Onyeneke *et al. Carbon Research* (2024) 3:53
https://doi.org/10.1007/s44246-024-00130-3

Carbon Research

ORIGINAL ARTICLE Open Access

Impact of Information and Communication Technologies and Renewable Energy Consumption on Carbon Emissions in Africa

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Abstract

The pursuit of economic growth has implications for carbon emissions and climate change. Achieving low carbon development is important for attaining the targets of the sustainable development goals. Africa is often described as a largely import-dependent continent. The continent also requires significant investment in information and communication technologies (ICT) and renewable energy to achieve low-carbon economic growth. However, empirical evidence on the joint impacts of imports of goods and services, clean energy use, ICT, and economic growth on carbon emissions in Africa is scanty and mixed. This paper investigated the impacts of information and communication technologies, renewable energy consumption, import and economic growth on carbon emissions by using rich data on total per capita carbon dioxide (CO_2) emissions, economic growth, import of goods and services, renewable energy consumption, fixed telephone subscriptions, mobile cellular subscriptions, and individuals using the internet in Africa (2001 — 2020) obtained from the World development indicators (WDI) database. Using the Panel autoregressive distributed lag model (PARDL), we found that mobile cellular subscriptions, and level of economic growth significantly increased per capita CO_2 emissions in Africa in the long run while renewable energy consumption and technologies and import of goods and services significantly decreased per capita CO_2 emissions in the long run. We conclude that information and communication technologies, level of economic growth, import of goods and services, and renewable energy consumption exert impacts on carbon emissions in Africa.

Highlights

- Achieving low-carbon development in Africa is possible.
- This research investigated the impacts of information and communication technologies, renewable energy consumption, import and economic growth on carbon emissions in Africa.
- This study utilized the Panel autoregressive distributed lag model and panel data from 31 African countries.
- The results shed new light on the emission reduction potential of renewable energy consumption and import of goods and services. The study also shows that ICTs increase carbon emissions in Africa.
- This article offers recommendations concerning carbon emissions reduction.

Handling Editor: Fengchang Wu

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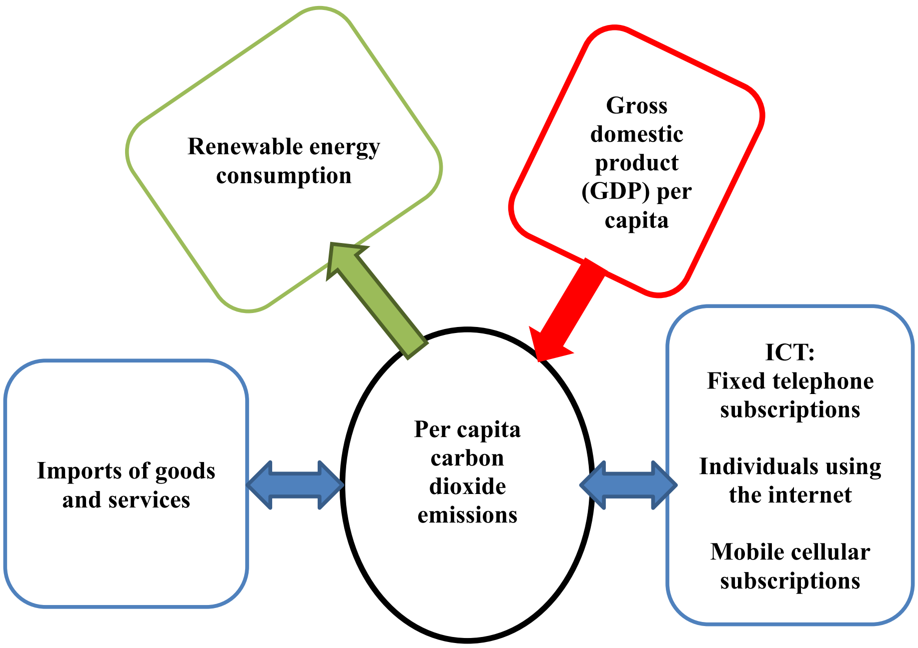
Keywords Fixed telephone use, Mobile cellular use, Carbon emissions, Import of goods and services, Renewable energy consumption, Panel autoregressive distributed lag model, Internet access

Graphical Abstract



1 Introduction

Climate change remains a global challenge with the effect going beyond national borders (Benzie and Persson 2019). The rise in sea levels, disruption in weather patterns (extreme heat), etc., continue to pose an existential threat to human lives and livelihoods (Nguyen et al. 2020). The impact of carbon emissions on climate change has been a concern for global leaders with a call on governments to adopt environmentally responsive approaches to economic growth and development. In response, countries worldwide have inclined to enact or adopt policies and practices that can lessen the negative effects of global warming on the environment and achieve carbon neutrality (Yu et al. 2022). These policies and actions require substantial investments to yield the outcomes needed and therefore call for national, regional, and global commitments. This is important because the impact of climate change transcends the geographical borders of any country or region. One area which has attracted attention from researchers and policymakers is the role of information and communication technologies on global carbon emissions.

Information and communication technologies contribute about 2% of global carbon emissions (Majeed 2018; Simpson et al. 2019; Ulucak and Khan 2020). Information and communication technologies (ICTs) have permeated all facets of human life and production, contributing to improvement in access and use of the internet across the African continent (Nchake and Shuaibu 2022). This has resulted in growth and development as well as energy consumption (Yu et al. 2022; Kim 2022). ICT development has impacted global energy consumption and carbon emissions (Ren et al. 2021; Nchofoung and Asongu 2022; Lee et al. 2022a, 2022b).

The promotion of cleaner production technologies and renewable energy consumption aligns with the sustainable development objectives that aim to reduce carbon emissions and conserve global temperature (Tariq et al. 2023). Clean energy such as natural gas, electricity, and renewable energy sources has lower carbon content than traditional fuel sources including coal and wood. Access to clean and renewable energy is therefore essential in the global campaign to reduce carbon emissions for a healthier, happier environment and livelihoods. Energy from renewable sources and technology is essential to achieve sustainable economic growth and development. Yahong et al. (2022) suggested that access to clean fuels and technology affects carbon emission. Similarly, clean fuels and technologies, according to Tariq et al. (2023) are helpful in reducing carbon emissions that impact negatively on environmental degradation. In this regard, a shift towards the consumption of renewable energy at both domestic and industrial levels will contribute to reducing carbon emissions. For instance, access to clean fuel at the household level can potentially reduce indoor air pollution levels and contribute to reducing the negative health impacts and deaths associated with indoor air pollution (World Health Organization [WHO] 2018).

In addition, the link between import of goods and services, economic growth and carbon emissions remains a contested space in the literature. The results of the effect of imports on carbon dioxide (CO_2) emissions from previous studies are mixed. For example, Kim (2022) avers that the Organization for Economic Cooperation and Development (OECD) countries have profited from technological advancements and innovation in developed countries through trade openness (especially import of goods and services), and this has improved the environmental quality. Other scholars have a divergent view. Amri (2018) and Faisal et al. (2020) reported that trade openness negatively impacts the environment. There have been remarkable increase in internet penetration in Africa in recent years. However, it is reported that Africa still lags behind in technological advancement (Owolabi et al. 2023). Africa can take advantage of the technological advancements of developed countries through imports. However, the effect of imports and ICT usage on carbon emissions in Africa is understudied. More so, economic growth has generally been associated with increases in carbon emissions due to the increase in energy consumption, and production of goods and services. Some scholars however hold the view that economic growth helps in reducing carbon emission levels (Lee and Brahmasrene 2014; Oryani et al. 2021). The data suggests that trade volumes are linearly correlated with carbon emissions. For instance, data from the World Development Index (WDI) shows that trade volume increased by 450% between 1980 and 2012. Over the same period, the Energy information administration (EIA) of the United States estimates that the amount of carbon emissions increased by 75% (EIA 2013). This is not limited to only developed countries. Carbon emissions have significantly gone up in developing countries and expected to be 127% higher that developed countries by 2040 (EIA 2013). Wang et al. (2014) argued that the rise in carbon emission in developing countries may be due to free trade policies and high demand for energy.

Available literature suggests that carbon emission increases with economic growth (Kasman and Duman 2015), making the nexus between economic growth and carbon emissions a major concern in the fight against global carbon emissions. While economic growth remains the primary preoccupation of developing and emerging economies, the more developed economies have been concerned about the environmental consequences and how to minimise them (Raworth 2017). Our study therefore examines the impacts of information and communication technologies (ICT), and other control variables such as access to clean fuels and technologies, imports of goods and services and economic growth on carbon emissions in Africa. Due to data availability, the sample includes 29 African countries only. Current literature on the role of ICT on carbon emission has been biased in favour of the Asian countries which lacks the contextual perspective. Moreover, literature on the impact of ICT, renewable energy consumption, imports and economic growth is scant, especially that relate to Africa.

Previous studies have established the ICT and carbon emissions nexus largely in developed countries with little attention on emerging economies. In fact, the studies related to developing countries have focused on China and India with very little attention on the African continent, especially sub-Saharan Africa. Resolving the ICT carbon emissions nexus requires multi-country level data over a period (Tsaurai 2019). It is therefore important to empirically investigate this relationship from developing countries perspective. The paper therefore aims to address this gap in literature using multi-country data from 29 African countries. Despite Africa being a developing continent, ICT penetration has been impressive in the past decade. This makes the inclusion of selected African countries appropriate for the study. The objectives of the study include analysing the impact of ICT on carbon emissions in Africa and determining the effect of other control variables (clean energy use, import of goods and services, and economic growth) on carbon emissions in Africa.

To address the research objective, multiple indicators (fixed telephone subscriptions, mobile cellular subscriptions, and individuals using the internet) were used in this study to measure ICTs impact on carbon dioxide (CO_2) emissions. This approach was considered superior and more comprehensive relative to existing studies that have used specific indicators such as mobile phone subscription or fixed broadband subscription as a measure of ICT.

The study deployed the Panel autoregressive distributed lag model. The findings suggest that renewable energy consumption has a significantly negative effect on per capita CO_2 emissions in Africa. That is, as more and more people in Africa use renewable energy, per capita CO_2 emissions will reduce. This finding is consistent with a priori expectation and that of the literature. For instance, Tariq et al. (2023), Chidiebere-Mark et al. (2022) and WHO (2018) argued that access to clean fuel and technologies and renewable energy consumption reduce carbon emissions. The study further suggested that ICT indicator (i.e, mobile cellular subscriptions) contributes to per capita CO_2 emissions in Africa. This finding aligns with the school of thought that ICTs contribute to greenhouse gas emissions. The works of Malmodin and Lundén (2018a), Asongu (2018), Lu (2018), Özcan and Apergis (2017), and Higón et al. (2017) belong to this school of thought. However, it remains unknown if the energy used to power the ICT equipments accounts for the carbon emissions, or if the effect is a reflection of a spillover effect.

The remainder of this paper is structured as follows. The literature review is presented in Sect 2, data and research methodology are discussed in Sect 3. Section 4 presents the results and discussion respectively. The final section (Sect 5) presents the conclusion of the paper and policy recommendations.

2 Literature review

2.1 Renewable energy consumption and carbon emissions

Global energy consumption and carbon emissions have witnessed significant increases in recent decades (Ahmad and Zhang 2020). The increasing world's population and the environmental degradations have contributed to affecting the achievement of global sustainable development. Finding appropriate energy consumption mix that reduces the negative impact on the environment remains a concern for humankind (Bogdanov et al. 2021). Renewable energy resources defined as the energy that comes from natural sources such as sunlight, wind, rain, tides, and geothermal heat, which are renewable (naturally replenished) appear as a strategic solution to this global challenge. It is estimated that nearly a fifth (18%) of global energy consumption in 2014 came from renewable sources and half of that was sourced from traditional biomass used mostly for heating, while the other half was sourced from hydro, wind, and solar power (Dong et al. 2020; Ahmad and Zhang 2020).

Renewable energy has many forms and continues to evolve with advancement in the development of technologies. Renewable energy sources are important because they are clean, carbon emission free, and a cleaner alternative to fossil fuel (Hoang et al. 2021). The major type of renewable energy is solar energy, which is derived from the radiation of the sun, wind energy, which is generated from the movement of the wind, geothermal energy generated from the heat produced inside the earth, tidal energy which is generated from the motion of the water caused by the gravitational pull of the sun and the moon, and wave energy produced by the motion of the waves. Thus, renewable energy can offer a range of possibilities and it is clear that increasing research in this area will lead to further renewable options in the future, which would be useful in different circumstances and will contribute to the reduction of pollution (Sutopo et al. 2020; Salimi et al. 2022).

Despite the known benefits of adopting renewable energy sources, factors such as initial capital investment serves as a barrier to the adoption and consumption of renewable energy (Zebra et al. 2021; Zafar et al. 2021). That is, compared to the traditional energy sources such as fossil fuels that have well-established technology, renewable energy tends to be more expensive at the initial stage and many people may not be able to afford it. Other factors such as geography, and government policies have also been identified to contribute to the uptake and consumption of renewable technologies (Yang et al. 2021a, 2021b; Abbasi et al. 2022; Usman et al. 2022).

Several scholars have attempted to determine the impact of renewable energy on carbon emissions (Saidi and Omri 2020; Akram et al. 2020; Doğan et al. 2021; Kirikkaleli et al. 2022). Kumar (2020) for example explored the consumption of renewable energy in the context of climate change and focused on the impact that renewable energy has on reducing carbon emissions. In his research, Takawira observed that renewable energies such as solar and wind have benefits in the reduction of greenhouse gases and subsequently lessen the impacts of climate change. In examining the causal relationship between renewable energy consumption and carbon emissions, Saad and Taleb (2018) concluded that an increase in renewable energy consumption significantly reduces carbon emissions. According to Ma and Oxley (2012), renewable energy reduces environmental degradation and carbon emissions. Similarly, the literature clearly establishes that increase in renewable energy consumption is associated with lowered carbon emissions. The evidence further shows that increase in renewable energy consumption led to substantial decrease in carbon emissions, making adoption of renewable energy a critical solution to reducing carbon emissions (Khan et al. 2020; Jebli et al. 2020; Dong et al. 2020; Yuping et al. 2021; Bekun 2022).

Other similar previous studies investigated the link between renewable energy consumption and carbon emissions. Research suggests that using renewable energy can lower carbon emissions and improve environmental quality (Doğan and Pata 2022; Pata et al. 2024). For example, Chidiebere-Mark et al. (2022) discovered that renewable energy usage is connected with lower carbon dioxide emissions in a sample of 31 African countries during a 20-year period. This suggests that switching to renewable energy sources can play an important role in decarbonizing the energy sector and meeting the sustainable development goals.

However, the relationship between renewable energy consumption and carbon emissions is complex and nuanced. Some studies have identified potential obstacles and constraints in completely replacing fossil fuels with renewable energy sources. Chen et al. (2022) for example found that countries with stronger institutions and developed nations have lower carbon dioxide emissions per capita growth when they consume a specific amount of renewable energy. However, for countries that consume less than these threshold amounts of renewable energy, increasing renewable energy consumption does not result in a decrease in CO_2 emissions per capita. The results highlight the importance of reaching a particular level of renewable energy consumption to successfully cut carbon emissions, with institutional quality and development status. The findings highlight the importance of achieving a particular level of renewable energy consumption in order to effectively reduce carbon emissions, with institutional quality and development status being critical in determining the influence of renewable energy consumption on emissions reduction. However, the expense of shifting to renewable energy may provide a significant barrier in some developing countries.

2.2 ICTs and carbon emissions

Information and communication technologies (ICTs) refer to a wide range of different technologies. This could be assessed from different perspectives. For instance, from a data collection and analysis perspective, it can often be difficult to isolate emissions that are specifically due to the use of ICTs. Emissions may occur due to the direct use of ICT equipment, such as computers, or they may arise from the services enabled by ICTs, such as online shopping. Several scholars concluded that growth in the ICT sector and increased use of ICTs are leading to a rapidly growing carbon footprint from ICTs (Faisal et al. 2020; Raheem et al. 2020: Nguyen et al. 2020; Anser et al. 2021; Haini 2021). Emissions may come from direct sources (emissions that are owned or controlled by the reporting entity) or indirect emissions sources (emissions that do not occur as a consequence of the actions of the reporting entity, but from sources that are neither owned nor controlled by that entity) (Raheem et al. 2020; Usman et al. 2021).

The relationship between ICTs and carbon emissions is a complex and multidimensional one. On one hand, ICTs offer innovative solutions that can help reduce carbon emissions by enabling virtual communication, remote work, and digital services (Doğan and Pata 2022). These advancements have the potential to replace traditional carbon-intensive practices such as physical meetings, commuting, and paper-based transactions (Pata and Destek 2023). On the other hand, the growing demand for ICT devices and services has led to an increase in energy consumption and carbon emissions. The manufacturing process of these devices involves the extraction and processing of raw materials, energy-intensive production stages, and the disposal of electronic waste. Understanding and managing this relationship is crucial for sustainable development and minimizing the carbon footprint associated with ICTs.

Similarly, mobile phone subscriptions have become ubiquitous in today's society, connecting people from all corners of the world (Economic and Social Commission for Asia and the Pacific 2020; Hui et al. 2022; Mapiye et al. 2023). However, the widespread use of mobile phones comes with its own environmental implications. The carbon emissions associated with mobile phone subscriptions can be attributed to various factors. Firstly, the production of mobile phones involves the extraction and processing of minerals, such as rare earth metals, which have significant environmental impacts (Murthy et al. 2021). Additionally, the manufacturing process and transportation of these devices contribute to further carbon emissions (Lundquist and Kang 2021; Prieto-Egido et al. 2023). Furthermore, the energy consumption during the usage phase of mobile phones, including charging and data usage, adds to the overall carbon footprint (Stute et al. 2020). As mobile phone subscriptions continue to rise globally, it becomes increasingly important to find sustainable solutions and reduce the environmental impact of these devices.

While the popularity of mobile phones has soared over the years, fixed phone subscriptions still play a significant role in communication networks. Evidence abounds on the contributory factors of fixed phone subscriptions in predicting carbon emissions (Ruiz et al. 2022; Ji et al. 2023; Lin and Ullah 2023; Saia 2023; Zhou et al. 2023). From landline phones to broadband connections, fixed phone subscriptions have their own contribution to carbon emissions. The manufacturing process of fixed phone devices, including landline phones and modems, involves resource extraction, energy-intensive production stages, and transportation. Additionally, the energy consumption during the usage phase of these devices contributes to carbon emissions. Despite the declining usage of fixed phone subscriptions in some parts of the world, they still remain an essential means of communication and should be taken into account when assessing the environmental impact of ICTs (Viana et al. 2022; Schien et al. 2021).

The internet has revolutionized the way humans access information, communicate, and interact with the world. The surge in demand for internet services has been associated with higher carbon emissions (Heberlein et al. 2022; Arts et al. 2023). This is due to the continued increase in the number of users and the ever-growing demand for more data and higher speeds for internet services. Internet traffic, measured in Terabytes per month, has continued to increase steadily over the past years. However, this remarkable advancement also comes with environmental implications. Internet use contributes to carbon emissions through various channels. Firstly, the energy consumption of data centers, server farms, and the infrastructure required for internet connectivity accounts for a significant portion of carbon emissions. The demand for faster data transfer and higher quality streaming services further intensifies the energy requirements, leading to a larger carbon footprint (Holland 2020; Lakshmanan et al. 2022). Moreover, the production and disposal of ICT devices, such as computers, laptops, and routers, contribute to carbon emissions. The extraction of raw materials, the manufacturing process, and the electronic waste generated from these devices all have significant environmental impacts. As internet use continues to grow exponentially, it is crucial to implement sustainable practices, such as energy-efficient technologies and responsible disposal methods, to mitigate the carbon emissions associated with this essential tool of modern life (Urbańska et al. 2023; Chinwego 2023; Das et al. 2023).

Despite a broad consensus among scholars on the possible influence of ICT in carbon emissions (Hu et al. 2022; Khan et al. 2022; Yang et al. 2021a, 2021b; Wu et al. 2021; Ren et al. 2021), academics disagree on the relationship between ICT and carbon emissions. The research has identified three main nexuses between ICT and carbon emissions: negative, positive, and non-linear or inconclusive (Yu et al. 2022; Khan et al. 2022; Faisal et al. 2020; Tshahnazi and Shabani 2019; Danish et al. 2018; Bekaroo et al. 2016; Houghton 2009). Research indicates that global efforts are being done to investigate the influence of ICT on carbon emissions (Appiah-Otoo et al. 2022; Danish et al. 2018; Malmodin and Lundén 2018a, 2018b; Asongu 2018; Lu 2018; Özcan and Apergis 2017; Higón et al. 2017). Currently, various schools of thought highlight the ICT carbon emission nexus. First, some scientists believe that ICT contributes to carbon emissions (Malmodin and Lundén 2018a; Zhang and Liu 2015; Lee and Brahmasrene 2014). Other schools of thought strongly disagree, claiming that ICT does not contribute to carbon emissions but rather reduces them (Anser et al. 2021; Lu 2018; Hart 2016; Stewart 2015). For example, the use of ICT, such as videoconferencing and virtual meetings, can enable remote work, reducing the need for driving to work and other business travels, and thereby lowering carbon emissions. Similar findings have been reported in the use of ICT in the transportation sector, where ICT has been used to implement Intelligent transport systems (ITS) to monitor real-time traffic, route optimization, and so on, resulting in lower carbon emissions (Chatti 2021; Kwakwa et al. 2022).

A third group claims that the available information on the impact of ICT on carbon emissions is insufficient and thus inconclusive (Bekaroo et al. 2016; Houghton 2009). For example, TShahnazi and Shabani (2019) conclude from their research that investment in ICT increases carbon emissions in the near run while decreasing carbon emissions in the long run. This school also argues against the premise of a relationship between ICT and carbon emissions, which has been highlighted in most empirical investigations.

2.3 Imports and carbon emissions

Several studies have looked at the link between imports and carbon emissions, providing insight on the complex interactions between international trade and environmental sustainability (Hu et al. 2020; Mpeqa et al. 2023). Import-related carbon emissions are a major problem because they represent the environmental effect of the goods and services that countries consume. According to previous findings, importing goods with high carbon intensity from countries with less stringent environmental rules might result in a cross-border transfer of carbon emissions, contributing to global carbon footprint. Furthermore, the concept of "carbon leakage" has been a focus in the literature, highlighting how imports of carbon-intensive products can offset domestic emission reductions, emphasizing the importance of comprehensive policies that consider the carbon implications of international trade. Furthermore, the literature underlines the necessity of international collaboration and harmonized environmental standards in addressing carbon emissions from global trade and transitioning to a more sustainable and low-carbon economy.

2.4 Economic growth and carbon emissions

The relationship between GDP/economic growth and carbon emissions has been extensively studied in the fields of environmental economics and sustainability. Studies have frequently identified a positive relationship between economic growth, as measured by GDP, and carbon emissions, implying that when economies expand, they tend to emit higher quantities of greenhouse gases. This pattern, known as the environmental Kuznets curve, argues that environmental degradation worsens as countries industrialize and grow economically before gradually improving once a certain level of development is reached (Ye et al. 2021; Rafindadi 2016). However, the research emphasizes the significance of decoupling economic growth from carbon emissions by implementing cleaner technology, energy-efficiency measures, and sustainable development practices.

Furthermore, researchers investigated the intricacies of the GDP-carbon emissions link across countries and regions, taking into account aspects such as energy consumption habits, industrial structure, and governmental interventions (Zhang et al. 2023; Ata et al. 2023). Previous research has shown that, while economic growth is often associated with increased carbon emissions, there is a potential to promote sustainable development pathways that prioritize environmental conservation and carbon reduction (Aye and Edoja 2017). The relationship between economic growth and carbon emissions has been well studied. For example, in Turkey, Ozatac et al. (2017) employed the Autoregressive Distributive Lag (ARDL) to estimate the incidence of pollution haven hypothesis from 1963 to 2013. The result confirmed the Environment Kuznet Curve phenomenon. Likewise, majority of previous studies observed the incidence of Environment Kuznet Curve phenomenon such as Emenekwe et al. (2023) in the globe; Galvan et al. (2022) in middle income countries; Shahbaz et al. (2017) for G-7 nations; Dong et al. (2017) in China; Aung et al. (2017) in Myanmar; and Apergis et al. (2017) in United States of America.

Table 1 List of countries studied

Code	Country
1	Algeria
2	Angola
3	Benin
4	Botswana
5	Burkina Faso
6	Burundi
7	Cabo Verde
8	Cameroon
9	Chad
10	Côte d'Ivoire
11	Egypt
12	Eswatini
13	Gabon
14	Gambia
15	Ghana
16	Kenya
17	Madagascar
18	Mali
19	Mauritania
20	Mauritius
21	Morocco
22	Namibia
23	Senegal
24	South Africa
25	Tanzania
26	Togo
27	Tunisia
28	Zambia
29	Zimbabwe

3 Methodology

3.1 Data source

The paper primarily used data from twenty-nine (29) African countries where access to clean energy, level of economic growth, and access to information and communication technologies are still low, and import dependency high. Please see Table 1 for the list of countries.

Twenty-nine (29) African countries were sampled due to data availability and used in the final analysis. Panel data obtained from the World development indicators (WDI) were used for this paper. Per capita carbon dioxide emissions was the dependent variable while renewable energy consumption, fixed telephone subscriptions, individuals using the internet, mobile cellular subscriptions, imports of goods and services, economic growth (proxied by GDP per capita) were the independent variables. The variables and their descriptions are presented in Table 2.

3.2 Econometric strategy

The paper used the pooled mean group and dynamic fixed effect estimators of the Panel autoregressive distributed lag regression to model the long-run and short-run impacts of clean fuels and technologies, information and communication technologies, imports and economic growth on carbon emissions in Africa. The estimation approach provides several advantages (including cross-sectional dependence, flexibility, mixed integration orders and unit roots) over the use of other standard panel regression estimation techniques including panel fully modified ordinary least square, dynamic ordinary least square models, etc.

Other panel regression approaches do not produce lagged output (Baltagi 2008), and this is against the popular strong-path-dependency evidence in carbon emissions (Gasser et al. 2018). Also, other standard panel regression estimation approaches assume homogenous gradient for the cross-sectional units (in this case the countries) (Baltagi 2008). However, this is not true in Africa considering the different levels of economic development, internet access, mobile phone

Table 2 Variables and descriptions

Variable	Description
Renewable energy consumption (% of total final energy consumption)	Renewable energy consumption is the share of renewables energy in total final energy consumption.
Fixed telephone subscriptions	Fixed telephone subscriptions refers to the sum of active number of analogue fixed telephone lines, voice-over-IP (VoIP) subscriptions, fixed wireless local loop subscriptions, ISDN voice-channel equivalents and fixed public payphones.
Individuals using the internet (% of population)	Internet users are individuals who have used the Internet (from any location) in the last 3 months.
Mobile cellular subscriptions	Mobile cellular telephone subscriptions are subscriptions to a public mobile telephone service that provide access to the PSTN using cellular technology.
Imports of goods and services (% of GDP)	Imports of goods and services represent the value of all goods and other market services received from the rest of the world.
GDP per capita (constant 2015 US$)	Gross domestic product divided by midyear population. Data are in constant 2015 US$.
CO_2 emissions (metric tons per capita)	Carbon dioxide emissions are those stemming from the burning of fossil fuels and the manufacture of cement.

Source: World development indicators (World Bank 2023)

subscriptions, fixed telephone subscriptions, imports of goods and services, and access to clean energy in the countries (Aluko et al. 2021; Chidiebere-Mark et al. 2022; Onyeneke et al. 2023b, c). Moreover, other panel regression estimation techniques require the variables to demonstrate cross-sectional independence with same order of integration (Baltagi 2008). However, macroeconomic variables such as access to clean energy, imports of goods and services, economic growth, and information and communications technologies use traditionally demonstrate cross-sectional dependence with different orders of integration and unit roots. Neglecting the cross-sectional dependence, mixed orders of integration and unit roots could produce spurious results that can affect policy decisions. These factors therefore require an estimation technique that addresses all the shortcomings in standard panel regression techniques. The Panel autoregressive distributed lag (PARDL) model addresses these shortcomings because it is more flexible, and controls heterogeneous gradients, cross-sectional dependence, mixed integration orders and unit roots (Bildirici 2014). The PARDL and autoregressive distributed lag models also produce both short-run and long-run dynamics of the explanatory variables on the dependent variable (Chidiebere-Mark et al. 2022; Emenekwe et al. 2022a, 2022b; Onyeneke et al. 2023d; Onyeneke et al. 2024; Elom et al. 2024a; Munonye et al. 2024) which are important for policymaking.

Identifying the short-run dynamics of each group (in this case country) is important in estimating the long-run impacts and rate of adjustment of in the long term. The Hausman test was used to determine which of the two estimators – pooled mean group (PMG) and dynamic fixed effect (DFE) estimators – would be preferred.

The implicit model of the Panel autoregressive distributed lag regression used is stated as follows:

$$Y = f(X1, X2, X3, X4, X5, X6, \varepsilon) \tag{1}$$

where

$Y = CO_2$ emissions (metric tons per capita).

$X1 =$ Renewable energy consumption (% of total final energy consumption).

$X2 =$ Fixed telephone subscriptions.

$X3 =$ Individuals using the internet (% of population).

$X4 =$ Mobile cellular subscriptions.

$X5 =$ Imports of goods and services (% of GDP).

$X6 =$ GDP per capita (constant 2015 US$).

$\epsilon =$ *error term.*

The observations were converted to their natural logarithmic values to reduce heteroscedasticity in the dataset. The explicit form of the panel ARDL model is thus stated:

$$\begin{aligned}\Delta \ln Y_{it} = {} & \beta_i + \beta_{1i} \ln Y_{i,t-1} + \beta_{2i} \ln X1_{i,t-1} + \beta_{3i} \ln X2_{i,t-1} + \beta_{4i} \ln X3_{i,t-1} + \beta_{5i} \ln X4_{i,t-1} \\ & + \beta_{6i} \ln X5_{i,t-1} + \beta_{7i} \ln X6_{i,t-1} + \sum\nolimits_{j=1}^{p_1} \gamma_{1ij} \Delta \ln Y_{i,t-j} + \sum\nolimits_{j=1}^{p_2} \gamma_{2ij} \Delta \ln X1_{i,t-j} \\ & + \sum\nolimits_{j=1}^{p_3} \gamma_{3ij} \Delta \ln X2_{i,t-j} + \sum\nolimits_{j=1}^{p_4} \gamma_{4ij} \Delta \ln X3_{i,t-j} + \sum\nolimits_{j=1}^{p_5} \gamma_{5ij} \Delta \ln X4_{i,t-j} \\ & + \sum\nolimits_{j=1}^{p_6} \gamma_{6ij} \Delta \ln X5_{i,t-j} + + \sum\nolimits_{j=1}^{p_7} \gamma_{7ij} \Delta \ln X6_{i,t-j} + \epsilon_{it},\end{aligned} \tag{2}$$

where Δ is first differences, β_i is a constant, $\gamma_{nij(n=1,\ldots,7)}$ are short-run coefficients, $\beta_{mi(m=1,\ldots,7)}$ denote long-run coefficients and ϵ_{it} is an error term.

4 Results and discussion

4.1 Summary statistics

The results of the summary statistics of the dependent and independent variables are shown in Table 3. The results show that average renewable energy consumption was 53.77%. This implies that slightly more than half of the population use renewable energy in the region. This indicates that a slight majority of individuals and families use renewable energy. The use of non-renewable energy by the remaining 46.33% resulted in emission of greenhouse gases, and this adversely affects the climate.

The result of the summary statistics shows that an average of 807,915 persons in the continent had fixed telephone subscriptions. The low subscription rate relative to the population in the continent may signify a preference for mobile cellular subscriptions. The result further shows that the minimum of the population using the internet was 0.05% and the maximum was 84.12%, with an average of 15.85% of the population using the internet. This shows low penetration of the internet in the region.

The result further shows that average imports of goods and services on the continent was 37.46% of the GDP. The result of imports of goods and services showed a modest liberalized market for trade across borders in Africa. Trade reforms and liberalization policies were predicted to facilitate economic growth (Jun et al. 2020).

The average GDP per capita (constant 2015 US$) on the continent was $2415.37. From the result, average carbon dioxide emission was 1.22 (metric tons per capita). Africa accounts for the smallest share of total greenhouse gases emitted globally (Kwakwa et al. 2022). However, Africa is highly vulnerable to climate change owing to its dependence on rain-fed agriculture.

4.2 Correlation analysis of the dependent and independent variables

The paper conducted correlation analysis to determine if the multiple independent variables exhibit independence or correlation. The result is presented in Table 4. The table shows that fixed telephone subscription, individuals using the internet, mobile cellular subscription, imports of goods and services, and economic growth yielded significant positive association with carbon emissions, while renewable energy consumption demonstrated significant negative association with carbon emissions. The table further reveals that fixed telephone subscription, individuals using the internet, mobile cellular subscription, and economic growth yielded significant negative relationship with renewable energy consumption. Individuals using the internet, mobile cellular subscription, and economic growth yielded significant positive association with fixed telephone subscription, while imports of goods and services had significant negative relationship with fixed telephone use. The table also indicates that mobile cellular subscription, imports of goods and services, and economic growth yielded significant positive association with individuals using the internet. Imports of goods and services had significant negative relationship with mobile cellular subscription while economic growth demonstrated significant positive relationship with mobile phone use. Import of goods and services was significantly and positively associated with economic growth. These results are just linear associations between the dependent and independent variables and do not connote any cause and effect between the variables. The data were further subjected to detailed econometric analysis to have in-depth knowledge of the impacts of the independent variables on the dependent variables.

4.3 Multicollinearity test

The explanatory variables in the model were subjected to a multicollinearity test using the Variance inflation factor (VIF), and the results are shown in Table 5. The result showed an absence of multicollinearity, as the

Table 3 Summary statistics

Variable	Minimum	Maximum	Mean	Std. deviation	Skewness	Kurtosis
Renewable energy consumption (% of total final energy consumption)	0.06	96.04	53.77	29.63	−0.38	− 1.32
Fixed telephone subscriptions	5340.00	11,852,539.00	807,914.75	1,833,715.62	3.48	13.00
Individuals using the Internet (% of population)	0.05	84.12	15.85	18.45	1.40	1.08
Mobile cellular subscriptions	22,000.00	102,958,194.00	12,606,589.23	19,447,268.87	2.57	7.14
Imports of goods and services (% of GDP)	13.21	113.66	37.46	13.20	1.12	2.30
GDP per capita (constant 2015 US$)	263.36	10,956.95	2415.37	2091.41	1.37	1.48
CO_2 emissions (metric tons per capita)	0.02	8.45	1.22	1.60	2.51	7.16

Number of observations = 580

Table 4 Correlation results of the dependent variables versus the independent variables

	LNX1	LNX2	LNX3	LNX4	LNX5	LNX6	LNY
LNX1	1.00						
LNX2	−0.69[a]	1.00					
LNX3	−0.40[a]	0.39[a]	1.00				
LNX4	−0.30[a]	0.57[a]	0.61[a]	1.00			
LNX5	−0.06	−0.12[a]	0.14[a]	−0.31[a]	1.00		
LNX6	−0.54[a]	0.46[a]	0.59[a]	0.15[a]	0.29[a]	1.00	
LNY	−0.64[a]	0.59[a]	0.60[a]	0.24[a]	0.23[a]	0.94[a]	1.00

[a] Correlation is significant at the 0.01 level (2-tailed)

Variable list: Y = CO_2 emissions (metric tons per capita); X1 = Renewable energy consumption (% of total final energy consumption); X2 = Fixed telephone subscriptions; X3 = Individuals using the internet (% of population); X4 = Mobile cellular subscriptions; X5 = Imports of goods and services (% of GDP); X6 = GDP per capita (constant 2015 US$)

values were less than 5. Previous studies (Emenekwe et al. 2022a; Onyeneke et al. 2023a, e; Elom et al. 2024a, 2024b; Munonye et al. 2024) have used this limit to ascertain the absence of multicollinearity. The absence of multicollinearity makes the data reliable, as it can be used for statistical inference.

4.4 Cross section dependence test

The presence of Cross-section dependence (CD) in the dataset was tested using the CD-test. The hypothesis that there is no cross-section dependence in the dataset was tested. The results of the cross-section dependence test are presented in Table 6. It was found that there is cross-section dependence in the dataset, leading to the rejection of the null hypothesis of no cross-sectional dependence at the 1% level of significance. Further tests and estimations were subsequently conducted.

4.5 Unit root tests of the variables

Before co-integration testing and examination of potential long-run and short-run relationships, it is deemed essential to assess the unit root properties of the variables to prevent spurious outcomes in the estimations. Unit root testing was performed utilizing Pesaran's Cross-section Augmented Dickey-Fuller test, the Cross-sectionally Augmented Im-Pesaran-Shin unit-root test, and the Cross-sectionally Augmented Im-Pesaran-Shin test with trend to ascertain the stationarity levels of the dependent and independent variables. The outcomes of the unit root test are displayed in Table 7. It was observed that renewable energy consumption, fixed telephone subscriptions, individuals using the internet, mobile cellular subscriptions, imports of goods and services, and carbon dioxide emissions were stationary at level according to the Pesaran's Cross-section Augmented Dickey-Fuller test. Renewable energy consumption, individuals using the internet, mobile phone subscriptions, and carbon dioxide emissions exhibited stationarity at level based on the Cross-sectionally Augmented Im-Pesaran-Shin test, while carbon dioxide emissions and import of goods and services were stationary at level under the Cross-sectionally Augmented Im-Pesaran-Shin test with trend. However, all variables were stationary at the first difference as per the Cross-section Augmented Dickey-Fuller test, Cross-sectionally Augmented Im-Pesaran-Shin test, and the Cross-sectionally Augmented Im-Pesaran-Shin test

Table 5 Multicollinearity test result using the variance inflation factor (VIF)

Independent variable	VIF	Tolerance
lnX1	2.23	0.45
lnX2	3.10	0.32
lnX3	3.27	0.31
lnX4	3.43	0.29
lnX5	1.38	0.72
lnX6	2.49	0.40

Variable list: Y = CO_2 emissions (metric tons per capita); X1 = Renewable energy consumption (% of total final energy consumption); X2 = Fixed telephone subscriptions; X3 = Individuals using the internet (% of population); X4 = Mobile cellular subscriptions; X5 = Imports of goods and services (% of GDP); X6 = GDP per capita (constant 2015 US$)

Table 6 Cross section dependence test

Variable	CD-test	*p*-value
lnY	34.19	0.000
lnX1	36.17	0.000
lnX2	13.88	0.000
lnX3	86.26	0.000
lnX4	88.04	0.000
lnX5	9.45	0.000
lnX6	42.72	0.000

Variable list: Y = CO_2 emissions (metric tons per capita); X1 = Renewable energy consumption (% of total final energy consumption); X2 = Fixed telephone subscriptions; X3 = Individuals using the internet (% of population); X4 = Mobile cellular subscriptions; X5 = Imports of goods and services (% of GDP); X6 = GDP per capita (constant 2015 US$)

Table 7 Unit root test results

H_0= All panels contain unit roots

H_0= series have unit roots

Variable	At level I(0) *t*-statistic	At first difference I(1) *t*-statistic	Decision:H_0	Result
Pesaran's Cross-section Augmented Dickey-Fuller test				
lnX1	−2.18[b]	−2.93[b]	Reject	I(0) at 1%
lnX2	−2.16[a]	−3.21[b]	Reject	I(0) at 5%
lnX3	−2.35[b]	−2.80[b]	Reject	I(0) at 1%
lnX4	−2.59[b]	−3.35[b]	Reject	I(0) at 1%
lnX5	−2.03[a]	−3.04[b]	Reject	I(0) at 5%
lnX6	−1.65	−2.21[b]	Reject	I(1) at 1%
lnY	−2.45[b]	−2.00[b]	Reject	I(0) at 1%
Cross-sectionally Augmented Im-Pesaran-Shin test				
Variable	At level I(0) *t*-statistic	At first difference I(1) *t*-statistic	Decision:H_0	Result
lnX1	−2.21[a]	−3.88[b]	Reject	I(0) at 5%
lnX2	−1.79	−3.63[b]	Reject	I(1) at 1%
lnX3	−2.50[b]	−3.82[b]	Reject	I(0) at 1%
lnX4	−2.38[b]	−3.94[b]	Reject	I(0) at 1%
lnX5	−1.95	−4.12[b]	Reject	I(1) at 1%
lnX6	−1.43	−3.24[b]	Reject	I(1) at 1%
lnY	−2.54[b]	−4.17[b]	Reject	I(0) at 1%
Cross-sectionally Augmented Im-Pesaran-Shin test with trend				
Variable	At level I(0) *t*-statistic	At first difference I(1) *t*-statistic	Decision:H_0	Result
lnX1	−2.42	−4.08[b]	Reject	I(1) at 1%
lnX2	−2.28	−3.59[b]	Reject	I(1) at 1%
lnX3	−2.45	−3.94[b]	Reject	I(1) at 1%
lnX4	−2.66	−4.06[b]	Reject	I(1) at 1%
lnX5	−2.79[a]	−4.01[b]	Reject	I(0) at 5%
lnX6	−1.89	−3.47[b]	Reject	I(1) at 1%
lnY	−2.69[b]	−4.27[b]	Reject	I(0) at 1%

[a] and [b] indicate significance at 5% and 1% levels, respectively

Variable list: Y = CO_2 emissions (metric tons per capita); X1 = Renewable energy consumption (% of total final energy consumption); X2 = Fixed telephone subscriptions; X3 = Individuals using the internet (% of population); X4 = Mobile cellular subscriptions; X5 = Imports of goods and services (% of GDP); X6 = GDP per capita (constant 2015 US$)

with trend. This indicates that the panel ARDL model is suitable for modeling the impact of the dependent variables on the independent variable. Subsequently, co-integration testing was conducted to examine co-integration among the variables using the Pedroni test and the Westerlund test for co-integration.

4.6 Cointegration tests

A co-integration test to establish a long-run relationship between the dependent and independent variables was performed. The result of the co-integration test is presented in Table 8. The result shows a long-run relationship between the dependent variable (per capita carbon dioxide emissions) and the independent variables (renewable energy consumption, fixed telephone subscriptions, individuals using the internet, mobile cellular subscriptions, imports of goods and services, and GDP per capita). The results of the Modified Phillips–Perron t, Phillips–Perron t, Augmented Dickey–Fuller t were all statistically significant at 1%, while the variance ratio test of the Westerlund test for co-integration was statistically significant at 5%.

4.7 Panel ARDL elasticities of impact of information and communication technologies, renewable energy consumption, economic growth and imports on carbon emissions

The Pooled mean group (PMG) and the Dynamic fixed effect (DFE) model was used to estimate the long-run and short-run relationship between the dependent variable (total greenhouse gas emissions) and the independent variables (ICT - fixed telephone subscriptions, individuals using the internet, mobile cellular subscriptions) and control variables (renewable energy consumption, imports of goods and services, and GDP per capita) in the presence of cross-section dependence. The results of the PMG and DFE estimates are presented in Table 9. The Hausman test was used to determine the method that best fits the dataset and to determine the most appropriate model. The Hausman test result showed that the PMG model is most suited, and it had the highest number of variables being significant in both the long and short run. The result of the PMG model was used for further discussion.

The result in Table 9 shows that renewable energy consumption significantly decreased per capita carbon dioxide emissions in the long run and in the short run. A 1% increase in renewable energy consumption decreased carbon dioxide emissions by 0.14% in the long run. With a large population growth in Africa, uptake of renewable energy and technologies will significantly mitigate greenhouse gas emissions. The effect in the reduction in greenhouse gas emissions will be more profound if a larger number of the population switches to and renewable energies in the long-run. Aemro et al. (2021) suggested that if renewable carbon-free electricity is used, that electric cook stoves can reduce CO_2 emissions by 100%.

The result of the effect of ICT usage on per capita carbon dioxide emissions shows that only mobile cellular subscriptions significantly affected per capita carbon dioxide emissions in the long-run. Fixed telephone subscriptions and individuals using the internet did not exhibit significant long-run impact on per capita carbon dioxide emissions. Mobile cellular subscriptions significantly increased per capita carbon dioxide emissions in the long-run. A 1% increase in the mobile cellular subscription increased per capita carbon

Table 8 Cointegration test

***H₀*: No cointegration**		
***Hₐ*: All panels are cointegrated**		
Pedroni test for cointegration		
Test	**Statistic**	***p*-value**
Modified Phillips–Perron t	6.89	0.000
Phillips–Perron t	−9.13	0.000
Augmented Dickey–Fuller t	−7.70	0.000
Westerlund test for cointegration	**Statistic**	***p*-value**
Variance ratio	−2.04	0.021

Table 9 PARDL results from pooled mean group (PMG) and dynamic fixed effect (DFE) estimators

Variables	PMG	DFE
Panel A: long-run estimates		
lnX1	−0.14[b]	−0.20
	(−2.07)	(−1.40)
lnX2	−0.02	−0.12[b]
	(−1.02)	(−2.11)
lnX3	0.002	0.02
	(0.08)	(0.48)
lnX4	0.08[a]	−0.01
	(3.57)	(−0.16)
lnX5	−0.27[a]	0.18
	(−3.86)	(1.46)
lnX6	0.69[a]	0.15[b]
	(5.50)	(2.11)
Panel B: short-run estimates		
ECT	0.18[a]	0.18[a]
	(2.89)	(7.31)
ΔlnX1	−2.19[a]	−0.33[a]
	(−3.79)	(−6.56)
ΔlnX2	0.10	0.05[b]
	(1.50)	(2.26)
ΔlnX3	0.04	0.02
	(0.95)	(1.10)
ΔlnX4	−0.01	0.03
	(−0.47)	(1.21)
ΔlnX5	−0.02	0.01
	(−0.61)	(0.38)
ΔlnX6	0.63[a]	0.63[a]
	(4.52)	(7.00)
Constant	0.86[a]	0.47
	(2.84)	(1.15)
Hausman test of poolability (*H₀*: difference in coefficients not systematic)		
		PMG and DFE
$\chi^2(6)$		0.01
p-value		1.0000
Decision		The PMG is preferred over the DFE

z-values are presented in parentheses. [a] denotes statistical significance at 1%, [b] denotes statistical significance at 5%, and. ECT is the error correction term of adjustment towards the long-run equilibrium. Variable list: Y = CO_2 emissions (metric tons per capita); X1 = Renewable energy consumption (% of total final energy consumption); X2 = Fixed telephone subscriptions; X3 = Individuals using the internet (% of population); X4 = Mobile cellular subscriptions; X5 = Imports of goods and services (% of GDP); X6 = GDP per capita (constant 2015 US$)

dioxide emissions by 0.08%. Though the use of ICT brings improvements in energy efficiency and economic growth, the production and consumption of ICT technologies may significantly increase carbon emissions from the energy used in the process (Kwakwa et al. 2022). Ebaidalla and Abusin (2022) argued that high ICT usage may result in high energy use, and this increases carbon emissions. ICT use may contribute to carbon emissions from all the processes - electricity to power the gadgets, internet traffic, importation of gadgets, dual mobile telephone ownership and subscription, e-waste, poor infrastructure, etc. However, some scholars predicted that ICT will reduce carbon emissions in other sectors through the use of smart grids, smart buildings, smart transportation, telework, digitization, smart tourism, with the potential to boost green growth, environmental sustainability and achieve the sustainable development goals by 2030 (Charfeddine and Umlai 2023; Malmodin and Bergmark 2015).

The result shows that imports of goods and services significantly decreased per capita carbon dioxide emissions in the long run. A 1% increase in imports of goods and services decreased per capita carbon dioxide emissions by 0.27%. This shows an inverse relationship. Imports of goods and services can improve access to more energy-efficient technologies and renewable energies that can reduce carbon emissions, such as solar panels. However, there are mixed results from previous research on imports of goods and services and carbon emissions. Previous scholars have established that international trade has negative impact on carbon emissions (Galvan et al. 2022; Li and Haneklaus 2022). Imports contribute to carbon emission as the goods are transported over long distances. The findings of Ho and Iyke (2019) in a study on trade openness in Central and Eastern Europe, contradict earlier results. They established that high trade openness in the long-run is linked with low CO_2 emissions.

Economic growth measured by GDP per capita (constant 2015 US$) significantly increased per capita CO_2 emissions in the long run. The result shows that a 1% increase in GDP per capita increased per capita CO_2 emissions by 0.69%. Though every nation aims at economic growth, our result shows that economic growth can have environmental consequences as it leads to increased CO_2 emissions. Various scholars (Danish et al. 2018; Olubusoye and Musa 2020; Osadume and University 2021) asserted that an increase in economic growth induces higher CO_2 emissions in Africa.

5 Conclusions

World leaders at the Twenty First Session of the Conference of Parties on Climate Change (COP21) committed to work together to collectively address the challenges of climate change. Despite ongoing works in the field, the COP21 brought about renewed efforts in attempts at understanding the challenges to inform policy. This study was aimed at understanding the impacts of information communication technologies, renewable energy consumption, imports of goods and services, and economic growth on carbon emissions from 29 African countries.

The pooled mean group and dynamic fixed effect estimators of the Panel autoregressive distributed lag regression were utilized to model the long-run and short-run impacts of information and communication technologies (fixed telephone subscriptions, individual internet usage, mobile cellular subscriptions), control variables (renewable energy consumption, imports of goods and services, economic growth per capita) on CO_2 emissions using panel data obtained from the World development indicators database of the World Bank.

In the analysis, a statistically significant and negative relationship between CO_2 emissions and renewable energy consumption was observed, indicating that renewable energy consumption contributes to a reduction in CO_2 emissions on the continent. The results also indicated that over half (53.77%) of the African population utilizes renewable energy, suggesting a potential for further reductions in CO_2 emissions if a larger proportion of the continent's population adopts cleaner fuels, technologies, and renewable energy sources. This underscores the need for deliberate policies that promote the consumption of renewable energy, particularly among disadvantaged populations.

Furthermore, a direct and significant relationship between information and communication technologies and per capita CO_2 emissions was identified. The findings suggested that mobile cellular subscriptions lead to increased CO_2 emissions in the long run. While ICTs can enhance efficiency and contribute to growth and development, the energy consumption associated with producing and powering ICT equipment may result in elevated CO_2 emissions. It is recommended that governments in Africa take proactive measures to adopt high-quality ICT and renewable energy technologies to complement efforts in reducing CO_2 emissions. The integration of high-quality ICT can enhance energy efficiency and support carbon emissions reduction initiatives.

The results further show an inverse relationship between imports of goods and services and per capita CO_2 emissions. That is, the import of goods and services significantly decreased per capita CO_2 emissions in the long run in Africa. This could be because production takes places outside the continent. In addition, imports of goods and services present opportunity for African governments to access efficient and cleaner technologies and renewable energies, which can contribute towards reduction in CO_2 emissions. Given the desire of African governments to industrialize, efforts must be put in place to import energy-efficient and renewable technologies that will not undo the gains achieved in reducing per capita CO_2 emissions.

More so, the results show that economic growth has a significantly direct relationship with CO_2 emissions. An increase in GDP per capita also increased per capita CO_2 emissions. The continent of Africa like many developing regions has been concerned with economic growth and development. Africa is making efforts at industrializing the continent to minimize its dependence on import. While the continent's industrialization drive has several benefits including employment creation and balance of payment dividends, it also has the potential of having an adverse effect on the environment and contributes to greenhouse gas emissions. African governments must make efforts to adopt clean and renewable energies for its production and consumption related activities to avert the impact on the environment.

The policy implications derived from the paper point to the need for a coordinated approaches in exploiting the synergies between renewable energy consumption and ICT while at the same time paying attention to the challenges and trade-offs that arise from them. One such strategy is the need to exploit the full potential of ICT in expanding the use of renewable energy resources. Such a strategy must have two foci: first, ICT should be used in the development of a responsive and efficient grid infrastructure that can support the fluctuations in supply that are associated with most renewable energy resources. Secondly, ICT should be used in the development of smart system operation algorithms and also monitoring and control interfaces that can support the integration of different renewable energy sources into the grid while at the same time minimizing the need for short term or backup power solutions.

A major limitation to the study is the lack of or incomplete data from several African countries. This explains why only 29 African countries were used for the current study. If other country-level datasets were available, the study could have benefited from additional insights from all the variables of interest across Africa. It is, therefore, imperative for African governments to be intentional in their data collection, reporting, and recording on important climate change explanatory variables such as renewable energy use, information and communication technologies (fixed telephone subscriptions, individual internet usage, mobile cellular subscriptions), imports of goods and services, and economic growth to fully monitor progress on the continent. The availability of data in the future would provide a more comprehensive analysis on the impact of ICTs, renewable energy consumption, imports of goods and services and economic growth on carbon emissions in Africa. This will make it easy to compare data with other regions of the world. The above notwithstanding, the current study employed robust analytical methods in arriving at the conclusions.

Abbreviations

CO_2	Carbon dioxide
COP21	Twenty first session of the conference of parties on climate change
CD	Cross-section dependence
DFE	Dynamic fixed effect
EIA	Energy information administration
ECT	Error correction term
GDP	Gross domestic product
ICT	Information and communication technology
ITS	Intelligent transport system
LM	Lagrange multiplier
OECD	Organization for economic cooperation and development
PARDL	Panel autoregressive distributed lag
PMG	Pooled mean group
VIF	Variance inflation factor
WDI	World development indicators
WHO	World health organization

Authors' contributions

All authors (Robert Ugochukwu Onyeneke, Nneka Maris Chidiebere-Mark, and Hayford Mensah Ayerakwa) contributed to study conceptualization. Methodology and data analysis were done by Robert Ugochukwu Onyeneke. Literature search and review were done by all authors. All authors wrote the original draft of the manuscript and reviewed and edited the manuscript. All authors have read and agreed to the published version of the manuscript.

Funding

No external funding was received for the research.

Availability of data and materials

The data used for this study are openly available. The data can be downloaded from the World development indicators' website. https://databank.worldbank.org/source/world-development-indicators#.

Declarations

Competing interests

The authors declare no known competing interests.

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Received: 15 January 2024 Revised: 8 April 2024 Accepted: 21 April 2024
Published online: 01 June 2024

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