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Renewable energy, energy efficiency, and eco-friendly environment (R-E^5) in Nigeria

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Abstract

Background: Renewable energy (RE) has been talked about for more than 30 years while there is an increased use of fossil fuels accompanied by subsequent negative environmental impacts and supply decline. This study explores the linkages between renewable energy and energy efficiency in ensuring an eco-friendly environment in Nigeria. Four independent variables (economic growth, fossil fuel energy consumption, renewable energy consumption, and population) were examined using time series data from 1981 to 2013 with pollution (CO_2) emission as an indicator (dependent variable) for environmental degradation. The study also emanates with the view of proffering policies on how the use of renewable energy resulting in energy efficiency instead of the traditional fossil fuel can be used to sustain the environment.

Methods: The autoregressive distributed lag (ARDL) bounds testing approach to co-integration and the vector error correction model (VECM)-Granger causality test were applied to estimate both long- and short-run parameters as well as the direction of causation.

Results: The results from the analysis confirmed the existence of co-integration among the variables both in long- and short-run paths. The increasing negative impact of renewable energy consumption on environmental degradation validates the renewable energy-environmental quality nexus. The increased pollution emission due to fossil fuel consumption calls for a shift in the energy consumption policy from the traditional fossil fuel to renewable energy. However, an economic growth impact on environmental degradation in the long run invalidates the environmental Kuznets curve (EKC) hypothesis for CO_2 emission in Nigeria.

Conclusions: The adoption of renewable and alternate energy resources will support sustainable growth with reduced adverse environmental impacts and ensure an eco-friendly environment in Nigeria.

Keywords: Renewable energy, Energy efficiency, Eco-friendly environment, CO_2 emission, EKC

Background

The demand for energy and its associated services, to meet social and economic development and improve human welfare and health, is on the increase. Every society requires energy services to meet basic human needs (e.g., lighting, cooking, space comfort, mobility, and communication) and to serve productive processes. Since approximately 1850, the global use of fossil fuels (coal, oil, and gas) has increased to dominate the energy supply, leading to a rapid growth in carbon dioxide (CO_2) emissions [1].

The world can become increasingly environmentally clean and friendly if countries shift to and promote the use of cleaner energy sources that are renewable. Renewable energy (RE) has been talked about for more than 30 years while fossil fuels have increased in use and declined in supply. While significant gains have been made, we are currently challenged to make the switch to renewable energy in time to avoid significant environmental and climatic changes. At the recent World Summit on Sustainable Development (WSSD), held in Johannesburg in 2002, energy was one of the most contentious issues. Setting targets for new renewable energy (defined as modern biomass, solar, the wind, and small-scale hydro, geothermal, and marine energy) as well as reducing perverse and

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harmful energy subsidies were hotly debated. In the end, no target was agreed upon. However, at the final plenary session more than 30 countries announced their commitment to promoting renewable energy sources and setting their own goals. As part of this, Germany agreed to host Renewable—which will focus on a way forward to substantially increase the proportion of new renewable energy in both industrialized and developing countries [2]. At the just concluded World Climate Summit tagged "COP21, 2015" held on 17 December 2015, governments of more than 190 nations discussed a possible new global agreement on climate change towards curbing carbon emissions [3]. In the words of Jürgen Trittin, the former German Federal Environment Minister (1998–2005):

> *I am convinced the development of renewable energies is a win-win strategy for both industrial and developing countries. Renewable brings together climate protection, poverty reduction, technology development and the securing of jobs-* [4].[1]

Climate change is a phenomenon that has remained a threat to development globally. It has been identified as one of the greatest challenges facing all nations, governments, business, and citizens of the globe and the biggest problem of the twenty-first century. The threat of climate change on our green planet "Earth" demands that the renewable energy share in the total energy generation, and consumption should be substantially increased as a matter of urgency. Climate change has implications for both human and natural systems and could lead to significant changes in resource utilization, production, and economic activities [1]. In response to the impact and possible effects of climate change due to the predominance of fossil fuel, international, regional, national, and local initiatives have been developed and implemented to limit and mitigate the future greenhouse gases (GHGs) concentration in the Earth's atmosphere [5].

Numerous examples from history illustrate how the success of civilization and human welfare is intimately linked to climate [6]. Fossil fuel use will affect future climate. Fossil fuels, currently the mainstay of economically developed and developing countries, supply energy either directly as fuel or indirectly as generated electricity, for manufacturing, agriculture, transportation, and space heating. Future GHG emissions and the resultant climate change will depend largely on the future rates of fossil fuel consumption.

The Intergovernmental Panel on Climate Change (IPCC), a body set up in 1988 by the World Meteorological Organization and the United Nations Environmental Programme to provide authoritative information about the climate change phenomenon, asserts that the warming of the last 100 years was unusual and unlikely to be natural in origin [7]. The IPCC has attributed the warming of at least the second half of the century to an increase in the emission of greenhouse gases into the atmosphere, largely caused by human activity: CO_2 is produced by the burning of fossil fuels (coals, oil, gas) as well as by land use activities such as deforestation; methane is produced by cattle, rice agriculture, fossil fuel use, and landfills, whereas nitrous oxide is produced by the chemical industry, cattle feedlots and agricultural soils. As humans have increased their levels of production and consumption, greenhouse gas emissions have also increased. Since 1750, at the time of the industrial revolution, the emission of CO_2, methane, and nitrous oxide have increased by 31, 15, and 17 %, respectively. Moreover, the emissions of these gases continue to rise steadily [8].

Many complex and interacting factors determine the consumption rate of fossil fuels. Demand is a result of population growth rate, availability of fossil fuel, energy efficiency, conservation measures and use of non-fossil energy sources, general industrial productivity, energy policy, and future climate [9]. All these factors will affect the fossil fuel utilization rates and the future climate.

Nigeria is one of the highest emitters of greenhouse gases in Africa [10]. The practice of flaring gas by the oil companies operating in Nigeria has been a major means through which greenhouse gases are released into the atmosphere. Carbon dioxide emissions in this area are among the highest in the world [11]. Some 45.8 billion joules of heat are discharged into the atmosphere of the Niger Delta from flaring 1.8 billion ft^3 of gas every day [6]. Gas flaring has raised temperatures and rendered large areas uninhabitable. Between 1970 and 1986, a total of about 125.5 million m^3 of gas was produced in the Niger Delta region, about 102.3 million m^3 (81.7 %) were flared, while only 2.6 million m^3 were used as fuel by oil-producing companies and about 14.6 million m^3 were sold to other consumers [12, 13]. The use of renewable energy sources will reduce the over dependence on the burning of fossil fuel. Moreover, instead of flaring gas in Nigeria, the gases can be converted to methanol and used as a fuel for both domestic and industrial use. With good energy efficiency practices and products, the burning of fossil fuel for energy will be greatly minimized.

Though some researches on the use of renewable energy to mitigate climate change have been carried out, such researches failed to empirically identify the best combination of energy needed to mitigate or ensure an eco-friendly environment in Nigeria. Against this backdrop, the study intends to close this gap by identifying the combination of energy consumption that reduces the emission of GHGs capable of ensuring an eco-friendly environment for sustainable development in Nigeria. The two questions underpinning this study are as follows:

1. Does renewable energy consumption mitigate climate change and promote an eco-friendly environment in Nigeria?
2. Can economic growth improve the environmental quality in the long run?

The objective of the study, therefore, revolves around the following:

1. To investigate the potentials of renewable energy consumption to mitigate climate change and promote an eco-friendly environment in Nigeria and
2. To assess the probability of economic growth in improving environmental quality in the long run.

An auto-regression distributed lag (ARDL) model analysis is used to estimate the environmental impact of both fossil fuel and non-fossil fuel consumption with the aim of examining the contribution of renewable and green energy in ensuring an eco-friendly environment in Nigeria.

Theoretical issues

Climate change scenario in Nigeria

GHGs are gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and emit radiations at specific wavelengths within the spectrum of thermal infrared radiation emitted by the Earth's surface, the atmosphere itself, and by the clouds. The primary greenhouse gases are water vapor (H_2O), carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4), and ozone (O_3) [9]. Although carbon dioxide is the most abundant of the greenhouse gases, methane and nitrous oxide have more global warming potential than carbon dioxide. Carbon dioxide emission should be strictly under control in Nigeria. Even though the emission level in Nigeria is not so significant, the impact of such GHGs emitted in one location may be felt in a completely different location. Major areas of greenhouse gas emissions include the burning of fossil fuels in cars as well as in industrial processes and deforestation leading to a high concentration of carbon dioxide in the atmosphere. In Nigeria, the most important sources of greenhouse gases include electricity generators, motor vehicles, waste dumps, burning of fuel wood and coal, agricultural activities, land use changes and deforestations, gas flaring, and bush burning in general [10]. In addition to the CO_2 emission, these processes emit methane, sulfur dioxide, and nitrous gases.

Nigeria's energy scene

The energy consumption mix in Nigeria is dominated by fuelwood (50.45 %), petroleum products (41.28 %), and hydroelectricity (8 %). Coal, nuclear, geothermal, tidal, the wind, and solar energy are currently not part of Nigeria's energy mix, as they have either been neglected, not discovered, or are currently at their early stage of development [14]. The energy utilization sector in Nigeria can be grouped into industry, transport, commercial, household, and agricultural sectors. Fuelwood is used by over 60 % of people living in the rural areas and 80 % of Nigerians as an energy source. Nigeria consumes over 50 million metric tons of fuel wood annually, which is a major cause of desertification and erosion in the country. The rural areas are generally inaccessible due to the absence of good road networks, even with the ongoing power reform and privatization of the electricity industry; it is obvious that for logistic and economic reasons, rural areas which are remote from the grid and/or have low power purchase potential will not be attractive to private power investors. Meanwhile, electricity is required for basic developmental services as well as economic growth. The absence of reliable energy supply has left the rural populace socially backward and their economic potentials untapped [14].

The transport sector is a consumer of oil accounting for 60 % of the total consumption. Despite the vast oil and gas reserves, a small amount is used in Nigeria. The country imports more than 70 % of domestic fuel requirements because none of the four refineries have functioned efficiently. The high oil import bill exposes Nigeria's energy sector to the external energy price shocks. Nigeria has the ninth largest natural gas reserve in the world and exports large quantities of liquefied natural gas (LNG) to other countries, but her gas-dominated electricity grid still experiences frequent collapses due to inadequate gas supply and obsolete infrastructures. Nigeria flares 75 % of its natural gas for lack of processing facilities and that amounts to 12.5 % of all globally flared gas [10].

For Nigeria to meet up with its energy needs, it must look for alternative energy sources especially for the rural populace. While it is recognized that renewable energy cannot solve all of Nigeria's energy problems, renewable energy technology is still seen as having a significant unexploited potential to enable the countries to meet their growing energy requirements. If renewable energy is properly harnessed, it could meet a significant proportion of energy demand with less deteriorating effects on the environment.

Renewable energy potentials in Nigeria

Hydro energy The country is reasonably endowed with large rivers and some few natural falls. Small rivers and streams also exist within the present split of the country into 11 River Basin Authorities, some of which maintain minimum discharges all year round. Hydropower currently accounts for about 29 % of the total electrical power supply. In a study carried out in 1990 in 12 states and 4 river basins, over 278 unexploited small hydropower (SHP) sites with total potentials of 734.3 MW were identified [15]. However, SHP potential sites exist in virtually all parts of Nigeria with an estimated total capacity of 3500 MW. They indicate that Nigeria possesses the potential renewable source of energy along her numerous river systems, a total of 70 micro-dams, 126 mini dams, and 86 small sites have been identified. A private company, the Nigerian Electricity Supply Company (NESCO), and the government have installed eight SHP stations with an aggregate capacity of 37.0 MW in Nigeria. Most of these stations are found around Jos at Kwall and Kurra Falls. The total technically exploitable hydropower potential based on the country's river system is conservatively estimated to be about 11,000 MW of which only 19 % is currently being tapped or developed [16]. These rivers, waterfalls, and streams with high potentials for hydropower, if properly harnessed, will lead to decentralized use and provide the most affordable and accessible option to off-grid electricity services, especially to the rural communities.

Solar energy Nigeria lies within a high sunshine belt and thus has enormous solar energy potentials. Solar radiation is fairly well distributed with an average solar radiation of about 19.8 MJm^{-2} day^{-1} and average sunshine hours of 6 h per day. If solar collectors or modules were used to cover 1 % of Nigeria's land area, it is possible to generate 1850×10^3 GWh of solar electricity per year, which is over 100 times the current grid electricity consumption level in the country [17].

Several pilot projects, surveys, and studies have been undertaken by the Sokoto Energy Research Center (SERC) and the National Center for Energy Research and Development (NCERD) under the supervision of the Energy Commission of Nigeria (ECN). Several PV-water pumping, electrification, and solar-thermal installations have been put in place. Such solar thermal applications include solar cooking, solar crop drying, solar incubators, and solar chick brooding. Other areas of application of solar electricity include low- and medium-power applications such as water pumping, village electrification, rural clinic and power supply for schools, vaccine refrigeration, traffic lighting, and lighting of road signs.

Wind energy Wind energy is available at annual average speeds of about 2.0 m/s at the coastal region and 4.0 m/s at the far northern region of the country. With an air density of 1.1 kg/m^3, the wind energy intensity perpendicular to the wind direction ranges between 4.4 W/m^2 at the coastal areas and 35.2 W/m^2 at the far northern region [18].

At present, the share of wind energy in the national energy consumption has remained on the lower end with no commercial wind power plants connected to the national grid. Only a few number of stand-alone wind power plants were installed in the early 1960s in five northern states mainly to power water pumps and a 5-kW wind electricity conversion system for village electrification installed at Sayyan Gidan Gada, in Sokoto State [17]. In recent times, numerous studies have been carried out to assess the wind speed characteristics and the associated wind energy potentials in different locations in Nigeria. Promising attempts are being made in the Sokoto Energy Research Centre (SERC) and Abubakar Tafawa Balewa University, Bauchi, to provide the capability for the development of wind energy technologies.

Biomass The biomass resources of Nigeria can be identified as crops, forage grasses and shrubs, animal wastes, and wastes arising from forestry, agriculture, municipal, and industrial activities, as well as aquatic biomass. Crops such as sweet sorghum, maize, and sugarcane were the most promising feedstocks for biofuel production [19]. Plant biomass can be utilized as a fuel for small-scale industries. It could also be fermented by anaerobic bacteria to produce a cheap fuel gas (biogases). Biogas production from agricultural residues, industrial, and municipal waste does not compete for land, water, and fertilizers with food crops as is the case with bioethanol and biodiesel production and will thus reduce the menaces posed by these wastes. In Nigeria, the feedstock substrates suitable for an economically feasible biogas production include water lettuce, water hyacinth, dung, cassava leaves, and processing waste, urban refuse, solid (including industrial) waste, agricultural residues, and sewage [20]. It has been estimated that Nigeria produces about 227,500 tons of fresh animal waste daily. Since 1 kg of fresh animal waste allows to produce about 0.03 m^3 biogas, Nigeria can potentially produce about 6.8 million m^3 of biogas every day from animal waste only [20]. Although the biogas technology is not common in Nigeria, various research works on the technology and policy aspects of biogas production have been carried out by various scientists in the country. Some significant researches have been done on a reactor design that would lead to process optimization in the development of anaerobic digesters [20]. Sawdust and wood wastes are other important biomass resources associated with the lumber industry. Small particle biomass stoves already exist for burning sawdust and wood shaving. Biomass utilization as an energy resource is currently limited to the thermal application as fuels for cooking and crop drying.

Role of renewable energy in ensuring eco-friendly environment

Renewable energy is clean, inexhaustible, unlimited, and rapidly replenished naturally. Renewable energy sources have brought about the need for technology innovation as a means of addressing climate change challenges, i.e., by reducing the rate and volume of GHG concentrations in the atmosphere and saving the ozone layer from ongoing depletion. The use of renewable energy sources will also significantly reduce the over-dependency on the burning of fossil fuel. Moreover, instead of flaring gas in Nigeria, the gases can be converted to methanol and used as a fuel for both domestic and industrial applications. When using the best practices and products with regards to energy efficiency, the burning of fossil fuels for energy generation will be greatly minimized. Nigeria has an abundance of renewable energy resources to be harnessed. Given the abundant availability of sun for solar energy generation in Nigeria and if the needed political will to tap these resources into place, the country will definitely surmount the challenges of climate change and global warming. The sun, with an estimated diameter of 1.4 million km and at a black body temperature of 6000 K, produces about 4.506×10^{20} MW of power. About 2.055×10^{11} MW of this power gets to the Earth's surface and which translates into a solar intensity of about 1.58 kW/m^2 on the Earth's surface. If 1 % of the Nigerian landmass of 794,000 is used to collect solar power at an efficiency of 5 %, the available power will be approximately 627,260 MW [21].

The ECN has significantly done well in this regard. Between 1999 and 2009, several installations of solar PV systems have been executed in the country. In 2008 and 2009 alone, the Commission installed over 300 kWp and 1.01 MW, respectively, of solar PV power systems all over the country. The installations were mainly for water pumping, streetlight applications, and powering of offices. The current estimate of solar PV installations in the country is put at 6 MW of power [21]. Wind energy is also important in mitigating climate change. About 2.5 % of solar energy captured by the atmosphere is being converted into wind. The development of wind power plants is being undertaken by many countries including Nigeria, for the generation of electricity in their quest to exploit renewable energy sources. With wind energy available at an annual average speed of 4.0 m/s at the coastal borders and northern regions, the country possesses enormous potential to develop and utilize energy from the wind for electricity generation. The coastal regions of the south and the northern part of the country are possible suitable sites for wind energy exploitation.

Clean energy technology and sustainability

Energy efficiency and renewable energy technologies are prominent in most sustainable development programs, for example, the Agenda 21 [22]. According to the IPCC's second assessment report, the stabilization of atmospheric greenhouse gas concentrations at levels that will prevent serious interference with the climate system can only be achieved by dramatically increasing the implementation of renewable energy. In one IPCC scenario, in which greenhouse gases are stabilized by the year 2050, the share of renewable energy in the global energy balance must increase tenfold from the current level. In developing countries, the required increase is, even more, dramatic and was estimated to be a 20-fold between 1990 and 2050. Further improvements in energy efficiency and energy conservation can reduce emissions in the shorter term, thus "buying time" for the required changes in energy production [23].

Methods

In this section, an appropriate econometric model, which theoretically established the relationship between variables of interest, are specified and used to practically demonstrate energy use and environmental quality in Nigeria. According to the World Bank, four drivers that constitute the basis for emission scenarios are as follows:

1. Population growth. More people, more energy use,
2. Energy choices. The choice of energy we consume determines the emission of CO_2. Whether we will be building more coal or more solar, wind, and renewable energy.
3. The third factor is the economic growth. The faster economies grow, the more energy they will need, and the more fossil fuels they are likely to consume.
4. And the fourth factor is technological innovation; some people think that technological innovation will save us by, for example, allowing us to pull CO_2 from the air or, in a less dramatic way, removing through scrubbers, from power plants and pumping it under the Earth. In any case, it is these four drivers that together constitute the basis for emission scenarios [24].

In line with the theoretical considerations, we specified the models as follows:

$$\mathrm{CO}_{2t} = f(\mathrm{FUE}_t, \mathrm{GDP}_t, \mathrm{REN}_t, \mathrm{POP}_t)U, \tag{1}$$

where

CO_{2t} = carbon dioxide emission
REN_t = renewable energy consumption
FUE_t = fossil fuel consumption
GDP_t = gross domestic product proxy for economic growth
POP_t = population.

μ is the error term of Eq. 1.

In a more explicit form, the model can be written in a log-linear form to transform the variables into the same unit and base. Thus,

$$\mathrm{InCO}_{2t} = \beta_0 + \beta_1 \mathrm{InFU}_t + \beta_2 \mathrm{InGDP}_t + \beta_3 \mathrm{InREN}_t + \beta_4 \mathrm{InPOP}_t, \quad (2)$$

where β_1, β_2, and $\beta_4 > 0$ and $\beta_3 < 0$.

The bound test approach to co-integration which is based on the ARDL procedure proposed by Pesaran et al. [25] is used in the study to examine the relationship between fossil fuel consumption, renewable energy consumption, carbon emissions, population, and gross domestic output in Nigeria. The study covers the periods from 1981 to 2012 by relying on annual time series data for Nigeria, which are mainly taken from the World Bank country data base (2014), the Carbon Dioxide Information Analysis Center, USA, and the Central Bank of Nigeria Statistical Bulletin 2014. The variables used are renewable energy consumption (REN_t) and fossil fuel consumption (FUE_t) as components of disaggregated energy use. The fossil fuel is made of coal, oil, petroleum, and natural gas. Others are real gross domestic product [(GDP_t) proxy for economic growth] and total carbon dioxide emissions [(CO_{2t})] measured in million metric tons. All data are converted into natural logarithm. E-views 8.0 and Stata 12.0 econometrics software were used for the analysis.

Time series properties of data

It is important to investigate the time series characteristics of the variables. The purpose is to determine the order of integration because the (ARDL) bounds testing approach to co-integration becomes applicable only in the presence of $I(0)$ or $I(1)$ variables, that is, being stationary/integrated at the level form or at first difference. Thus, the assumption of bounds testing will collapse in the presence of $I(2)$ variable [26] (see Fig. 1).

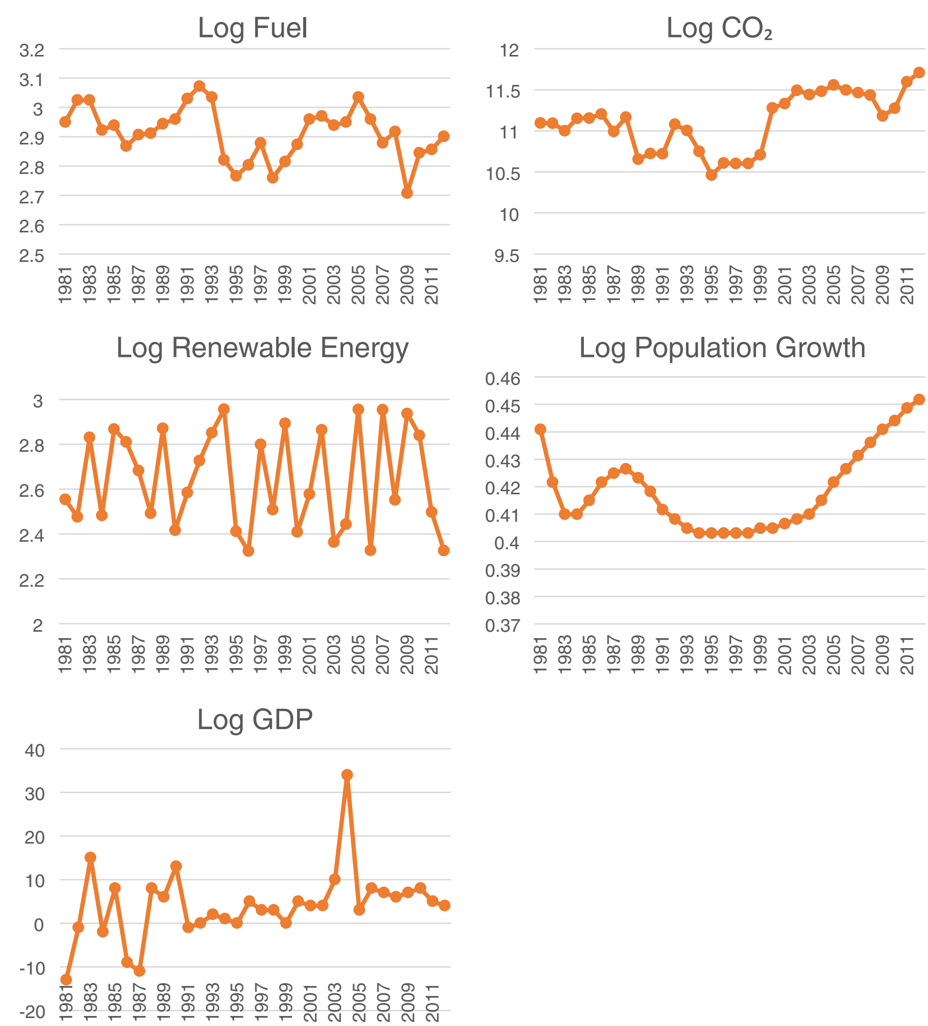

Fig. 1 Plots of trends of variables in their logarithm forms

Figure 1 shows the trend of variables in their logarithm form from 1981 to 2012. The vertical axes indicate the variables measured in different units but converted to logarithm forms to bring them to the same base or unit. The trends of the variables include CO_2 emission, fossil fuel consumption as a percentage of total energy consumption, GDP growth, population growth, and renewable energy consumption as a percentage of total energy consumption. The graphs exhibit trends and structural breaks. CO_2 structural break occurred in 1995 and showed an upward trend, while fossil fuel structural breaks occurred in 1986, 1991, and 2008. The population growth, however, displayed a trend while the GDP structural break occurred in 2004. And last but not least, renewable energy alternated up and down.

We conducted unit root tests using the variables included in the regression by employing both the Augmented Dickey-Fuller (ADF), the Phillips-Peron (PP), and the Kwiatkowski-Phillips-Schmidt-Shin (KPSS) tests at 1, 5, and 10 % levels of significance. The null hypothesis is that unit root problem exists, that is, $\beta_1 = \beta_2 = \beta_3 = \beta_4 = 1$ against the alternative hypothesis that there exists no unit root problem, that is, $\beta_1 \neq \beta_2 \neq \beta_3 \neq \beta_4 \neq < 1$.

Bounds testing approach to co-integration

As pointed out by the authors of [27], the bounds testing approach to co-integration is preferred to other conventional co-integration tests because it has several important advantages over other conventional tests. The approach effectively corrects for a possible endogeneity of explanatory variables. Another important advantage of the ARDL approach is that one can avoid the uncertainties created by unit root pre-testing as the test can be applied regardless of whether the series is $I(0)$ or $I(1)$. An added bonus of this approach is that unlike other conventional tests for co-integration, it can be applied to studies that have a small sample size [27]. In addition, both the short- and the long-run relationship can be simultaneously estimated. In this paper, the ARDL approach to co-integration is estimated using the following unrestricted error correction (UREC) regressions.

$$\begin{aligned}\Delta \ln CO2_t = \alpha_1 &+ \sum_{i=1}^{p} \beta_{1i} \Delta \ln CO_{2_{t-i}} + \sum_{i=0}^{p} \kappa_{1i} \Delta \ln FUE_{t-i} \\ &+ \sum_{i=0}^{p} \varpi_{1i} \Delta \ln REN_{t-i} + \sum_{i=0}^{p} \varphi_{1i} \Delta \ln GDP_{t-i} \\ &+ \sum_{i=0}^{p} \gamma_{1i} \Delta \ln POP_{t-i} + \eta_{1Y} \Delta \ln CO_{2_{t-1}} \\ &+ \eta_{2Y} \Delta \ln FUE_{t-1} + \eta_{3Y} \Delta \ln REN_{t-1} \\ &+ \eta_{4Y} \Delta \ln GDP_{t-1} + \eta_{5Y} \Delta \ln POP_{t-1} + \mu 1\end{aligned} \tag{3}$$

$$\begin{aligned}\Delta \ln FUE_t = \alpha_2 &+ \sum_{i=0}^{p} \beta_{2i} \Delta \ln CO_{2_{t-i}} + \sum_{i=1}^{p} \kappa_{2i} \Delta \ln FUE_{t-i} \\ &+ \sum_{i=0}^{p} \varpi_{2i} \Delta \ln REN_{t-i} + \sum_{i=0}^{p} \varphi_{2i} \Delta \ln GDP_{t-i} \\ &+ \sum_{i=0}^{p} \gamma_{2i} \Delta \ln POP_{t-i} + \eta_{1C} \Delta \ln CO_{2_{t-1}} \\ &+ \eta_{2C} \Delta \ln FUE_{t-1} + \eta_{3C} \Delta \ln REN_{t-1} \\ &+ \eta_{4C} \Delta \ln GDP_{t-1} + \eta_{5C} \Delta \ln POP_{t-1} + \mu 2\end{aligned} \tag{4}$$

$$\begin{aligned}\Delta \ln REN_t = \alpha_3 &+ \sum_{i=0}^{p} \beta_{3i} \Delta \ln CO_{2_{t-i}} + \sum_{i=1}^{p} \kappa_{3i} \Delta \ln FUE_{t-i} \\ &+ \sum_{i=0}^{p} \varpi_{3i} \Delta \ln REN_{t-i} + \sum_{i=0}^{p} \varphi_{3i} \Delta \ln GDP_{t-i} \\ &+ \sum_{i=0}^{p} \gamma_{3i} \Delta \ln POP_{t-i} + \eta_{1V} \Delta \ln CO_{2_{t-1}} \\ &+ \eta_{2V} \Delta \ln FUE_{t-1} + \eta_{3V} \Delta \ln REN_{t-1} \\ &+ \eta_{4V} \Delta \ln GDP_{t-1} + \eta_{5V} \Delta \ln POP_{t-1} + \mu 3\end{aligned} \tag{5}$$

$$\begin{aligned}\Delta \ln GDP_t = \alpha_4 &+ \sum_{i=0}^{p} \beta_{4i} \Delta \ln CO_{2_{t-i}} + \sum_{i=0}^{p} \kappa_{4i} \Delta \ln FUE_{t-i} \\ &+ \sum_{i=0}^{p} \varpi_{4i} \Delta \ln REN_{t-i} + \sum_{i=1}^{p} \varphi_{4i} \Delta \ln GDP_{t-i} \\ &+ \sum_{i=0}^{p} \gamma_{4i} \Delta \ln POP_{t-i} + \eta_{1R} \Delta \ln CO_{2_{t-1}} \\ &+ \eta_{2R} \Delta \ln FUE_{t-1} + \eta_{3R} \Delta \ln REN_{t-1} \\ &+ \eta_{4R} \Delta \ln GDP_{t-1} + \eta_{5R} \Delta \ln POP_{t-1} + \mu 4\end{aligned} \tag{6}$$

$$\begin{aligned}\Delta \ln POP_t = \alpha_5 &+ \sum_{i=0}^{p} \beta_{5i} \Delta \ln CO_{2_{t-i}} + \sum_{i=0}^{p} \kappa_{5i} \Delta \ln FUE_{t-i} \\ &+ \sum_{i=0}^{p} \varpi_{5i} \Delta \ln REN_{t-i} + \sum_{i=1}^{p} \varphi_{5i} \Delta \ln GDP_{t-i} \\ &+ \sum_{i=0}^{p} \gamma_{5i} \Delta \ln POP_{t-i} + \eta_{1S} \Delta \ln CO_{2_{t-1}} \\ &+ \eta_{2S} \Delta \ln FUE_{t-1} + \eta_{3S} \Delta \ln REN_{t-1} \\ &+ \eta_{4S} \Delta \ln GDP_{t-1} + \eta_{5S} \Delta \ln POP_{t-1} + \mu 5\end{aligned} \tag{7}$$

Here, Δ is the first difference operator, In denotes the natural logarithm, and p is the lag order selected by Akaike's information criterion (AIC). The parameters β, κ, ω, φ, and γ are the short-run dynamic coefficients while the parameters η_1 to η_5 function as the long-run multipliers of the underlying ARDL model. The residuals μ_i are assumed to be normally distributed and white noise.

In Eq. 3, the tests for co-integration are carried out by examining the joint significance of the lagged levels of the variables using the *F*-test where the null of no co-integration is defined by the following:

$H0$: $\eta_1 Y = \eta_2 Y = \eta_3 Y = \eta_4 Y = \eta_5 Y = 0$ against the alternative that $H1$: $\eta_1 Y \neq 0$, $\eta_2 Y \neq 0$, $\eta_3 Y \neq 0$, $\eta_4 Y \neq \eta_5 Y = 0$. Other tests for co-integration in Eqs. 4–7 can also be carried out using similar procedures. The asymptotic distribution of the *F*-statistic is non-standard under the null, and it was originally derived and tabulated by [25], but later modified by [26]. Two sets of critical values are provided: one, which is appropriate when all the series are $I(0)$ and the other for all the series that are $I(1)$.

According to [27], in testing for co-integration, if the computed *F*-statistic falls above the upper critical bounds, a conclusive inference can be made regarding co-integration without the need to know whether the series were $I(0)$ or $I(1)$. In this case, the null of no co-integration is rejected regardless of whether the series is $I(0)$ or $I(1)$. Alternatively, when the test statistic falls below the lower critical value, the null hypothesis is not rejected regardless of whether the series is $I(0)$ or $I(1)$. In contrast, if the computed test statistic falls inside the lower and the upper bounds, a conclusive inference cannot be made unless we know whether the series was $I(0)$ or $I(1)$. To ascertain the goodness of fit of the ARDL model, the stability test is conducted by employing the cumulative sum of recursive residuals (CUSUM) and the cumulative sum of squares of recursive residuals (CUSUMsq).

Granger causality test

According to the concept of Granger causality, "*X* causes *Y*" if and only if the past values of *X* help to predict the changes of *Y*, while "*Y* causes *X*" if and only if the past values of *Y* help to predict the changes of *X*. The vector auto-regression (VAR) model is likely to be used for this purpose. However, Granger [28] noted that if a set of variables is co-integrated, there must be a short- and long-run causality which cannot be captured by the standard first difference VAR model. In this case, we must implement the Granger causality test with the vector error correction model (VECM) framework as follows:

$$\begin{aligned}\Delta \ln \mathrm{CO2}_t = a_1 &+ \sum_{i=1}^{p} \beta_i \Delta \ln \mathrm{CO}_{2_{t-i}} + \sum_{i=1}^{p} \kappa_i \Delta \ln \mathrm{FUE}_{t-i} \\ &+ \sum_{i=1}^{p} \varpi_i \Delta \ln \mathrm{REN}_{t-i} + \sum_{i=1}^{p} \varphi_i \Delta \ln \mathrm{GDP}_{t-i} \\ &+ \sum_{i=1}^{p} \gamma_i \Delta \ln \mathrm{POP}_{t-i} + \delta_1 \mathrm{ECM}_{t-1} + \nu_{1t}\end{aligned} \tag{8}$$

$$\begin{aligned}\Delta \ln \mathrm{FUE}_t = a_1 &+ \sum_{i=1}^{p} \kappa_i \Delta \ln \mathrm{FUE}_{t-i} + \sum_{i=1}^{p} \beta_i \Delta \ln \mathrm{CO}_{2_{t-i}} \\ &+ \sum_{i=1}^{p} \varpi_i \Delta \ln \mathrm{REN}_{t-i} + \sum_{i=1}^{p} \varphi_i \Delta \ln \mathrm{GDP}_{t-i} \\ &+ \sum_{i=1}^{p} \gamma_i \Delta \ln \mathrm{POP}_{t-i} + \delta_2 \mathrm{ECM}_{t-1} + \nu_{2t}\end{aligned} \tag{9}$$

$$\begin{aligned}\Delta \ln \mathrm{REN}_t = a_1 &+ \sum_{i=1}^{p} \varpi_i \Delta \ln \mathrm{REN}_{t-i} + \sum_{i=1}^{p} \beta_i \Delta \ln \mathrm{CO}_{2_{t-i}} \\ &+ \sum_{i=1}^{p} \kappa_i \Delta \ln \mathrm{FUE}_{t-i} + \sum_{i=1}^{p} \varphi_i \Delta \ln \mathrm{GDP}_{t-i} \\ &+ \sum_{i=1}^{p} \gamma_i \Delta \ln \mathrm{POP}_{t-i} + \delta_3 \mathrm{ECM}_{t-1} + \nu_{3t}\end{aligned} \tag{10}$$

$$\begin{aligned}\Delta \ln \mathrm{GDP}_t = a_1 &+ \sum_{i=1}^{p} \varphi_i \Delta \ln \mathrm{GDP}_{t-i} + \sum_{i=1}^{p} \beta_i \Delta \ln \mathrm{CO}_{2_{t-i}} \\ &+ \sum_{i=1}^{p} \kappa_i \Delta \ln \mathrm{FUE}_{t-i} + \sum_{i=1}^{p} \varpi_i \Delta \ln \mathrm{REN}_{t-i} \\ &+ \sum_{i=1}^{p} \gamma_i \Delta \ln \mathrm{POP}_{t-i} + \delta_4 \mathrm{ECM}_{t-1} + \nu_{4t}\end{aligned} \tag{11}$$

$$\begin{aligned}\Delta \ln \mathrm{POP}_t = a_1 &+ \sum_{i=1}^{p} \gamma_i \Delta \ln \mathrm{POP}_{t-i} + \sum_{i=1}^{p} \beta_i \Delta \ln \mathrm{CO}_{2_{t-i}} \\ &+ \sum_{i=1}^{p} \kappa_i \Delta \ln \mathrm{FUE}_{t-i} + \sum_{i=1}^{p} \varpi_i \Delta \ln \mathrm{REN}_{t-i} \\ &+ \sum_{i=1}^{p} \varphi_i \Delta \ln \mathrm{GDP}_{t-i} + \delta_5 \mathrm{ECM}_{t-1} + \nu_{5t},\end{aligned} \tag{12}$$

where Δ is the first difference operator and ln is the natural logarithm. The residuals υ_{it} are assumed to be normally distributed, and white noise is the one-period lagged error correction term derived from the co-integration equation. The ECM_{t-1} variable will be excluded from that model if the variables are not co-integrated. The optimal lag length p is determined by the AIC because of its superior performance in small sample [29]. Next, we apply the likelihood ratio (LR) statistics to ascertain the direction of Granger causality between the variables of interest. In this study, we test the following hypotheses[2]:

$H0 : \kappa_1 = \kappa_2 = \ldots = \kappa_p = 0$, implying that FUE_t does not Granger-cause CO_{2t},
$H0 : \varpi_1 = \varpi_2 = \ldots = \varpi_p = 0$, implying that REN_t does not Granger-cause CO_{2t},

$H0: \varphi_1 = \varphi_2 = \ldots = \varphi_p = 0$, implying that GDP_t does not Granger-cause CO_{2t},
$H0: \gamma_1 = \gamma_2 = \ldots = \gamma_p = 0$, implying that POP_t does not Granger-cause CO_{2t}

Results and discussions

Unit root

Table 1 shows the ADF, PP, and KPSS unit root results for all the variables. The table indicates that all the variables are integrated or stationary at the first difference, $I(1)$, except $InREN_t$ and GDP_t which are stationary at levels. In the presence of $I(2)$ or higher-order variables, the computed statistics provided by [25] and [27] are not valid [30]. The presence of a combination of order one and zero implies that we can confidently apply the Pesaran et al.'s ARDL methodology in our tests for co-integration.

Having examined the time series characteristics of our data, in the next step, Eqs. 3–7 are estimated to examine the long-run relationships among the variables. However, it is a pre-requisite to select an appropriate lag length before proceeding to the ARDL co-integration test. We apply the lag selection criteria to choose the lag length, and the result is presented in Table 2.

The selection criteria results show that the whole criteria selected lag 4. The likelihood ratio, the final prediction error, the Akaike information, the Schwarz, and the Hannan-Quin information criteria selected lag 4 as shown by the asterisk at the 0.05 significance level.

As suggested by [31] and [27], since the observations are annual, we choose four as the maximum order of lags in the ARDL and estimate for the period of 1981–2013. This is sufficiently long for an annual data study to capture the dynamic relationship so that the AIC statistic could then be used to choose the best ARDL models. We used the AIC to determine the optimal number of lags to be included in the conditional error correction model (ECM) since it produced better estimates than the Schwarz-Bayesian information criteria (SBC). AIC statistics is preferred in this study, as it has superior properties, particularly in small samples [32]. In addition, a set of diagnostic tests is conducted on the selected ARDL models. Overall, the selected ARDL models passed a number of diagnostic tests. The Jarque-Bera normality tests indicate that the residuals are normally distributed. The Ramsey RESET and the autoregressive conditional heteroskedasticity (ARCH) tests show that the selected models are free from the general specification error and also ARCH problems. Finally, the Breusch-Godfrey LM test cannot reject the null hypothesis of serial correlation up to second order, meaning that the selected ARDL models have no serial correction problems. Therefore, we surmise that the selected ARDL models are appropriate to be used for the bounds testing approach to co-integration. The calculated *F*-statistics for co-integration are reported together with the diagnostic tests in Table 3.

Table 1 Augmented Dickey-Fuller, Philip-Perron, and KPSS unit root tests

Variables	ADF statistic	PP statistic	KPSS statistic
$InREN_t$	−7.1190*	−10.2891*	0.1288
$\Delta InREN_t$	−4.5976*	−17.7251*	0.18848**
$InPOP_t$	−3.5147	−1.7788	0.057359
$\Delta InPOP_t$	−3.7071**	−3.8137*	0.1880**
$InGDP_t$	−5.2226*	−5.2407*	0.0770
$\Delta InGDP_t$	−8.1553*	−24.3946*	0.3493*
InFUEt	−2.9590	−2.9986	0.0578
$\Delta InFUE_t$	−5.9338*	−6.8035*	0.2283*
$InCO_{2t}$	−1.8842	−1.8247	0.1413
$\Delta InCO_{2t}$	−5.4920*	−6.0445*	0.1820**

The optimal lag order for ADF test is determined by AIC, while the bandwidths for PP and KPSS tests are determined by using the Newey-West Bartlett kernel (the unit root test indicates that all the variables are integrated or stationary at the first difference, $I(1)$ except $InREN_t$ and GDP_t which are stationary at levels)
*Significance at 1 % level; **significance at 5 % level; ***significance at 10 % level

In all cases, the calculated *F*-statistics are greater than the 1 % upper bound critical values provided by [25]. Therefore, the null hypothesis of no co-integration can be rejected, implying that a long-run equilibrium relationship exists between CO_2 emission, fossil fuel consumption, economic growth, population growth, and renewable energy consumption in Nigeria.

To further consolidate on the co-integration nature of the variables, a residual unit root test for co-integration is carried out. The null hypothesis of unit root is tested against the alternative hypothesis of no unit root. The result is presented in Table 4.

The stationarity of the residuals obtained from the co-integration regression of the dependent variables (CO_{2t}) on the independent variables (FUE_t, GDP_t, POP_t, and REN_t) has been tested using the ADF test. Based on the result shown in Table 4, we rejected the null hypothesis of the presence of unit root in the residual. The result revealed that the residual is stationary at the 0.01 level of significance and also confirmed the presence of co-integration among the variables. The test included none, intercept, trend, and intercept.

After determining the presence of co-integration, it is also interesting to perform the Granger causality test to provide a clearer picture for policymakers to formulate energy consumption and economic and environmentally friendly policies by understanding the direction of causality. As the variables are co-integrated, we employed the Granger causality in the VECM framework to determine the direction of causality between the variables.

Table 2 Lag length selection order criteria

Lag	L	LR	*df*	P	FPE	AIC	HQIC	SBIC
0	−35.9035				0.000013	2.9217	2.9944	3.15957
1	47.2408	166.29	25	0.0000	2.1e−07	−1.2315	−0.7951	0.1959
2	82.139	69.796	25	0.0000	1.2e−07	−1.9385	−1.1385	0.6783
3	163.329	162.38	25	0.0000	3.9e−09	−5.9521	−4.7885	−2.1458
4	238.602	150.55[a]	25	0.0000	4.6e−10[a]	−9.5431[a]	−8.0158[a]	−4.5473[a]

Endogenous: $lnC0_{2t}$, $lnFUE_t$, $lnGDP_t$, $lnPOP_t$, $lnREN_t$. Exogenous: constant
[a]Lag selection by the criteria

The results of Granger causality are presented in Table 5. Since the variables are co-integrated, the direction of causality can be divided into a short- and long-run causation. The *t* significance of the one-period lagged error correction term represented the long-run causality, whereas the joint significance LR tests of the lagged explanatory variables represented the short-run causality. Starting with the long-run causality, our empirical results suggest that the coefficients are negatively signed and statistically significant in all VECMs, implying that there is bi-directional causality between the variables of interest in the long-run. In addition to that, the significance of ECT_{t-1} also exhibits that if the system is exposed to shock, it will converge to the long-run equilibrium at a relatively slow speed for CO_2 emission (−0.7443), fossil fuel consumption (−0.5768), and renewable energy consumption (−0.5294) VECMs compared to the convergence speed of economic growth (−0.3729) and population (−0.2214) VECMs.

Contrary with the findings of long-run causality, we find that the short-run causality varies among VECMs. In summary, our empirical evidence shows that at the 1 and 10 % levels, Granger causality runs from fossil fuel consumption and renewable energy consumption to CO_2 emission, respectively. However, at the same 1 % level of significance, the results show Granger causality runs from CO_2 emission to fossil fuel consumption. With respect to these findings, we affirmed that CO_2 emission and fossil fuel consumption have bi-directional causality, while renewable fuel consumption unidirectionally Granger-caused CO_2 emission. One interesting finding of this result that makes it plausible is the bi-directional causality between renewable energy consumption and fossil fuel consumption. This implies that as the consumption of renewable energy increases, fossil fuel consumption decreases which invariably ensured an eco-friendly environment. In addition to the plausibility of the result, population shows a unidirectional causality to fuel, implying that as the population of a country increases, consumption of fossil fuel also increases, while the environment deteriorates. Renewable energy plays a significant role in ensuring economic efficiency through Granger-causing GDP. These results are significantly consistent with the findings provided in earlier studies for Nigeria [33–35]. As a result, the Nigerian dataset supported the renewable energy eco-friendly environmental

Table 3 The result of ARDL co-integration

Bounds testing to co-integration		Diagnostic tests				
	Optimal lag	*F*-statistics	X^2 normal	X^2 ARCH	X^2 reset	X^2 serial
F_{CO2}(CO_2/FUE, GDP, POP, REN	4, 2, 2, 1	14.2739	1.1704	[1] 0.5462	[1] 0.0150	[2] 1.8323
F_{FUE}(FUE/CO_2, GDP, POP, REN	4,1, 2, 1	30.7047	0.2829	[1] 0.7610	[1] 1.2294	[2] 3.9920
F_{GDP}(GDP/CO_2, FUE, POP, REN	2, 2, 1, 1	6.7908	1.1704	[1] 0.0150	[1] 1.1809	[2] 5.5904
F_{POP}(POP/CO_2, FUE, GDP, REN	2, 1, 2, 1	14.4282	0.5437	[1] 0.1968	[1] 2.1207	[2] 2.7049
F_{REN}(REN/CO_2, FUE, GDP, POP	2, 1, 1, 1	5.0009	1.8256	[1] 0.2633	[1] 1.9967	[2] 1.8149
	Critical values ($T = 32$)[a]					
Significance level (%)	Lower bounds (0)			Upper bounds (1)		
1	3.43			4.60		
5	2.86			3.99		
10	2.57			3.66		

The optimal lag length determined by AIC. Numbers in square brackets ([]) indicate the order of diagnostic tests
*Significance at 1 % level; **significance at 5 % level; ***significance at 10 % level
[a]Critical values are collected from [25] (in all cases, the calculated *F*-statistics are greater than the 1 % upper bound critical values provided by [25], table, case III (intercept and unrestricted trend))

Table 4 Residual ADF unit root test

Variable	None	Constant	Constant and trend	Conclusion
Residual/	t-obs	t-obs	t-obs	OI Lag
Error term	−5.2985	−5.1772	−5.0410	*I*(0) [1]

The number in square brackets ([]) indicates the order of diagnostic tests

nexus, the renewable energy-led growth nexus, the fossil fuel-environmental degradation, and the population-led environmental deterioration hypotheses. These evidences strongly indicate that the variables in the system dynamically interact. Therefore, an increase in the consumption of renewable energy and reduction in the consumption of fossil fuel in Nigeria will ensure efficiency and an eco-friendly environment which eventually leads to sustainable development.

In the first phase, we utilized traditional unit tests (i.e., ADF, PP, and KPSS) to check the order of integration among the variables. The results are provided in Table 2. The statistical values suggest that renewable energy consumption and GDP are stationary at levels where the population, fossil fuel consumption, and CO_2 emission have a unit root problem with intercept and trend. The combination of $I(0)$ and $I(1)$ justifies the use of the ARDL method in this study. One can avoid the uncertainties created by unit root pre-testing as the test can be applied regardless of whether the series is $I(0)$ or $I(1)$. However, the method cannot be applied in a situation where one of the variables is $I(2)$. This notion further enumerates that the series is integrated at $I(0)$ and $I(1)$. Those series with a unit root have problems arising due to structural breaks—and trends, further leading to a weak predicting power and misleading results. However, this issue can be solved by applying the ARDL method. These structural breaks and trends are present in the series of CO_2 in 1990, 1995, 2005, and 2012 while fuel structural breaks occur in 1986, 1991, and 2008. Population density, however, displays a trend. This indicates that a unique order of integration is established in all the variables. After passing through the unit root tests, the next stage was to check the long-run relationship among the variables using a co-integration approach. For this purpose, we choose to apply the ARDL bounds testing approach to co-integration proposed by [27]. It is the pre-requisite to choose an appropriate lag length before proceeding to the ARDL co-integration test. Moreover, the selection of lag length should be performed carefully because an inappropriate lag length may lead to biased results and is not acceptable for policy analysis. Therefore, to ensure that the lag length was selected appropriately, we used AIC that helps to identify a pertinent lag length. The AIC criterion provides dynamic results and has exceptional properties compared with the Schwartz-Bayesian criteria (SBC). The results are reported in Table 2. We identified lag 4 as appropriate for our sample size. The ARDL bounds testing results are shown in Table 3. The calculated *F*-statistics of all underlined variables (i.e., CO_2 emission, fossil fuel consumption, economic growth, population growth, and renewable energy consumption) fall outside of the critical bounds at both the 1 and 5 % levels of significance. This result showed that we have five co-integrating vectors and confirmed the presence of a long-run relationship between the variables over the period of 1981–2012; the structural breaks of 1998, 2003, and 2006 were adjusted. After finding the co-integration between the variables, the long-run and the short-run analyses were conducted (Table 6).

In the short-run, we found that economic growth, fossil fuel consumption, and population contribute to CO_2 emission at the 1 % level of significance. However, renewable energy consumption impacts negatively on the CO_2 emission in Nigeria given the sign and significance of the coefficients both in the short and long run. The negative effect of economic growth does not diminish in the long run indicating that the environmental Kuznets curve hypothesis does not hold in Nigeria when CO_2 is used for environmental degradation. This further shows that Nigeria has not reached the threshold or the turning point of the EKC curve since environmental

Table 5 The result of Granger causality test

Variable direction of Granger causality						
Short run						Long run
Likelihood ratio (LR) statistics						*t*-statistics
	$\sum\Delta\ln CO_{2t-i}$	$\sum\Delta\ln FUE_{t-i}$	$\sum\Delta\ln GDP_{t-i}$	$\sum\Delta\ln POP_{t-i}$	$\sum\Delta\ln REN_{t-i}$	$ECT_{(-1)}$
$\Delta\ln CO_{2t}$	–	4.4702* [0.0222	0.3639 [0.6989]	2.89808*** [0.0535]	2.8390*** [0.0791]	−0.7443* [−10.5207]
$\Delta\ln FUE_t$	7.6757* [0.0028]	–	0.0824 [0.9211]	0.6432 [0.5348]	2.2842** [0.1245]	−0.5768** [−2.4900]
$\Delta\ln GDP_t$	0.3687 [0.6956	0.5684 [0.5739]	–	0.3230 [0.7272]	3.2007 [0.0594]	−0.3729** [−2.8000]
$\Delta\ln POP_t$	0.3953 [0.6779]	2.1530** [0.1390]	0.0986 [0.9065]	–	0.1700 [0.8446]	−0.2214** [−2.1800]
$\Delta\ln REN_t$	0.3878 [0.6829	1.5640 [0.2307]	2.1906** [0.1364]	0.6250 [0.5441]	–	−0.5294** [−2.2300]

Numbers in square brackets ([]) indicate the order of diagnostic tests
*Significance at 1 % level; **significance at 5 % level; ***significance at 10 % level

Table 6 The Parsimonious model (long-run and short-run analysis)

Dependent variable = $\Delta lnCO_{2t}$

Variables	Coefficient Short run	Coefficient Long run	Standard error Short run	Standard error Long run	t statistic Short run	t statistic Long run	Problem Short run	Problem Long run
Constant	3.8005	0.72744	0.95809	2.2792	3.9668	0.3191	0.0166	0.7524
$lnCO_{2t}$	3.4174*	−1.1011*	0.1021	0.0606	33.4702	−18.17650	0.0000	0.0001
$lnFUE_t$	4.4476*	−0.0754	0.1799	0.1637	24.7113	−0.46031	0.0000	0.6692
$lnGDP_t$	0.0258*	0.0271*	0.0010	0.0018	25.0355	15.3483	0.0000	0.0001
$lnPOP_t$	49.8259*	5.0777*	2.3501	0.1652	21.2018	30.7378	0.0000	0.0000
$lnREN_t$	−0.5564*	−0.3083*	0.0489	0.0282	−29.8012	−10.9398	0.0000	0.0004
$ECT_{(-1)}$	−0.7443*	–	0.0708	–	−10.5208	–	0.0001	–
R^2	=0.99	R^2 Adjusted	=0.98					
F-statistic	=14.2740							
DW	=2.9372							

*Significance at 1 % level; **significance at 5 % level; ***significance at 10 % level

degradation in the form of CO_2 emission increases both in the short and long run as economic growth increases. Fossil fuel consumption and population diminished in the long-run. This notion confirms the energy efficiency in the use of fuel energy in the long run. One plausible issue about the result is the sign and significance of renewable energy consumption both in the short and long run. The negative sign and significance of the coefficient of renewable energy consumption show that it contributes to the reduction in CO_2 emission, hence, climate change mitigation and ensures an eco-friendly environment both in the short and long run, which is in line with the hypothesis of the study. An increase in economic growth by 1 % increases the CO_2 emission by 0.026 %, and in the long-run, if growth continues, this effect increases to 0.027 % indicating that Nigeria is almost reaching the turning point of EKC. Similarly, in the short run, a 1 % increase in the explanatory variables of fossil fuel consumption and population contributes 3.244 and 4.986 %, respectively, and, in the long run, −0.075 and 5.078 %, respectively. In addition, renewable energy consumption has the effect of ensuring environmental quality in Nigeria. A 1 % increase in renewable energy consumption decreases CO_2 emission by 0.556 and 0.3083 % in the short and long runs, respectively. Our results are consistent with the findings of [36–38] in terms of the effect of renewable energy consumption and energy efficiency on environmental quality. In addition, our results are in line with the findings of [39, 40] in terms of the economic non-existence of EKC in Nigeria. However, our results are inconsistent with the findings of [41, 42] especially with regards to the relationship between growth and environmental degradation. The general findings (in the light of the energy-consumption-environment hypothesis) can be justified, as Nigeria uses large sums of fossil fuels which are connected with the rising population. Efforts are also being made by the Federal Ministry of Environment to mitigate climate change impacts in the country; the Renewable Energy Programme has been initiated [43], which gave rise to findings in which renewable energy reduces emission. The results of the long-run and short-run analyses confirmed the relationship among the variables and agreed with the energy-consumption-environment-led hypothesis, where fossil fuel consumption, population, and economic growth lead to environmental degradation while renewable energy consumption ensures environmental quality. However, the results failed to validate the EKC hypothesis and also ignored the cause and effect connection. Therefore, we applied the VECM-Granger causality test, which detects the direction of causality among the underlined dependent and independent variables. The Granger causality test is an essential econometric technique that unveils causation among various vectors and possesses both long-term and short-term policy implications. The results of the VECM-Granger causality analysis are reported in Table 5. We found both short-run and long-run causality results. In the short-run, there exists a unidirectional causality from renewable energy consumption and CO_2 emission, and a bidirectional causal effect was detected between fossil fuel consumption and CO_2 emission. One plausible finding in the result is the unidirectional causality from renewable energy consumption to economic growth. It is plausible because it indicates the economic efficiency of renewable energy consumption. In the long run, however, economic growth and population Granger-cause energy consumption. The co-integrating vectors showed strong affiliation both in the short-run and long-run analyses. However, in terms of the renewable energy-consumption and environmental-quality nexus, the indicator improves the environmental quality by reducing CO_2 emissions both in the short run and long run. Economic growth, fossil fuel, population, and the environmental degradation nexus deteriorate the environmental degradation indicator (CO_2 emission) both in the short run and long run and do not support the EKC hypothesis.

Conclusively, the model was diagnosed for stability using the sensitivity analysis of the cumulative sum of recursive residual (CUSUM) and the cumulative sum of square of recursive residual (CUSUMsq) tests reported by Brown et al. [44]. The result of both the CUSUM and the CUSUMsq are shown in Figs. 2 and 3.

The two straight lines in Fig. 2 show critical bounds at the 5 % level of significance. The line within the critical bounds and the results of both the short-run and long-run analyses were presented. This implied that the coefficients of the error correction model are free from autoregressive conditional heteroskedasticity and serial correlation. Hence, the model is stable, and the results can be trusted for policy use. As indicated in both figures, the tests are within the critical bounds (represented by two straight lines).

Table 7 shows the diagnostic results of the underlying ARDL model for long-run elasticities and supporting statistics. The results also signify that the long-run model successfully passed all tests of normality, serial correlation, conditional heteroskedasticity, and functioning form. The robust results of the diagnostic test implied that the result of the ARDL model can be trusted and relied upon for policy modeling on the energy-growth-environment nexus.

Conclusions

This study explores the nexus between the pollution emission (CO_2), energy consumption, and the economic growth linkages using population as an additional explanatory variable. We employed the ARDL bounds testing approach to co-integration and the VECM-Granger causality test to investigate the existence of the energy consumption-emission-led hypothesis and economic growth-environmental quality hypothesis popularly known as the EKC hypothesis. The results confirm the characteristic energy consumption type and environmental quality hypothesis while at the same time refuted the inverted U-shaped relationship and invalidated the EKC hypothesis. Testing was conducted for both short-run and long-run paths, and the results suggest that a 1 % increase in renewable energy subtracts 0.556 % CO_2 emission in the short run; if renewable energy continues, the effect further subtracts 0.3082 % CO_2 emission in the long run. Similarly, in the short run, a 1 % increase in economic growth and population contributes 0.258 and 4.982 %, respectively, and in the long run, 0.027 and 5.077 %, respectively. In contrast, fossil fuel consumption has a positive effect by increasing environmental degradation in the short run; however, the effect is negative (improves environmental quality) in the long run in Nigeria. These latest findings suggest that in the long run when the energy efficiency is connected with cleaner technology, the impact of fossil fuel can be negative. There was a unidirectional causality between renewable

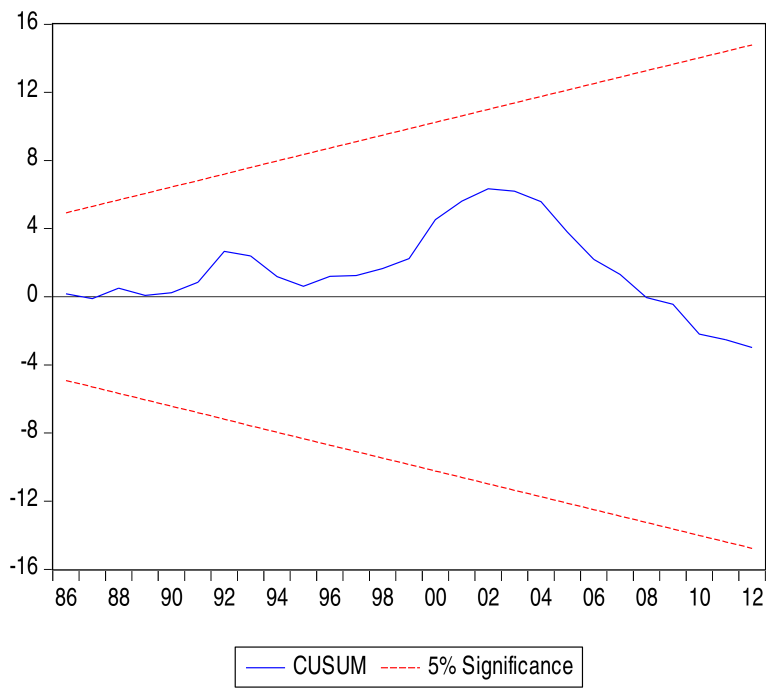

Fig. 2 Model stability test of cumulative sum residuals

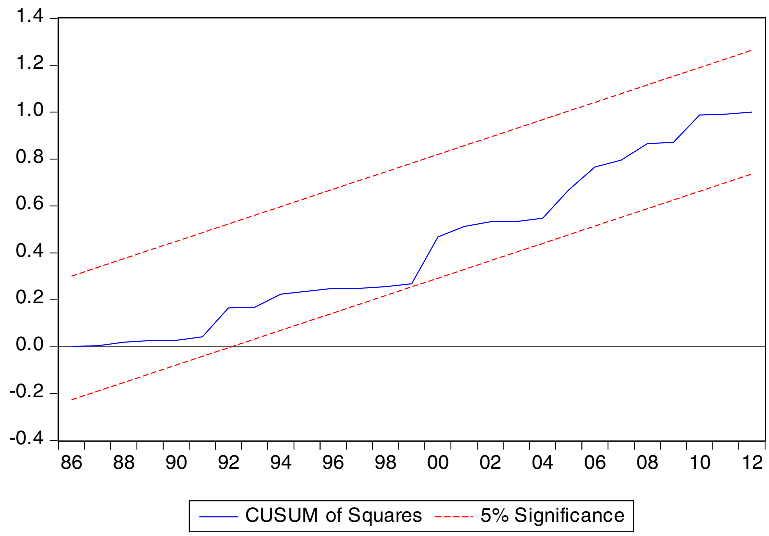

Fig. 3 Model stability test of cumulative sum of squares residuals

energy consumption and CO_2 emission, and a bidirectional causal effect was detected between fossil fuel consumption and CO_2 emission. Renewable energy consumption was also found to Granger-cause economic growth, an indication of economic efficiency. However, no clear causality was detected between economic growth, population, and CO_2. These findings further refuted the EKC hypothesis in Nigeria. The study suggests that renewable energy promotes an eco-friendly environment while fossil fuel, economic growth, and population degrade the environment of Nigeria.

Therefore, there is a strong need to embark on energy efficiency which encompasses conserving a scarce resource, improving the technical efficiency of energy conversion, generation, transmission, and end-use devices; substituting more expensive fuels with cheaper ones; and reducing or reversing the negative impact of energy production and consumption activities on the environment. Energy conservation is a tangible resource by itself that competes economically with contemporary energy supply options. The relationship between fossil fuel and the population is particularly worrisome because the population of the country is rising at an unprecedented rate while the use of fossil fuel is the order of the day considering the fact that the country has large potentials of fossil fuel reserves. Studies such as [5] reported that renewable energy consumption and energy efficiency contribute to the reduction of greenhouse gas levels. This study also supported their claim and found that fossil fuel, economic growth and population have direct negative links to the environmental quality, while renewable energy and energy efficiency has a positive link to an eco-friendly environment. This idea is further confirmed by the causality test, which suggests that there is unidirectional causality from renewable energy consumption to CO_2 emission, while a bidirectional causality was found between fossil fuel and CO_2 emission. We can conclude that economic growth, fossil fuel consumption, and population contribute to CO_2 emission in Nigeria. The bidirectional causality between fossil fuel energy consumption and CO_2 emission showed that there is a strong link between both indicators and their effect on each other. The creation of an eco-friendly environment in Nigeria, therefore, requires stabilization of temperature which in turn requires a stabilization of atmospheric CO_2 and other heat-trapping greenhouse gases produced through human activities. If Nigeria as one of the developing countries in the world can invest more in the use of renewable energy beyond what is currently planned fully knowing that the energy source is a free and inexhaustible gift of nature with little or no effect on the environment, then this will reduce the rate of greenhouse gases. This is because renewable energy and energy efficiency are two components that should go together to achieve a sustainable and eco-friendly environment. Hence, the need to conserve the present energy generated in the country using energy efficiency products and practices are essential for

Table 7 ARDL model long-run diagnostic test

S/number	Diagnostic tests	LM test	*F* test
A	Serial correlation	CHSQ(2) 0.5264 (0.3468)	1.2272 (0.3685)
B	Functional form	CHSQ(1) 0.0771 (0.7813)	0.1286 (0.9019)
C	Normality	CHSQ(1) 0.8131 (0.6659)	Not applicable
D	Heteroskedasticity	CHSQ(1) 2.6023 (0.1193)	2.5455 (0.1106)

A represents the Lagrange multiplier test of residual serial correlation, B the Ramsey's RESET test using the square of the fitted values, C based on a test of skewness and kurtosis of residuals, and D based on the regression of squared residuals on squared fitted values this initiative. In general, Nigeria is in dire need of technological change in both the energy and industrial sectors. The adoption of renewable and alternate energy resources will support sustainable growth with reduced adverse environmental impacts. The increasing population ratio is a fueling factor to worsening environmental conditions due to economic growth and energy use. Based on the empirical results of this study, the government of Nigeria needs to take remedial actions towards the sustainable development goals. In view of increasing energy consumption, the energy demand needs to be fulfilled by adopting renewable and alternative energy resources rather than depending on conventional fossil fuel energy sources. Moreover, economic growth as a whole causes environmental degradation both in the short and long-run; therefore, there is still need to mitigate carbon emission in industrial sectors and to adopt adaptation strategies in vulnerable areas to minimize the short-run and long-run damages. The government should establish performance standards and greenhouse gas emission baselines for major activities and major source and create awareness of renewable energy and energy efficiency. This research helps fill the knowledge gap in energy mix consumption and environmental impacts created with the convergence of the energy commission and the environment ministry, which has limited the scope of the environmental protection and management systems. There is an urgent need to carry out spatial planning analysis to know and project renewable energy combination in Nigeria. Also, environmental protection laws in terms of both human activities and a management system should be put in place to help mitigate climate change and ensure an eco-friendly environment and growth at the same time.

Endnotes

[1]German Federal Ministry of Environment, Nature Conservation and Nuclear Safety, 2000. Act on Granting Priority to Renewable Energy Sources (Renewable Energy Sources Act). http://www.bmub.bund.de/fileadmin/bmu-import/files/pdfs/allgemein/application/pdf/res-act.pdf.

[2]ARDL bound test for co-integration and VECM framework applied.

Competing interest
The authors declare that they have no any competing interests.

Authors' contributions
JSR personally contributed in terms of analyzing the data and produced the results of the manuscript. JSR also contributed in revising the manuscript. All authors read and approved the final manuscript.

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