goods and services as a share of GDP. The tendency is for high polluting manufacturing firms to relocate to countries with less stringent environmental regulations, and this is facilitated when countries are more open. Developing countries mostly find themselves in this situation. Thus, openness reduces environmental sustainability. Opoku & Aluko [17] have supported this view. The expectation therefore is that openness should adversely affect the environment.

3.2.2.7. Gross domestic product per capita. Gross domestic product (GDP) per capita, defined as GDP divided by the midyear population. Gross domestic product is the gross value added by all resident producers in the economy less subsidies plus expenditure taxes. It includes depreciation of fabricated assets and depletion and degradation of natural resources. Economic growth causes degradation of natural resources and overall environmental damage. Numerous empirical studies [8,14,18,36,40] have revealed that economic growth, measured by GDP causes degradation of the environment. Hence, in this study, we expect increased economic growth to lead to a reduction in the load capacity factor.

3.3. Review of Africa's industrial development

The manufacturing industry is of strategic importance in the development process. Innovation and research and development conducted by manufacturing firms remains the key driving force behind world technological advancement. In addition, the manufacturing sector has spill-over effects in other sectors like the financial sector in terms of the consumption of transportation, insurance and banking services. The sector has linkages with the agricultural sector through transformation of agricultural raw materials, and creates employment [47].

The pace of Africa's industrialization is slow. Most African economies are still highly involved in producing primary products, which remain vulnerable to global demand and supply shocks. There is limited structural change towards more productive activities and the labour market is under performant, as job creation is less than labour supply. The Covid-19 pandemic exposed the structural weaknesses of African economies, with high dependency of countries on foreign manufactured goods especially pharmaceuticals and medical equipment needed for immediate response to the health shock. The inability of Africa to integrate in to global value chains during the pandemic meant that the economic gains realized during the pre-covid 19 period could not be maintained and economic growth cannot be sustained [48]. Notwithstanding the dismal performance of Africa's industrial sector, some countries; Botswana, Gabon, Mauritius, Algeria, South Africa and Namibia are already advanced in manufacturing with others showing great signs of industrializing. For instance, the leather industry is rapidly growing in Ethiopia and pharmaceuticals in East Africa. Morocco, Rwanda and Ethiopia are constructing networks of industrial and special economic zones (SEZs) and taking other measures to promote growth of small and medium size enterprises.

According to Ref. [48], deindustrialization is on course in Africa. Manufacturing as a share of GDP decreased from 13% in 2000 to 10% in 2017 for Sub-Saharan Africa and 28%–20% in North Africa. Statistics from the FAO [49] data base shows a downward trend in valued added in manufacturing as a percentage of GDP for different African regions, as graphed in Fig. 1. Southern Africa is leading other regions in their share of manufacturing to GDP. For Southern, Northern, Western, Central and Eastern African regions, value added in manufacturing as share of GDP was respectively about 14%, 11%, 11%, 10% and 10% between 2000 and 2021 on the average. The regional average was about 12% within the same period.

The continent has largely been excluded from global value chains development due to poor performance of its manufacturing sector. About 80% of Africa's manufactures are locally consumed or traded in African markets, with value added to only about 14% of exports.

3.4. Empirical model

The empirical model of this study is supported by the theoretical arguments of the Stochastic Impacts Regression on Population, Affluence and Technology (STIRPAT) model and pollution haven hypothesis (PHH), following [14,17]. Furthermore, variables entering the model have been empirically supported. To estimate the effect of industrial production, and the moderating effects of renewable and non-renewable energy consumption on environmental sustainability, the following relationship between the variables is specified;

$$LCF = f(MAN, REC, GHG, POP, OPEN, TNR, GDP, MAN * REC, MAN * GHG) \tag{1}$$

Where; MAN is value added in manufacturing, REC is renewable energy consumption, GHG is GHG emissions, POP is population, OPEN is openness of the economy, TNR is total natural resources rents, GDP is per capita gross domestic product (GDP), MAN*REC is the interaction between manufacturing and renewable energy consumption and MAN*GHG is the interaction between manufacturing and GHG emissions used as proxy for fossil fuels energy consumption. Transforming Eq. (1) to a stochastic specification gives;

$$\begin{aligned} lnLCF_{it} = \beta_0 + \beta_1 lnMAN_{it} + \beta_2 REC_{it} + \beta_3 \ln GHG_{it} + \beta_4 POP_{it} + \beta_5 OPEN_{it} + \beta_6 TNR_{it} + \beta_7 GDP_{it} + \beta_8 MAN * REC_{it} \\ + \beta_9 lnMAN * lnGHG_{it} + \epsilon_{it} \end{aligned} \tag{2}$$

A priori $\beta_1 < 0$; $\beta_2 > 0$; $\beta_3 < 0$; $\beta_4 < 0$; $\beta_5 < 0$; $\beta_6 < 0$; $\beta_7 < 0$; $\beta_8 > 0$; $\beta_9 < 0$.

Where ln is a log transformation on non-negative and non-ratio variables. Logging linearizes the variables and enable the interpretation of the estimated coefficients directly as elasticity. It also reduces the influence of outliers. The parameters, β_1 to β_9 are coefficients to be estimated, ϵ is the error term, i represents the individual country and t is the time.

3.5. Estimation methods

Prior to applying panel data techniques to estimate the coefficients of the empirical model, this paper first conducts diagnostic tests to check for cross section dependence in the panel, in line with conventional panel data procedures. Cross section dependence exists when correlation is observed amongst different cross section units. This study employs Pesaran [50] CD test to test for cross section dependence. This test is relevant when large cross sections and short time period is involved [51]. Tests of cross section dependence inform the choice of either first generation or second-generation unit root tests or both. The null hypothesis of this test is that cross section independence exists against the alternative of cross section dependence. First generation panel unit root tests of [52,53] and the Fishers's test of Maddala & Wu [54] are relevant when cross section independence exist. In the presence of cross section dependence, Pesaran [55] and Pesaran [56] panel unit root tests are used.

This study employs two estimators to estimate the coefficients of the model; the fixed effects model and generalized least squares technique. The fixed effects model analyzes the impact of variables that change over time and across different entities, which in this case are the African countries. It takes care of the intrinsic characteristics of these countries in a panel data structure, thereby treating

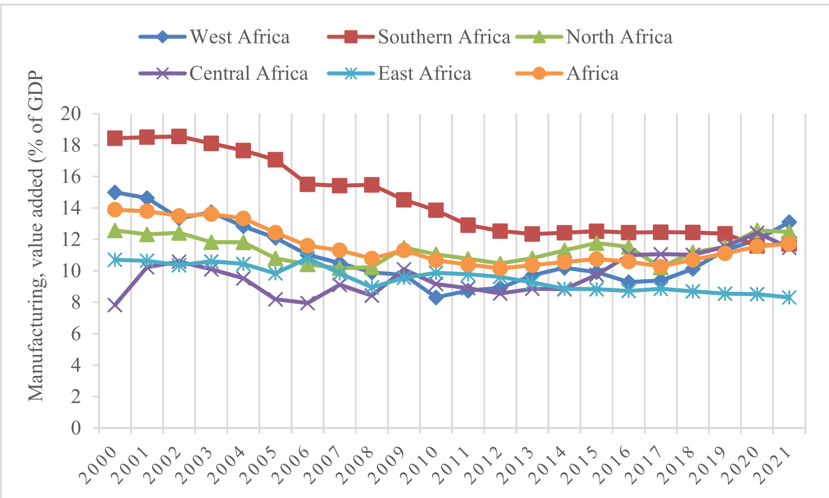

Fig. 1. Value added in manufacturing across African regions.

each country as heterogenous. This study considers robust estimators for the fixed effects model in order to correct for possible cross section dependence, heteroskedasticity and autocorrelation in the data.

The panel feasible generalized least squares (GLS) technique is also employed to estimate the coefficients of Eq. (2), as it tackles the problems of serial correlation, heteroskedasticity and cross-sectional correlations which often characterize the random terms of panel regression models. In the presence of heteroskedasticity, serial and cross-sectional correlations, the GLS estimator is more efficient than the ordinary least squares as it consistently estimates the large error covariance matrix [57].

4. Results and discussion

4.1. Descriptive statistics of the data

We first present the mean, standard deviation, minimum and maximum values of the variables to understand the nature of data used. This is shown on Table 3.

From Table 3, the overall sample size of the study is 1058, involving 46 African countries over a 23-year period. It shows the overall, between and within country variations for each variable. A visible trend in the dataset is that for all variables, the overall variations are explained more by the between group than the within group variations. This signifies a heterogenous pattern in the data, indicating the differences inherent in African countries included in this study. On the average, the load capacity factor for the total sample is 1.99 global hectares which exceeds the sustainability limit of 1, indicating high potentials for environmental sustainability in Africa. However, the overall minimum load capacity factor is 0.13 global hectares while the maximum is about 25 global hectares. This shows wide disparity in sustainability levels, notwithstanding the fact that the overall average shows the environment is sustainable. Most countries included in this study [28], actually have sustainability levels below 1 (see the appendix). Thus, the overall average is conditioned by the 18 countries with high sustainability levels.

The mean manufacturing for countries studied is 4469.78 million USD, which is substantially lower than the world average (10,451,807 million USD) within the same period [49], suggesting that the African manufacturing industry still has a long way in order to at least meet up with the other continents. Renewable energy consumption on the average is 59.35% of total final energy consumption, far above the world average (17%) within the period. This is said to be propelled by hydroelectric power, which constitutes about 75% of total energy consumption for Africa. Hydroelectricity is by far the most dependable source of renewable energy in Africa compared to other forms of renewable energy such as solar, wind, tidal and geothermal energy. Total GHG emissions for the 46 African countries is about 54,577 kt of CO_2 equivalent on the average, which makes up only 0.13% of the world's 43046356.94 kt of CO_2 equivalent on the average [46]. Though Africa relies mostly on fossil fuels for energy needs, its contribution to CO_2 emissions is highly insignificant compared to Asia, Europe and America. The average population stands at 22 million people, almost half the world average of 56 million people over the study period. Africa is the world's second largest and most populated continent. Between 2000

Table 3
Summary statistics of the variables.

Variable		Mean	Std.Dev.	Min	Max	Observations
Load capacity factor	Overall	1.99	3.74	0.13	24.89	N = 1058
	Between		3.69	0.22	21.86	n = 46
	Within		0.79	3.10	11.14	T = 23
Manufacturing	Overall	4469.78	10037.43	13.63	65952.78	N = 1058
	Between		9324.64	45.65	45546.95	n = 46
	Within		3951.07	−18731.47	35685.70	T = 23
Renewable energy consumption	Overall	59.35	30.28	0.009	98.34	N = 1058
	Between		30.16	0.26	96.53	n = 46
	Within		5.09	35.82	93.73	T = 23
GHG emissions	Overall	54577.10	94675.36	304.47	585421.60	N = 1058
	Between		94432.39	447.15	505035.10	n = 46
	Within		15216.84	−81680.20	5643.15	T = 23
Population	Overall	22.09	31.47	0.46	218.54	N = 1058
	Between		31.11	0.53	167.36	n = 46
	Within		6.53	−22.41	73.27	T = 23
Openness	Overall	70.95	36.98	16.35	347.99	N = 1058
	Between		32.38	32.48	191.22	n = 46
	Within		18.47	−31.33	227.73	T = 23
Total natural resources rents	Overall	12.07	12.44	0.002	88.59	N = 1058
	Between		10.86	0.03	42.31	n = 46
	Within	6.28		−18.76	59.42	T = 23
Per capita GDP	Overall	2204.13	2698.39	110.46	19849.72	N = 1058
	Between		2440.05	201.14	10132.03	n = 46
	Within		1204.73	−6400.84	11921.82	T = 23

and 2022, trade makes up 70.9% of Africa's GDP on the average, more than the world's average of 55.9%. Trade remains an important linkage between Africa and the rest of the world. The launching of the African Intercontinental Free Trade Area in 2018 will further open the continent up to trade. Table 3 also indicates that on the average, total natural resources rents contribute about 12% to GDP, by far greater than the world average of only 2.8% [46]. Indeed, Africa possess tantalizing potentials of natural resources, which forms a base for her economic and social development.

4.2. Cross-section dependence and unit root test

Table 4 reports the output of cross-section dependence test. From the results, it is observed that the p-values of the CD test for all variables is significant at 1% level. Hence, the null hypothesis of cross section independence is rejected for load capacity factor, manufacturing, renewable energy consumption, GHG emissions, population, openness, total natural resources rents and foreign direct investment. Thus, the data are correlated across heterogenous panels, suggesting that for these variables, similarities exist for African countries.

Given the presence of cross section dependence in the data, second generation panel unit root tests are employed to test the time series properties of the variables. Results of Pesaran's CADF and CIPS unit root test are reported on Table 5.

Pesaran's CADF unit root test result on Table 5 shows that all variables are stationary at level, I (0), indicating the absence of unit roots in the data. Apart from trade openness with a Z [t-bar] statistic being significant at 5% level, the Z [t-bar] statistic for the rest of the variables shows significance at 1% level. Pesaran's CIPS test results also confirm stationarity at level for all the variables, since the value of the CIPS test statistic is greater than the critical values at different levels of significance. Apart from trade openness which is significant at 10% level, the rest of the variables are significant at 1%. Since all variables were stationarity at levels, tests for long equilibrium relationships became irrelevant for this study, as cointegration is often only in the case of non-stationary data.

4.3. Pairwise matrix of correlations

To ensure the regressors of our empirical model are not strongly correlated, especially given the introduction of interaction terms, the pairwise matrix of correlations is computed, with the results being reported on Table 6.

From Table 6, manufacturing, population, gross domestic product and the interaction between GHG emissions and manufacturing are weakly and negatively associated with the load capacity factor, and equally significant at 10% level. Thus, they can worsen environmental sustainability and vice versa. On the other hand, renewable energy consumption, GHG emissions, openness, total natural resources rents and the interaction between renewable energy consumption and manufacturing are positively and weakly related to load capacity factor. Thus, the environment is not threatened by these factors over the study period. The correlations between independent variables are not greater than 0.8, thus multicollinearity is absent in the regression model.

4.4. Empirical results

The empirical findings of this study, based on the robust panel fixed effects estimator (column 1) and feasible generalized least squares estimator (column 2) are presented on Table 7. The p-values of the Frees and Pesaran's tests of cross section dependence are respectively 0.2129 and 0.2085, hence we fail to reject the null hypothesis of cross section independence, validating the use of the fixed effects estimator.

The first objective of this study was to analyze the effect of value added in manufacturing on load factor capacity. From Table 7, the coefficient of value added in manufacturing is negative, as a priori expected. What this means is that the growth of the manufacturing industry in Africa will lead to adverse environmental conditions. Quantitative results indicate that environmental sustainability will dwindle by 0.145% and 0.04% for a 1% increase in manufacturing output respectively for the fixed effects and generalized least squares estimates and both results are significant at 1% level. On this premise, the first null hypothesis of this study, that value added in manufacturing does not have a negative significant effect on load capacity factor is rejected. Hence, manufacturing sector development negates environmental sustainability in Africa and should therefore be at the fore of environmental policies formulation in Africa. Though Africa contributed only about 0.13%, on the average to the world's emission of greenhouse gases between 2000 and 2022 [46], the manufacturing sector in Africa currently accounts for about 30%–40% of total greenhouse gas emissions (about 440 megatons of

Table 4
Cross-section dependence test on variables.

Variable	CD test	p-value	Cross-section dependence
Log of load capacity factor	74.50***	0.000	Yes
Log of manufacturing	124.02***	0.000	Yes
Log of renewable energy consumption	59.51	0.000	Yes
Log of GHG emissions	88.47***	0.000	Yes
Log of population	151.95***	0.000	Yes
Openness	>11.38***	0.000	Yes
Log of total natural resources rents	110.88***	0.000	Yes
Log of per capita GDP	35.09***	0.000	Yes

Note: ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

Table 5
Second generation panel unit root tests on variables.

Variables	Pesaran's CADF test	Pesaran's CIPS test	
	Z [t-bar]	CIPS	Stationarity level
Log of load capacity factor	−6.639***	−2.759***	I (0)
Log of manufacturing	(0.000)	−3.027***	I (0)
	−7.001***		
	(0.000)		
Log of renewable energy consumption	−4.863***	−2.535***	I (0)
	(0.000)		
Log of GHG emissions	−8.196***	−2.936***	I (0)
	(0.000)		
Log of population	−8.357***	−3.025***	I (0)
Openness	(0.000)	−2.605*	I (0)
Log of total natural resources rents	−1.659**	−2.245***	I (0)
Log of GDP per capita	(0.049)	−2.563***	I (0)
	−2.559***		
	(0.000)		
	−6.027***		
	(0.000)		

Note: *** $p<0.01$, ** $p<0.05$, * $p<0.1$.

Table 6
Pairwise correlation matrix of the variables.

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
(1) lnlcf	1.00									
(2) lnman	−0.13*	1.00								
(3) rec	0.43*	−0.26*	1.00							
(4) lnghg	0.03	0.84*	−0.11*	1.00						
(5) lnpop	−0.04	0.73*	0.22*	0.84*	1.00					
(6) open	0.06*	−0.20*	−0.38*	−0.27*	−0.48*	1.00				
(7) tnr	0.33*	−0.04	−0.03	0.13*	−0.04	0.19*	1.00			
(8) lngdppc	−0.18*	0.40*	−0.74*	0.16*	−0.25*	0.37*	0.13*	1.00		
(9) rec*lnman	0.19*	−0.31*	0.34*	−0.33*	−0.21*	0.22*	0.00	−0.13*	1.00	
(10) lnghg*lnman	−0.41*	−0.04	−0.28*	−0.11*	−0.06	−0.08*	−0.12*	0.13*	−0.20*	1.00

Note: ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$. Llc = log of load capacity factor; lman = log of manufacturing; rec = renewable energy; lghg = log of GHG emissions; lpop = log of population; open = openness; tnr = total natural resources rents; lgdppc = log of per capita GDP; rec*lman = interaction between renewable energy consumption and manufacturing; lghg*lman = interaction between GHG emissions and manufacturing.

CO_2 equivalent), according to Ref. [5]. Furthermore, the effect of manufacturing on environmental degradation is felt through the discharge of wastewater containing chemicals, heavy metals, and other pollutants into rivers, lakes, and oceans. Water pollution has a devastating impact on ecosystems and human health. Industrial activities consume a high quantity of resources such as raw materials, water and energy, leading to the depletion of natural resources. This result is consistent with previous studies by Refs. [7,8,14,17,18,36] who align with the fact that manufacturing activities worsens environmental quality. Particularly, Ref. [36] uncovered that Africa's industrial pollution emanates from the agricultural, forestry, transport, food retail, fashion and energy sectors, thereby creating undesired effects such as extinction of wildlife species, deforestation, waste generation and water scarcity. Our empirical findings also corroborates with that of [8] who found in the case of South Africa that industrialization and economic growth adversely affects the load capacity factor. The above result is expected for Africa, which is still at an early stage of its industrialization drive.

The empirical results also support the argument that consumption of renewable energy brings about an increase in environmental sustainability. For both fixed effects and generalized least squares estimates on Table 7, the load capacity factor increases each by about 0.01% due to a 1% increase in renewable energy consumption. At 1% level of significance, this study therefore concludes that environmental sustainability significantly improves with increased consumption of renewable energy. Renewable energy plays a significant role in reducing greenhouse gas emissions, improving energy security, and promoting economic growth in Africa. This result is supported by those of [8,14,16] who found that renewable energy consumption is beneficial to the environment. For example, Ref. [8] showed that renewable electricity consumption increased load capacity factor both in the short run and long run for South Africa. Voumik & Sultana [14] also found that renewable energy use mitigates environmental degradation in newly industrialized countries.

The effect of GHG emissions, the proxy for non-renewable energy consumption on the load capacity factor is positive. This means increasing GHG emissions will increase environmental sustainability, all things being equal. Though, this finding does not align with the norm, in the African context, this suggest that CO_2 emissions can still increase without posing a threat to the environment especially given that Africa's contribution to global emissions is negligible. However, this finding is insignificant for both estimators. In contrast to this result, Refs. [39,58] argue that consumption of non-renewable energy exacerbates greenhouse gas emissions, and worsens

Table 7
Robust panel fixed effects and generalized least squares estimates.

Dependent variable: *load capacity factor*		
	(1)	(2)
Variables	FE	GLS
Log of manufacturing	−0.145***	−0.0403**
	(0.0528)	(0.0158)
Renewable energy consumption	0.0101***	0.0102***
	(0.00361)	(0.000834)
Log of GHG emissions	0.0905	0.0229
	(0.104)	(0.0200)
Log of population	−0.0330*	−0.0234***
	(0.0179)	(0.00314)
Openness	−0.0485	−0.0107
	(0.0760)	(0.0243)
Log of total natural resources rents	−0.0113	−0.00441
	(0.0165)	(0.00785)
Log of GDP per capita	−0.0292	−0.0148
	(0.0497)	(0.0200)
Interaction term1 (rec*man)	0.245***	0.00504
	(0.0650)	(0.0353)
Interaction term2 (ghg*man)	0.0288*	−0.0417***
	(0.0150)	(0.00617)
Constant	0.272	−0.0704
	(1.021)	(0.228)
Observations	1058	1058
R-squared	0.501	
P-value Frees CD test	0.2129 0.2085	46
P-value Pesaran's CD test	46	
Number of id		

Note: ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

environmental sustainability.

Population has a negative effect on environmental sustainability, as it negates the load capacity factor. We expect an increase in population to exert more pressure on cropland, grazing land, built-up land, fishing grounds, CO_2 emissions and forests than the regenerative capacity of the biologically productive area, hence increase in environmental degradation. Specifically, for the fixed effect model, the load capacity factor reduced by 0.03% when population grows by 1% and by 0.02% for generalized least squares estimates. Both outcomes are not only almost equal in magnitude but are equally significant. Thus, population significantly reduces environmental sustainability in Africa within the study period. This result is consistent with those of [10,14,24,36,40] who agree that urbanization and population growth negatively affect the environment. Africa's population is increasing rapidly and this is having a significant impact on the environment. Being dominantly an agrarian economy, agricultural employment constitutes between 65 and 70% of Africa's labour force, supporting 90% of livelihood according to OECD & FAO (2016) and World Bank (2016) as cited by Ref. [59]. FAO [49] puts the share of employment in agriculture, forestry and fishing in total employment at about 48% in 2021 down from 58% in 2000. Overall, population growth increases the demand for resources, pollution, deforestation, desertification and loss of biodiversity. This result signals the need for African governments, not to institute population control measures, but to ensure environmental policies are strong enough to mitigate the negative effects posed by the growing population.

Table 7 result also reveals that trade openness reduces environmental sustainability, signaling that globalization increases environmental degradation, hence the increased opening of African economies to international trade and foreign manufacturing companies is expected to reduce environmental degradation. Fixed effect estimate shows a 0.05 unit decrease while generalized least squares estimates indicates that a 0.01 unit decrease in environmental sustainability if the coefficient of openness increases by 1 unit respectively. For both results however, the effect of openness is insignificant. The negative effect of openness points to the validity of the pollution haven hypothesis in Africa. Because of stricter environmental regulations in developed nations, foreign heavy polluting companies are forced to relocate to developing countries with weak environmental regulations. This increases environmental degradation. This is because trade can lead to increased production and consumption, which can put a strain on natural resources and lead to pollution. Some previous studies have also found a negative but rather significant effect of openness on environmental degradation [17,60,61] thereby supporting the pollution haven hypothesis.

Furthermore, the empirical findings reveal that natural resources rents negate environmental sustainability in Africa. Natural resource rents incentivize the exploitation of natural resources which in turn lead to environmental degradation. Furthermore, revenues from natural resource extraction can provide a source of income used to finance unsustainable development practices. This result is consistent with expectation especially in the African context, where there is high dependence on natural resources for growth and development [62]. For both estimates, this effect is however insignificant. To buttress this result [60], found natural resource rents to significantly destroy the environment in Morocco, Nigeria, Egypt, South Africa and Algeria. Others have also associated a decrease in ecological footprint to natural resources exploitation [16,36,43]. For this study, the negative insignificant effect of natural resource rents on load capacity factor suggest that further resource exploitation will inhibit the sustainability of the environment.

Per capita GDP adversely affects the load capacity factor, indicating that accelerating economic growth will decrease environmental sustainability in Africa. This is because economic growth requires the extraction and utilization of natural resources, which leads to pollution and habitat destruction. Additionally, growth can result to increased resource consumption, which can also seriously strain the environment. The negative effect of income growth on the environment is supported by other studies such as [7,8,14,17,36,43]. For this study however per capita GDP has an insignificant effect on load capacity factor. This suggests that African countries still possess the potentials to grow their economies without the fear of harming the environment.

The interaction between renewable energy consumption and value added in manufacturing or their combined effect is positive. This means that the effect of manufacturing on environmental sustainability in Africa will increase, if more renewable energy is consumed. In other words, when industrial development is driven by renewable energy consumption, manufacturing will have a positive environmental sustainability effect. This finding suggests that industrialization growth in Africa can be sustainable so long as renewable energies constitute the major source of energy used for industrial activities. This interaction further means that as the manufacturing sector expands, it would it would need more renewable energy, which will in turn increase the load capacity factor, thereby improving environmental sustainability. Thus, the negative effects of manufacturing on environmental degradation are offset by the positive impacts of deploying renewable energies for manufacturing. This result aligns with [27,29] which found that renewable energy accelerates and is accelerated by value added in manufacturing. Also, in the case of Central Asia and Europe [28], found that industrialization degrades the environment through increased emissions of CO_2. However the interaction between industry and renewable energy is negative, highlighting the role renewable energy should play in reversing the negative impacts of non-renewable energy associated with industrialization. Furthermore, according to a report by UNECA [63], sustainable industrial development in the Central African sub-region is being propelled by renewable energies which augments energy supply, thereby increasing energy efficiency and reducing industrial-related environmental destruction. The positive effect of renewable energy consumption on growth in Pakistan as established by Ref. [35] implies that industrial activities are benefitting from renewable energy deployment, further confirming the result of this study. The implication of our result for the African countries is to increase renewable energy deployment in industrial operations.

The results of Table 7 show a positive interaction between non-renewable energy consumption and manufacturing for the fixed effect model. As in the case of renewable energy consumption, this result suggests that the effect of manufacturing on load capacity factor will be positive as more of non-renewable energy is used for industrial production. This does not imply that the deployment of fossil fuels in production is not harmful, but could instead imply that for Africa, the environmental consequences of using fossil fuels is not pronounced yet. Again, expansion in industrial processes increases consumption of fossil fuels. This finding contradicts that of [58] which argues that fossil fuel consumption is harmful to the environment but supports the many studies [30–34] which posit that non-renewable energy stimulates growth. Being the main source of energy for most countries especially developing countries, fossil fuels are the main energy source for manufacturing, hence economic growth. The GLS results of this study point to a negative interaction effect between non-renewable energy consumption and value added in manufacturing on environmental degradation. What this implies is that so long as fossil fuels consumption continue to drive industrial production in Africa, the effect of manufacturing on the environment will be negative. This is supported by the works of [39,58] which report a negative effect of fossil fuels consumption on the environment.

5. Conclusion and policy implications

A key policy objective for African countries is how to achieve sustainable industrialization—promote industrial development while curbing its environmental consequences, consistent and in furtherance of target two of sustainable development goal nine (SDG9), which is to promote inclusive and sustainable industrialization. Against this backdrop, this study sets out to analyze the effect of industrialization on environmental sustainability in African countries, taking in to consideration the moderation effect of renewable and non-renewable energy consumption. This is based on the understanding and argument that the environmental impacts of manufacturing are directly linked to the form of energy driving industrial development. Notably, from the start of the industrial revolution, non-renewable energy has been the dominant source of energy, but with its increasing contribution to greenhouse gas emissions and climate change, emphasis has been shifted to renewable energy consumption. Data for the study was obtained from a number of sources such as the Global Footprint Network, World Bank's World Development Indicators and the Food and Agricultural Organization from 2000 to 2022 for 46 African countries. The inclusion of countries in the study were based solely on availability of data. The load capacity, a more comprehensive indicator of environmental degradation than carbon dioxide emissions (CO_2) and ecological footprint was used as a measure of environmental sustainability. The data was analyzed using the panel fixed effects model and generalized least squares (GLS) method. The fixed effects estimator was robust, to automatically handle the problems of autocorrelation heteroskedasticity which are common with panel fixed effects regressions. The GLS estimator was relevant in the presence of autocorrelation, heteroskedasticity and cross section correlation. The empirical results showed that value added in manufacturing negatively and significantly affects the load capacity factor, hence industrialization increases environmental degradation, thereby retarding environmental sustainability in Africa. However, after accounting for the type of energy used in the industrialization process, manufacturing exerted a positive effect on the load capacity factor when interacted with renewable energy consumption. The implication here is that renewable energy has the ability to propel industrial progress in Africa while minimizing the environmental effects. The moderating effect of non-renewable energy and manufacturing is inconclusive, but increased fossil fuels consumption should affect environmental degradation negatively. Based on the above results, this study proposes short, medium and long term policy implications. In the short term, African countries should continue advancing their industrialization agenda by using cleaner fossil fuels or natural gas, as renewable energy use in the manufacturing sector is still at an embryonic stage and the renewable energy sector is still at infancy. This should be done while increasing the awareness of the necessity to transition to sustainable and renewable energy. In the medium term, African countries should double their investment in renewable energy technologies development while gradually transitioning to it. Also, African governments should institute and encourage green loans for investment at low interest rates. In the long term, Africa should grow her manufacturing industry by extending the range of manufactured products from light to heavy manufactures while prioritizing the use of renewable energy as the primary source of industrial energy supply.

For the current study, value added in manufacturing and energy consumption (renewable and non-renewable) were not decomposed in to their separate components and different indicators of environmental sustainability were not used for a comparative analysis. For specific policy prescription, a decomposition analysis of this nature is proposed. Future research should also consider country-specific studies.

Data availability statement

Data will be made available on request.

CRediT authorship contribution statement

Nkwetta Ajong Aquilas: Writing – original draft, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Forbe Hodu Ngangnchi:** Writing – review & editing, Validation, Resources, Investigation. **Mukete Emmanuel Mbella:** Writing – review & editing, Resources, Methodology, Investigation.

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.

Appendix

Countries below the sustainability limit		Countries above the sustainability limit	
Country	Load capacity factor	Country	Load capacity factor
Sierra Leone	0.99	Democratic Republic of Congo	21.86
Burkina Faso	0.93	Gabon	10.79
Senegal	0.88	Congo Republic	9.80
Tanzania	0.88	Central African Republic	5.90
Niger	0.84	Equatorial Guinea	2.94
Togo	0.69	Namibia	2.90
Gambia	0.68	Madagascar	2.70
Ghana	0.64	Angola	2.44
Benin	0.61	Guinea Bissau	2.37
Lesotho	0.60	Mozambique	2.32
Nigeria	0.58	Mauritania	1.97
Zimbabwe	0.58	Zambia	1.73
Burundi	0.51	Cameroon	1.59
Ethiopia	0.51	Guinea	1.47
Uganda	0.51	Mali	1.47
Eswatini	0.50	Cote D'ivoire	1.43
Kenya	0.50	Botswana	1.30
Tunisia	0.49	Chad	1.10
Rwanda	0.47		
Morocco	0.45		
Djiboutti	0.44		
South Africa	0.39		
Cabo Verde	0.35		
Algeria	0.33		
Comoros	0.25		
Mauritius	0.25		
Libya	0.24		
Egypt	0.22		

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