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ORIGINAL PAPER

Development of domestic technology for sustainable renewable energy in a zero-carbon emission-driven economy

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Abstract
The global outcry for a sustainable energy system—energy transition regime, involves the substitution of fossil fuels with clean and affordable energy and the amelioration of greenhouse gas (GHG) effects on global health and environment. Studies have shown that economic growth proportionally links energy consumption, as seen in developed countries. Hence, countries with low economic activities such as those in sub-Saharan Africa (SSA) are supposedly not to panic over CO_2 emissions. It is ascertained from energy reports, research articles, and several other sources of energy information and tools that economic activities in SSA resulted in 7.1% of the global share of carbon dioxide (CO_2) emission. Ironically, despite this low share, the region is highly vulnerable to climate change due to low economic and technological advancement. The results of the studies on renewable energy (RE), CO_2 emissions outlook, and global warming in SSA show that CO_2 emission is increasing; global warming is about 0.5℃; anthropogenic global warming is between 0.8; and 1.2 °C locally and is increased at about 0.2 °C per decade. If not abated, a global warming of 1.5 °C will be reached between 2030 and 2053. To effectively boost RE deployment, and mitigate CO_2 emissions in SSA, this study simplifies energy-GDP-CO_2 nexus and identifies research and development areas to facilitate energy transition paradigm. The paper sees domestication of energy technology, deployment, and development of sustainable RE policies which are stern steps in mitigating CO_2 emissions in SSA.

Keywords Renewable energy · CO_2 emission · Greenhouse gas · Global emission · Climate change · Sub-Saharan Africa

Introduction

This study echoes the importance of renewable energy (RE) infrastructure and domestic technology capacity building to the provision of adequate power supply without compromising the environment and future use of energy resources in sub-Saharan Africa (SSA). It orates that domestic R&D in RE technology is a key in curtailing carbon dioxide (CO_2) emissions in the region and, therefore, identifies contemporary areas of R&D in RE, CO_2 capturing and storing that will facilitate increase in RE deployment and CO_2 emissions mitigation in SSA. The article presents salient information vital to postgraduate studies, RE investors, guide the government, and policymakers to implement realistic and sustainable policy in the region. The study is intended to create awareness on the underlying nexus between CO2, gross domestic product (GDP), and energy consumption. In addition, the study will outline some steps policies that can be integrated into national policies, planning, and strategies towards climate change mitigation in SSA. To achieve a sustainable environment and energy system, countries in SSA need to develop a robust and sustainable economy domestically. As a developing region, the governments have to establish similar national energy and environmental policies to align economic development to secure and sustain clean energy supply and the environment.

Access to reliable and stable electricity supply in most countries in SSA is challenging for both urban and rural dwellers. The available power supply is characterised by chronic undesirable, and insufficient supply, long downtime, obsolete facilities, inadequate skilled personnel, exploitative billing system, and so on. Consequently, the region accommodates the highest percentage of people without access to electricity, living in abject poverty. About 40%

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of the SSA population lack access to safe drinking water sources; 68% lack access to improved sanitation facilities; 600 million people lack access to modern energy in 2018 (IEA 2019), relying on traditional biomass for heating, lighting, and cooking. This inadequate power supply limits the socio-economic growth of the region. As a result, the economies of countries in SSA, excluding South Africa (SA), survive on self-provide power generating scheme. The use of dedicated (off-grid) petrol and diesel generating sets by factories, service firms, shop clusters, and homes to generate electricity has become a norm in the region. Besides, estimated 900 million Africans are expected to primarily use solid fuels, such as charcoal, wood, and solid waste to cook, and 7% with kerosene (Kammila et al. 2014). It was reported in 2019 that SSA has the largest populations that cook with traditional biomass (Corfee-Morlot et al. 2019). These traditional practices and the use of fossil fuel emit carbon dioxide (CO_2) and particulate matter (PM), which are dangerous to health, into the biosphere (Agrawal and Yamamoto 2015; Amegah and Jaakkola 2016; Das et al. 2017). The noxious fumes released into the atmosphere are connected to about 2.8 million premature deaths annually (IEA 2017b).

The environment and human health are continually sacrificed for energy, needed for socio-economic activities. Despite this compromise, access to energy is still inadequate and challenging, about 50% of the population in 41 countries in SSA have no access to electricity, and 650 million people are expected not to have access to modern energy by 2030 (IEA 2017b). The use of fossil energy has been reported as the highest source of greenhouse gases (GHG) due to CO_2 emission, a by-product of combustion of fossil fuel (Nachmany et al. 2014). The CO_2 concentration in the atmosphere has reached dangerous levels—increased from 280 parts-per-million (ppm) during the pre-industrial era to 403 ppm in 2016, with the growth rate of 2 ppm annually (IEA 2017a). The problem of global warming is caused by high CO_2 concentration in the atmosphere resulting from quest for energy. The consequences of the use of fossil fuels and some other human activities (Aljazeera 2019; FloodList 2019a, b) that are inimical to the biosphere are evidenced in the increasing events triggered by climate change. These events include storms and ice melts, droughts, floods, cyclones, high temperatures, and migration. The call to end fossil fuel economy due to its consequential effects should be given urgent attention in the region. Subsequently, the Paris Agreement, which aims to mitigate climate change and keep temperature increase below 2 °C, considerably 1.5 °C, was established by united efforts of all countries (IPCC 2015). This goal with sharply cutting anthropogenic CO_2 emissions will require the implementation of negative CO_2 emissions technologies (NETs) to remove CO_2 (Rogelj et al. 2018).

Adequate energy supply is a panacea to socio-economic development and is amongst the critical issues in the global spotlight. Increasing efforts towards improving access to electricity in SSA is compounded and deterred by the world's stand on the utilisation of fossil fuel, which is the main driver of the region's economy. However, harmful gas emissions, GHG, are often associated with fossil fuel extraction and consumption. Energy and economic growth have proportional relations; high fossil energy consumption translates to high-volume CO_2 emissions. This correlation has attracted the world's attention, since the 1990s because of the potential threats of CO_2 to the ecosystem and human health. Apart from the consumption of fossil energy, there are other human activities (cement production, and deforestation) and natural sources (decomposition, ocean release, and respiration) of harmful gas emissions. However, the energy sector contributes the highest to global CO_2 emissions, and fossil and biomass fuels are the most exploited energy sources in SSA. About 90% of the households in 25 countries of SSA depend on wood, charcoal, and waste for cooking. These practices result in GHG emissions, climate change, increased morbidity, and mortality (Baloch et al. 2020; Ebhota 2019; Hickman et al. 2014; Inglesi-Lotz and Dogan 2018; Maji 2019).

Before industrialisation, there existed a natural balance of CO_2 in the ecosystem, such that the emitted gas is used up for other beneficial activities and continuously recycled to maintain the balance. These activities include plant photosynthesis, reforestation, soil improvement, fossil formation, and ocean intake, as shown in Fig. 1. The sources of CO_2 then were mainly through animal respiration, direct human-induced impacts on forestry and land use, for instance, deforestation, land clearing for agriculture, decay and decomposition of organic matter, and degradation of soils. Other

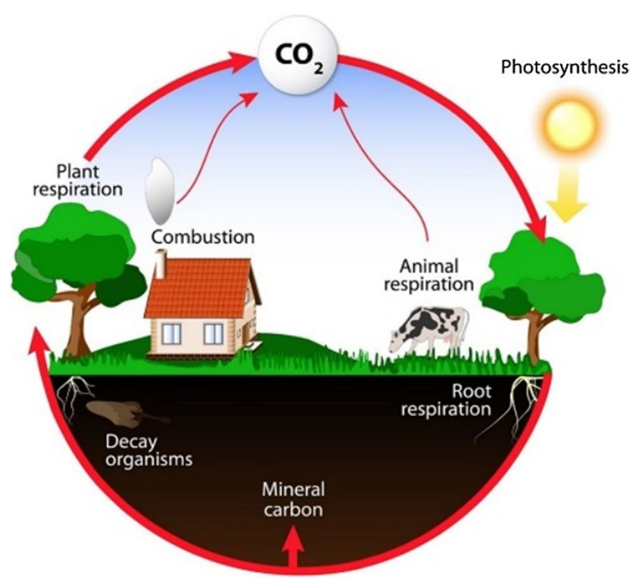


Fig. 1 Ideal carbon cycle

Table 1 Atmospheric gas components and their volumes (%) (Curry and Webster 1998; Glueckauf 1951)

Constituent	Formula	Volume (%)
Nitrogen	N_2	78.08
Oxygen	O_2	20.95
Argon	Ar	0.93
Carbon dioxide	CO_2	0.033
Neon	Ne	0.002
Helium	He	0.0005
Krypton	Kr	0.001
Xenon	Xe	0.00009
Hydrogen	H	0.00005

atmospheric air components and their expected volumes by percentage are presented in Table 1.

However, over the years, CO_2 and other GHG have been heavily released into the biosphere through direct and indirect human socio-economic activities since 1900. These activities include the increased use of automobiles (transportation), heating and cooking, production and consumption of energy, agriculture, and production of cement, as shown in Fig. 2. It has been reported that between 1850 and 2011, global CO_2 emission increased by over 15 times due to human activities (Friedrich and Damassa 2014). The highest amount of CO_2 released to the environment reported was 49 Gt between 2000 and 2010 and industry and the combustion of fossil fuels contributed 78% of this amount. The recorded amount of CO_2 released in 2014 only from coal uses was about 16 Gt (Abd et al. 2020).

Studies have shown that the concentration of CO_2 in the biosphere is increasing at a 286 parts per million (ppm) annually since 2016 (Barua et al. 2020; Watanuki 1997). The rise started at the beginning of the industrial era (1750), from about 277 ppm to about 414.7 ppm in 2019 and predicted to reach 500 ppm in 2050, as presented in Table 2 (Joos and Spahni 2008). This increase was originally attributed to deforestation and other land-use activities. However, this is mainly due to the unprecedented CO_2 emissions due

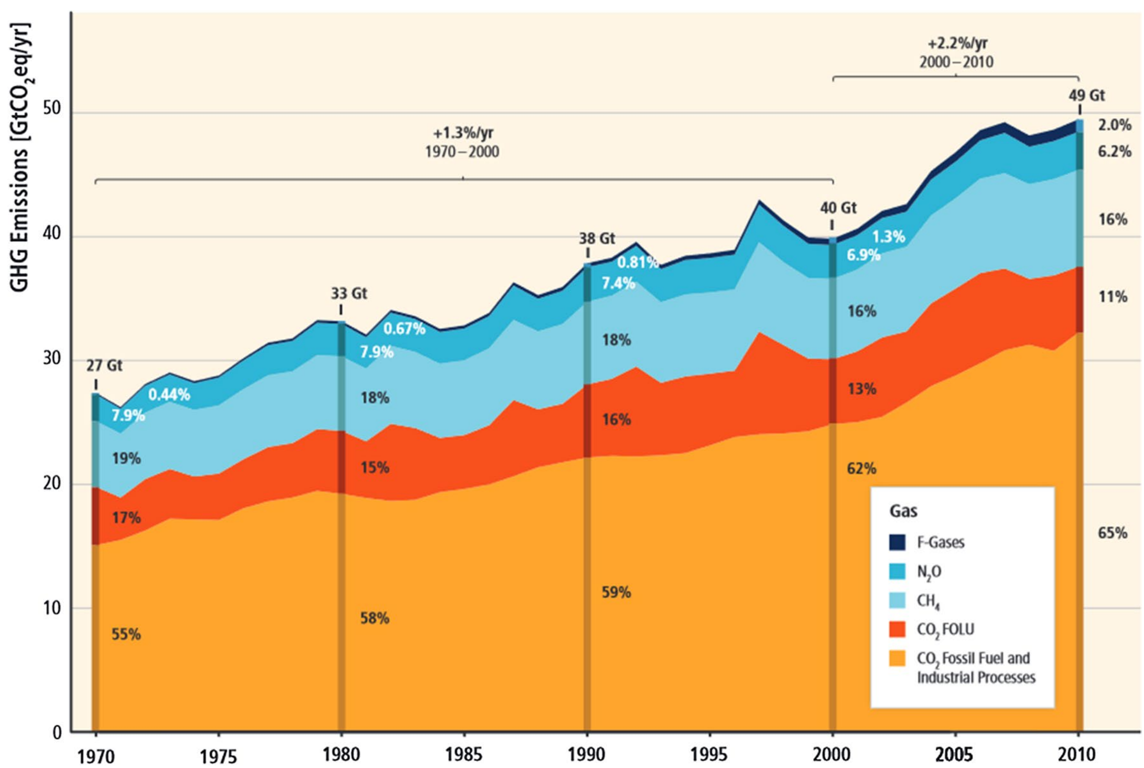


Fig. 2 Total annual anthropogenic GHG emissions (1970–2010) (PCC 2014)

Table 2 Concentration of CO_2 in the atmosphere

Year	1750	1958	2011	2014	2016	2017	2019	2050
Amount in the atmosphere in parts per million (ppm)	286	315	391	398	403.3	405.0 ± 0.1	414.7	500 (prediction)

to the consumption of fossil fuels witnessed during the industrial era.

Between 1970 and 2010, fossil fuel usage and other industrial processes contributed about 78% of the total GHG emissions while deforestation, agriculture, and other land-use released the second largest emission. The total annual anthropogenic GHG emissions from 1970 to 2010 are shown in Fig. 2.

Carbon dioxide emission accounts for the largest portion of GHG emissions and is a major source of environmental and health challenges. Therefore, this study examines and discusses the causal relationships between energy consumption (EC), economic growth (EG), and environmental pollution (EP); role RE plays in zero-CO_2 economy in SSA, significance of research and development (R&D) to sustainable RE deployment and climate change mitigation, and identifies research areas to boost the use of RE and reduce CO_2 emissions in the region. In addition, several steps and methods advanced, taken, and used to reduce CO_2 emissions and/or limit its consequential effects that are not adequately deployed in SSA will be briefly discussed, while the effects of domestication of RE technology on CO_2 mitigation will receive much more attention.

The rest of this study is structured as follows: Sect. "Materials and methods" presents research methodology; Sect. "Econometric techniques" provides the relationship between economic growth, CO_2 emissions, and energy consumption; 4—Climate change outlooks in SSA, while Sects. "Climate change outlooks in SSA" and "The role of domestic research and development in RE and CO_2 capturing and storing" deal with the role of domestic RE technology in curtailing CO2 emissions in SSA and conclusion, respectively.

Materials and methods

A broad review was performed considering the literature relevant to this research published most in the last five years to the present date. This study was conducted in the following manner: secondary data gathering via such platforms as Scopus, ScienceDirect, verified official websites of companies, published feasibilities, reports, and investigations by global organisations on energy and CO_2 emissions—the World Bank, Intergovernmental Panel on Climate Change (IPCC), and the United Nations (UN) and its subsidiaries, and online energy and CO_2 data applications, such as Worldmeter and Climatewatch. Other sources of data include national energy departments and international energy organisations, such as the national governments' reports in the region under investigation, International Energy Agency (IEA), World Energy Council, (WEC), and International Renewable Energy Agency (IRENE). The information obtained will be used to establish CO_2 emissions in SSA, the relationships that exist between economic growth, environment, and CO_2 emissions, the correlation between fossil energy and CO_2 emissions, and determine the type of energy for SSA and its development approach.

Econometric techniques

The relation existing between CO_2 emissions, energy consumption (EC), and gross domestic product (GDP) has been studied by several researchers employing diverse data set and econometric methods (Halicioglu 2009; Zaidi and Ferhi 2019). To understand the perceived correlation between these variables, a system that cointegrates the variables has been established to test the link between several time series in the long term. A variety of econometric methods and processes have been deployed by studies to test and analyse the actual nexus between economic growth, output-energy, and output-environmental pollutants. This concept, which is often called cointegration test, was first used in 1987 by Nobel laureates, Robert Engle and Clive Granger (CFI 2020). The studies relied on data frequency, underlying variables, and the development stages in arriving at conclusions and implications. Scenarios where two or more non-stationary time series are cointegrated in such a way that they cannot depart from equilibrium in the long term are identified by cointegration tests. The degree of sensitivity of two variables to the same average price over a stated period is recognised by the tests.

Based on the literature, the discussion on energy consumption, economic growth, and environmental pollutants can be categorised into two research components—first component tests to validate the environmental Kuznets curve (EKC) hypothesis, which focuses on environmental pollutants and output nexus. In 1955, Kuznets predicted that the varying correlation between per capita income and income inequality is a reversed U-shaped curve (Jovanovic 2018; Le et al. 2020; Olale et al. 2018), while the second component is a more recent and an emerging research approach that examines the dynamic correlation between energy consumption, economic growth, and environmental pollutants (Ito 2017; Muhammad 2019; Munir et al. 2020; Wasti and Zaidi 2020). Several studies have shown the causality between energy consumption and economic growth, and their outcomes can be categorised into four:

Neutrality hypothesis

Absence of causality between energy consumption and GDP; it is supported by the absence of a causal relationship between energy and real GDP.

Conservation hypothesis

Existence of unidirectional causality running from GDP to energy consumption.

Growth hypothesis

Existence of unidirectional growth.

Feedback hypothesis

Existence of bidirectional causality between energy consumption and economic growth.

In the past two decades, several econometric techniques have been developed, modified, and deployed to investigate and test energy consumption, economic growth, and environmental pollution functions. These include univariate cointegration approaches, such as Engle and Granger, and the fully modified ordinary least squares (FMOLS) procedures of Phillips and Hansen, and multivariate methods, such as Johansen (1988), Johansen and Juselius 1990, and autoregressive-distributed lag (ARDL) (Halicioglu 2009; Johansen 1995; Johansen and Juselius 1990). Despite these efforts, there still exist worrisome high degree of research results discrepancies, weakness, and flaws as studies have shown diverse results of GDP, environmental pollution, and energy consumption nexuses for same country at the period. Table 3 presents diverse outcomes of studies on the economic growth-energy-pollution nexus in some selected countries, deploying different econometric techniques.

Where $E \rightarrow Y$ depicts causality running from energy consumption to income; $Y \rightarrow E$ depicts causality running from income to energy consumption; $Y \leftrightarrow E$ depicts bidirectional causality between income and energy consumption; ARDL is autoregressive distributed lag; GDP is gross domestic product per capita; CO_2 is carbon dioxide emissions per capita; E and EC are energy and electricity consumption, respectively; $\rightarrow$ is the unidirectional causality hypothesis; $\leftrightarrow$ feedback hypothesis; and $\neq$ neutral hypothesis.

Results and discussion

Simplified energy consumption, GDP, and CO_2 emissions nexus

This study has come to the terms with the significance of nexus of energy consumption, GDP per capita, and CO_2 emissions in the contemporary national and regional sustainable development. The perceived relation must be treated with kid gloves to avoid misinformation because of its sensitivity and importance, as it involves economic growth, environment, and scarcity of resources. Subsequently, the drawbacks and gap created by the academic-based econometric techniques in describing the correlation between energy consumption, GDP, and CO_2 emissions can be surmounted and simplified, using mostly time series data. Several credible and up to information data on energy consumption, GDP, and CO_2 emissions are available in the databases of reliable international organisations, such as World Bank, UN, IEA, and IPCC.

Around 1950, the use of fossil fuel dominated the sources of anthropogenic emissions to the biosphere and there has been a rise in the consumption fossil energy since then. Relatively, fossil fuel shares in the global CO_2 sources have continued to rise due to its significance in the growth and sustenance of the economy. The results from the study and analysis of data obtained from Worldmeter (2019b) and the World Bank (2019) databases have clearly shown that the relation between energy consumption, CO_2 emissions, and GDP is unidirectional, causality running from energy consumption to GDP and CO_2. Quite often, the amount of fossil energy consumed controls and kick-starts the direction of the nexus. The persistence increase in population, civilisation, and industrialisation is responsible for the continue rise in CO_2 emissions due resulting from the rise in the energy consumed. The desire to create higher tax revenues by the government for economic growth will always be there due to inadequate fund to meet the onerous needs of the citizens. The economic growth required to build a comparative competitive GDP and reduce government borrowing will lead to more fossil fuel consumption with the consequential CO_2 emissions. The trend of annual global growth rate of GDP against energy consumed and CO_2 is presented in Table 4. Averagely, the annual global growth rates of fossil energy, CO_2 emissions, and GDP from 1990 to 1999 increased by 80%, 1%, and 2.66%, respectively; the three variables have the same direction trends. However, global recession occurred in 2009, having global GDP and CO_2 emission annual growth rates of − 1.73 and − 1.10, respectively; the negative sign shows a decline, which means economic retrogression. In 2010, both the global CO_2emission and GDP recorded 5.9% and 4.32%, respectively, depicting increase and a rebound. In the same vein, the trends between GDP and CO_2 emissions in SSA follow the same form, as depicted in Fig. 3a and b, and a rise in GDP corresponds to an increase in CO_2 emissions, vice versa. It was observed that the annual growth rate of 1% of global CO_2 emissions is associated with an increase in GDP growth rate. However, in 2009, the global growth rate for both CO_2 emissions and GDP declined by − 1.3% and − 1.73%, respectively, due to recession, while in 2010, both the global emission of CO_2 and GDP rebounded by 5.9% and 4.32%, respectively (Worldmeter 2019b, c).

In the climate change discourse, large economies, such as the USA, China, and Japan, are sometimes referred to as

Table 3 Outcomes of studies on economic growth-energy-CO_2 emission nexus in some Asia countries

Countries	Study period	Technique used	Causality correlation	Articles
Economic growth-energy nexus				
Thailand, the Philippines	1954–1976		E → Y: the Philippines Y ↔ E: Thailand	Yu and Choi (1985)
Indonesia, Malaysia, Singapore, the Philippines	1955–1990	Johansen's multivariate cointegration tests	≠: Malaysia, Singapore, the Philippines Y → E: Indonesia	Masih and Masih (1996)
Thailand	1955–1991	Multivariate model, vector error correction model (VECM)	E → Y: Thailand	Masih and Masih (1998)
Indonesia, Malaysia, Singapore, the Philippines	1970–1990	Granger test	≠: the Philippines Y → E: Indonesia E → Y: Singapore Y ↔ E: Malaysia	Murry and Nan (1994)
Singapore	1961–1990	Cointegration and error correction modelling	Y ↔ E: Singapore	Glasure and Lee (1998)
Indonesia, Malaysia, Singapore, Thailand, the Philippines	1971–2001	Panel data	≠: Indonesia, Thailand Y → E: Malaysia, Singapore, the Philippines	Chen et al. (2007)
Indonesia, Malaysia, Singapore, Thailand	1971–2002	Modern time-series	Y → E: Indonesia, Thailand Y ↔ E: Malaysia, Singapore	Yoo (2006)
Indonesia, Malaysia, Thailand	1971–2002	Panel cointegration	Y ↔ E: Panel	Mahadevan and Asafu-Adjaye (2007)
Indonesia, Malaysia, Singapore, Thailand, the Philippines	1971–2002	Panel cointegration	E → Y: Panel	Lee and Chang (2008)
Indonesia, Malaysia, Singapore, Thailand, the Philippines,	1980–2006	Panel cointegration	E → Y: Panel	Lee and Chang (2008)
Indonesia, Malaysia, Singapore, Thailand, the Philippines	1971–2009	Panel cointegration	Neutrality: Singapore Y → E: Indonesia, Malaysia, the Philippines Y ↔ E: Thailand	Yildirim et al. (2014)
GDP, EC and CO_2emissions nexus				
Turkey	1960–2005	Granger causality ARDL	GDP—E	Halicioglu, (2009)
Turkey	1960–2007	Granger causality ARDL cointegration	EC ≠ GDP CO_2 ≠ GDP	Ozturk and Acaravci (2013)
Malaysia	1980–2009	EKC hypothesis	CO_2 → GDP	Saboori et al. 2012)
Malaysia	1971–1999	Granger causality multivariate vector error correction model	GDP ↔ CO_2	Ang (2008)
China	960–2007	Granger causality VECM	GDP → E	Zhang and Cheng (2009)
6 Central American countries	1980–2004	Panel vector error correction model	E ↔ GDP	Apergis and Payne (2009)
Iran	1967–2007	Toda-Yamamoto method	GDP → CO_2	Lotfalipour et al. (2010)
Tunisia	1961–2004	Granger causality based on ECM	GDP → CO_2	Fodha and Zaghdoud (2010)
Russia	1990 – 2007	Granger causality vector error correction model (VECM), cointegration	GDP ↔ CO_2 EC ↔ GDP EC ↔ CO_2	Pao et al. (2011)

Table 4 Annual global growth rate of GDP and CO_2

Year	1990–1999	2000–2009	2009	2010
Average fossil fuel consumption (%)	80	80.56	80.61	80.78
Average CO_2 emissions growth rate (%)	1	2.55	− 1.10	5.72
Average GDP growth rate (%)	2.66	2.82	− 1.73	4.32

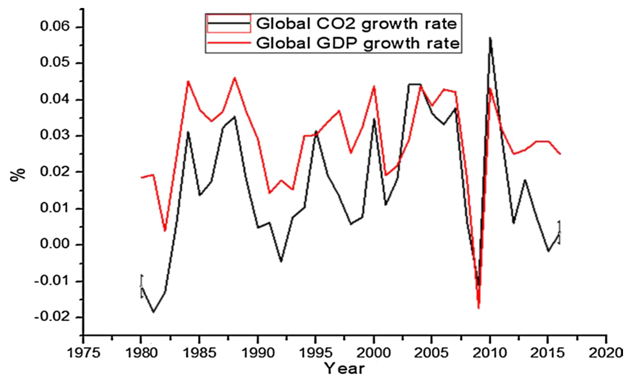


Fig. 3 (**a**) Global GDP growth and (**b**) global CO_2 emissions rates (1980–2016)

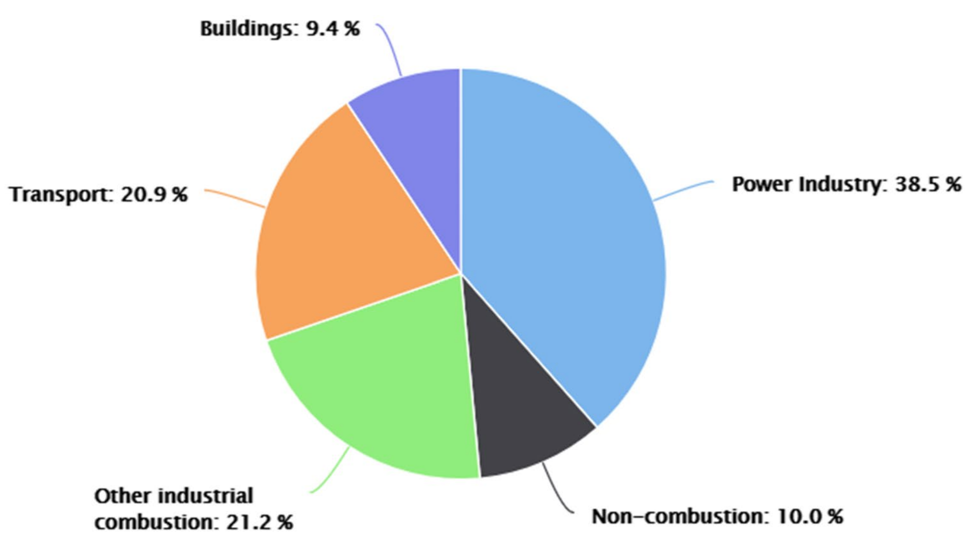
fossil economies because they are products of fossil fuels. The key components of large economies—transport (automobiles, trains, and planes), energy (power plants), and industrial sectors, are virtually run by fossil fuels—diesel, gasoline, natural gas, and coal. Figure 4 shows sources of fossil CO_2 emissions by sector.

Developing economies, such as SSA and India, are not exemptions of this scenario; they need affordable and adequate energy supply for socio-economic growth. The capacity of the deployed RE in SSA is grossly inadequate to the required energy for the rapidly growing population, urbanisation, and industrialisation. This implies that more CO_2 will be produced and released to the biosphere, as the region's main source of energy that is being enlarged is fossil energy. Available data (IMF 2019; OECD 2020; Worldbank 2020; Worldmeter 2019d) have shown that the top ten countries with the highest nominal GDP in 2017 produced the highest CO_2 (IEA 2020; Worldmeter 2019a) in the trend with GDP, as depicted in Fig. 5. Although the decision has reached to reduce the consumption of fossil fuels, SSA still needs a breakthrough in the energy sector that includes abundant fossil fuel energy to surmount poverty. In 2014, it was reported by IEA that fossil fuels contributed about 74% of SSA's power generation sources, with coal and oil accounting for 54% and 9%, respectively. According to the report, a leading scenario for 2040 has envisaged fossil fuels to contribute over 50% (coal 27%, gas 25%, and oil 4%) to the region's electricity. The CO_2 emissions from oil and gas are predicted to double, although those from coal will decrease (IEA 2014). South Africa the most developed African country generates electricity 77% coal. Available data (IMF 2019; OECD 2020; Worldbank 2020; Worldmeter 2019d) have shown the top ten countries with the highest nominal GDP in 2017 that produced the highest CO2 (IEA 2020; Worldmeter 2019a) in the trend with GDP, as depicted in Fig. 5.

Carbon dioxide emissions in SSA

Despite being home to 14% of the world's population, the region accounts for only 7.1% of the world's GHG emissions. Some countries in SSA are amongst the poorest countries in the world, and they do not emit a significant amount of CO_2 gas due low economic activities, although there are some notable exceptions. South Africa (SA), which is rich in coal, emits more CO_2 than Britain, despite having one-eighth of its economy size and 10 million fewer people than its population. The CO_2 emissions of selected countries in SSA are presented in Fig. 6. A big energy and chemicals firm, Sasol petrochemical, in Secunda, SA, is one of the world's largest sources of GHGs. South Africa has the largest share of CO_2 emissions in SSA, followed by Nigeria and Zambia consecutively, Zambia land-use-related emissions

Fig. 4 Global share of fossil CO_2 emissions by sector (Worldmeter 2019a)



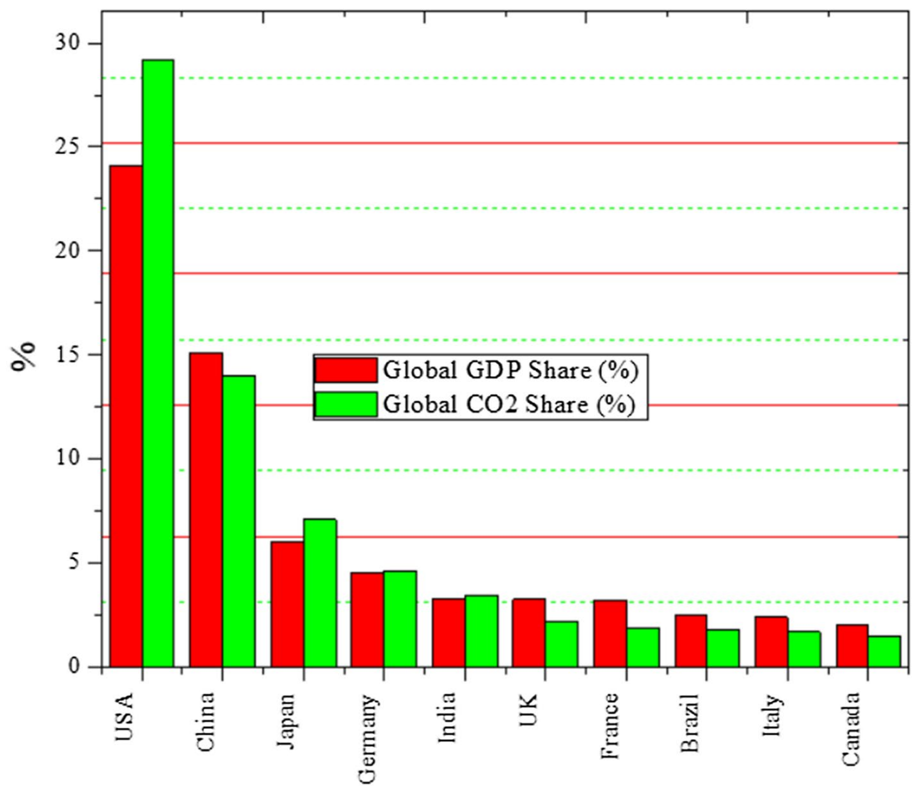


Fig. 5 Leading global share of GDP and CO_2 by Country

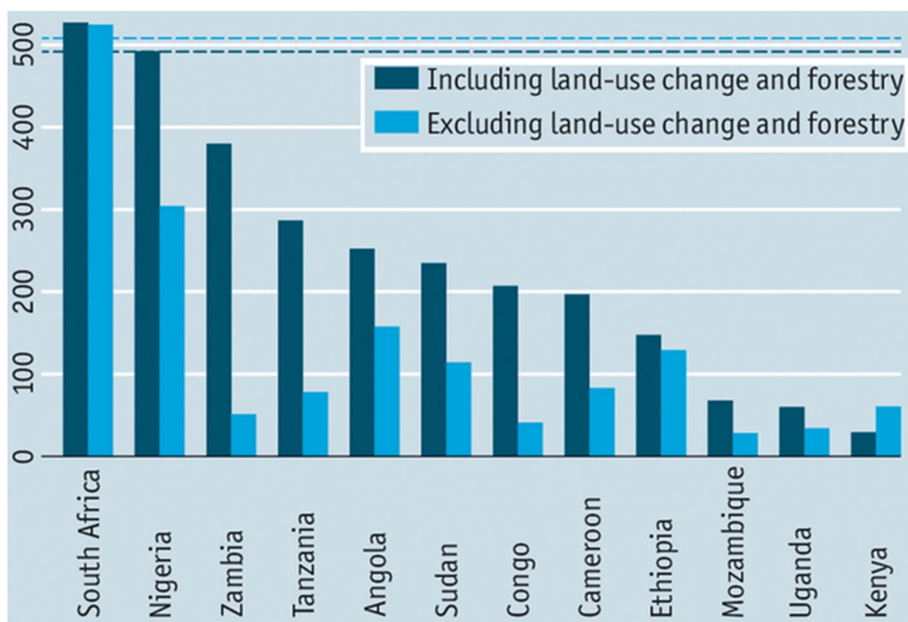


Fig. 6 Emission of CO_2 by selected countries in SSA (Economist 2018)

surpass that of Brazil, and in Nigeria, households and businesses depend on old and dirty diesel and gasoline generators for about 14 GW of power, which is more than the country's grid installed capacity of 10 GW (Economist 2018).

However, Africa has been flagged vulnerable to climate change due to low economic growth, low technological improvement, and high dependence on natural resources for agricultural production (Adzawla et al. 2019). Currently, the region is witnessing a wide range of direct and indirect impacts evidenced in the increase in natural disasters attributed to climate change. These include flooding, rising sea levels, drought, cyclone, temperature increase (global warming). Interestingly, there is an increasing consensus with the view of the transition to renewable energy (RE) systems, as a key scheme to address the climate change crisis. The continuous rise of CO_2 emissions in the region, as depicted in Fig. 7, should be of interest, considering the increase in the occurrences of climate change propelled extreme conditions in recent times. Presently, the region's economy, society, and civilisation run primarily on fossil fuel, which gives out dangerous emissions to the biosphere that aid anomalous climate change. As a heed to clarion calls, the United Nations (UN) in 2015 assembly resolved to decrease the consumption of fossil fuels and increase the deployment of RE (UN 2015). Since energy is what powers economic growth, the development or use of alternative energy sources to fossil fuels is now a necessity.

Ways of curtailing and mitigating CO_2 emissions in SSA

Currently, there are national initiatives on CO_2 mitigation and adaptation but they are simply not enough or inadequately implemented to keep the temperature below the limits in accordance with Paris Agreement. Certainly, limiting global warming to 1.5 °C will require a much more than transitions in carbon intensity of fuels, energy efficiency, electrification source, and land-use change, which are either put in place or underway in many countries. Several other steps and methods have been advanced, taken, and used to reduce CO_2 emissions and/or limit its consequential effects that are not yet inadequately deployed in SSA. These include the application of CO_2, domestication of technology and CO_2 taxation method, GHG emissions assessment, carbon capping, promotion of green transport sector, and increase in the deployment of RE, carbon offsetting, sustainable building, expanding, restoring, and managing forests. In this section, some of these initiatives will be briefly discussed, while the effects of domestication of RE technology will receive much more attention.

Carbon capping

The cap-and-trade system involves the obtaining of specific amount of allowances of CO_2 to emit by parties, such as fuel refiners or electricity generators, responsible for these emissions. Surpassing these allotted allowances by a participating member of the cap and trade will require purchasing more of allowances from members who did not exceed all of their allowances; these members are at liberty in selling off their remaining allowances within the emission trading system (ETS). Although this approach is beneficial to the regulation of emissions to a specific level, critics are of the opinion that cap system is comparatively less transparent and requires huge administrative support to implement.

A green/sustainable building

This is an outcome of a design ideal, which aims at increasing the efficiency of resource used, such as energy, water, and materials. They are planned and operated, such that during design, construction, operation, maintenance, and removal they do not impact on human health and the

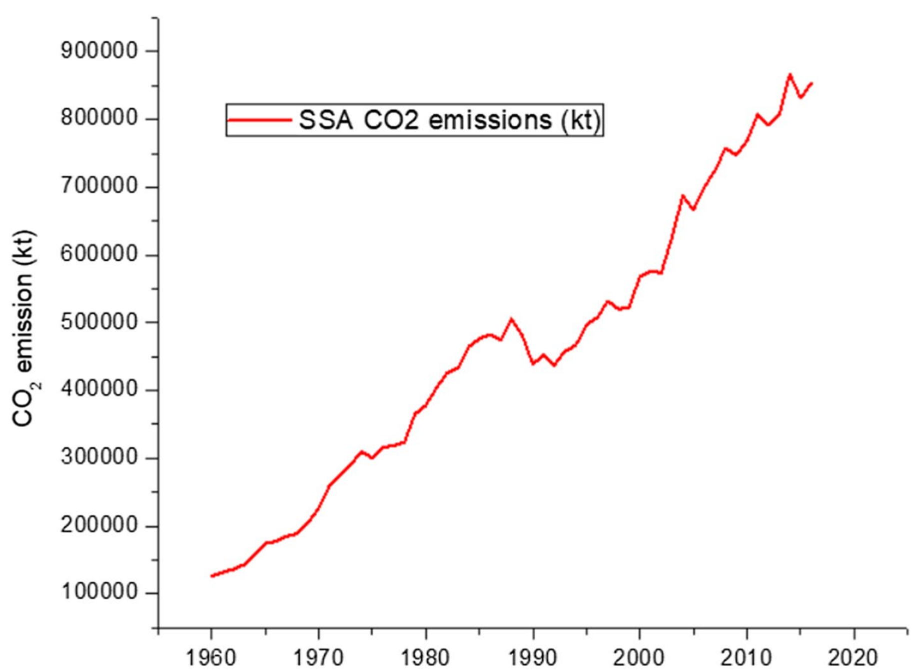


Fig. 7 Sub-Saharan Africa CO_2 emissions (1960–2016) (Worldbank 2019)

environment negatively. This system ensures the protection of human health and enhancement of employee's productivity: pollution, waste, and environmental degradation reduction and efficient use of resources, such as energy and water.

Encouraging demotorisation and decarbonisation

Rewarding both transporters and commuters of clean energy vehicles and users of energy-efficient appliances can have tremendous effects on CO_2 emissions. This can be achieved through carpooling, biking, telecommuting, use of electric vehicles, switching to public transportation, and other environmentally friendly commutes.

Harnessing new opportunities

Despite the deleterious effects of CO_2 to human health, it equally serves as essential ingredient to many processes and raw material to products, as shown in Fig. 8. Five key categories of CO_2-derived products and services are fuels, building materials from minerals, building materials from waste, and biological processes yielding improvement. Carbon dioxide in solid and liquid forms is used in fire extinguishers, for refrigeration, and cooling. Others uses include in the manufacture of casting moulds, as a pressurising gas in air guns and oil recovery, chemical feedstock and supercritical fluid solvent in decaffeination of coffee and supercritical drying, and addition to drinking water, carbonated beverages, beer, and sparkling (Roberts 2017; UIG 2016). Efforts are being made through research and development to create new products from CO_2, a development that is receiving a tremendous attention in the global north including India and China. The main primary driver of this increased interest is climate change mitigation. This is prompting massive research on bioenergy with carbon capture and storage (BECCS) (Kumar and Kumar 2016; Stephenson 2018) and CO_2 direct air capture (DAC) (Fasihi et al. 2019) (Drechsler and Agar 2020; Rodríguez-Mosqueda et al. 2019; Sanz-Pérez et al. 2019) technologies to aid humankind to control and mitigate climate change. In this regard, global south, which SSA belongs, is lagging behind greatly. The exploitation of CO_2 applications will strengthen industrialisation while mitigating climate change in the region.

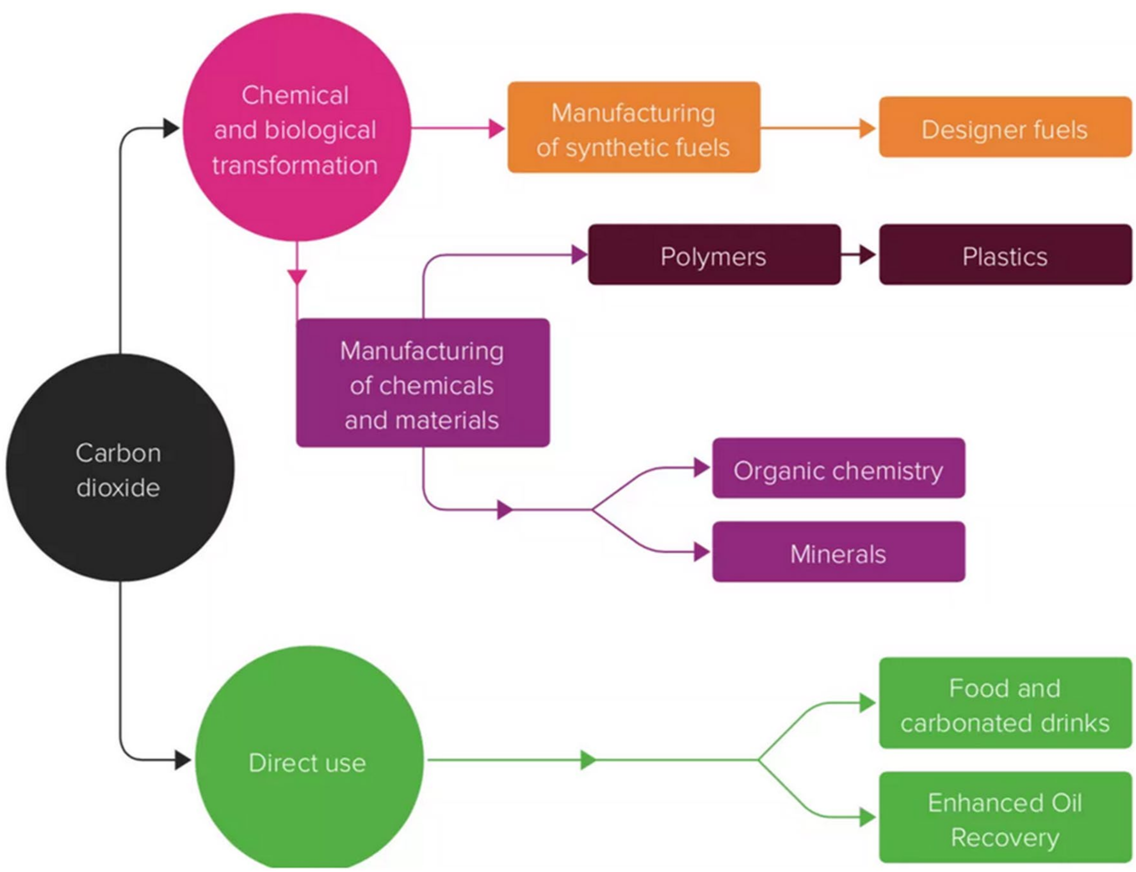


Fig. 8 Uses of CO_2 (Roberts 2017)

Incentives for RE: soft loan, subsidy, tax waiver for standalone clean energy, and CO_2 exploitation

Government policies and schemes, such as soft loan and tax waivers on RE, CO_2, and use projects, should be designed to support incentives on RE electricity generated from RE should have tax privileges as this will encourage energy companies, investors, and end users to sustain and increase the utilisation of clean energy and the emitted CO_2. The RE resources to be considered are solar, biomass, wind, hydropower, and geothermal. However, more attention of these incentives should be given to PV, wind, and small hydropower technologies, since the region is hugely endowed with these renewables. A sizeable population will capitalise on this to take the advantage of rapidly declining costs of PV.

Climate change outlooks in SSA

Understanding climate change outlooks and how the impacts affect the region directly or indirectly is critical to appropriate mitigation responses. Several studies (Abid 2016; Acheampong et al. 2019; Al-mulali and Binti Che Sab 2012; Chakamera and Alagidede 2018; Ebohon and Ikeme 2006; Hickman et al. 2014; Inglesi-Lotz and Dogan 2018; Maji 2019; Tiwari et al. 2016) and EU funded Research Framework Programmes, both past and ongoing projects, are aiding African institutions to make up-to-date decisions for future climate change mitigation (UNEP 2012). Global warming of about 0.5 °C and the alteration of the behaviours of extreme climate events have been observed across Africa for the past 50 years. The anthropogenic global warming has reached between 0.8 and 1.2 °C locally, and this is continuing at the rate of 0.2 °C per decade (Diedhiou 2019). If this continues, the global warming of 1.5 °C will be reached between 2030 and 2053. The occurrence of the intensity of extreme temperatures will be experienced all over SSA if the mean temperature of global warming gets to 2 °C (Shepard 2019). Climate change varies across Africa, and possibly, Sahel is the most affected in the world, a region characterised by rapid population growth (about 2.8% yearly) amid shrinking natural resources. The predictions of climate change in SSA by several studies, as presented in Table 5, are worrisome and challenging (IPCC 2014; Steynor et al. 2020). Conversely, the negative impacts of climate change will be curtailed to acceptable levels if the rise in temperature is kept at 1.5 °C rather than reaching to 2 °C.

The role of domestic research and development in RE and CO_2 capturing and storing

This paper argues that the needed transformation in RE and CO_2 applications requires advancements in engineering and investment. Continues advances are the key to further exploit the already achieved and continuing cost decline of renewables, as well as other recent advances in energy efficiency, smart grids to connect generation, storage, and PV cell materials. Development of domestic capacity in RE technologies and CO_2 applications is a sustainable way of salvaging the huge problem of power deficit and continuous deterioration of power infrastructure in SSA without compromising the safety of the environment and human health. The capacity development should centre on CO_2 emission, capturing and applications, and RE components and systems design, development, and maintenance (Ebhota et al. 2014; Ebhota and Inambao 2015–2017). This will involve massive research and development R&D activities of new and improved adaptive CO_2 and RE devices, systems, capturing,

Table 5 Dangerous predictions of climate change in SSA (AfDB 2012; Bunn et al. 2019; Clay and King 2019; Mason-D'Croz et al. 2019; Matewos 2019; Mueller et al. 2020; Shepard 2019; Stanzel et al. 2018; Steynor et al. 2020)

South Western Africa is envisaged to see a reduction in water availability of more than 10% because of climate change
Southern Africa's vegetation vulnerable due to climate change caused by increasing in temperature
The occurrence of climate extremes and variability weather events, such as droughts, cyclones, and floods, which will trigger infectious disease epidemics, which include malaria, dengue fever, diarrhoea, etc
Crop net revenues are predicted to fall by as much as 90% by 2100, which will mostly affect small-scale farmers
More people in Africa will experience hunger in 2050 resulting from climate change consequences
Africa needs US$40 billion yearly until 2030 to combat climate change
Possibility of decreasing river discharge due to global warming and will pose a serious threat to hydropower in SSA
At both 1.5 °C and 2 °C, West and Central Africa will experience substantial increases in hot days
At 2 °C, Southern Africa region are expected to have increase in the number of consecutive dry days and decrease in precipitation of about 20% in Namibia, Botswana, northern Zimbabwe, and southern Zambia. This is expected to reduce the volume of Zambezi basin by 5% to 10%
In Western Sahel (e.g. Senegal), drought durations are expected to be increasingly long
Central Sahel is expected to have an increase in heavy rainfall with consequential flood risks in urban areas

Table 6 Identified R&D areas to boost RE and mitigate CO_2 emissions in SSA

The various RE technology research areas		
Photovoltaic (PV) technologies		
Concentrated PV (CPV) cells	Perovskite PV cells	Crystalline Silicon
Nanofibre PV cells	Dye PV cells	Cadmium Telluride (CdTe)
Inverter	Silicon germanium (SiGe) PV cells	Copper Indium Gallium Diselenide (CIGS)
Hybrid Organic–Inorganic Halide	Multi-junction /Tandem /Cascaded PV cells	
Geothermal		
Evaluate the sustainability of geothermal production	Cost of construction	Policy to break geothermal barriers
Techno-economic assessment	Heat exchanger materials	
Hydroelectricity		
Hydraulic performance testing and improved flow measurement	Small hydropower	Storage pump, turbine configuration,
Certification and verification of hydropower as green energy	Optimisation of the control system	Improving the efficiency of small hydroturbine
Cost reduction strategies for maintenance of facilities	Predictive maintenance/repair and condition monitoring	New technology to enhance downstream water quality
Simulation and optimisation models for machine and operational improvements, etc	Improving environmental flow requirements at peaking projects	Water quality management and mitigation
Wind turbine		
Wind turbine mechanical structure and material	Developing standards for wind turbine design	Operation and maintenance strategies
Operation and maintenance strategies	Wind turbine flow device	Wind turbine control system
Wind turbine monitoring, control, and reliability	Reducing component weight and manufacturing costs	Grid integration and optimising performance, etc
Energy storage technology		
Battery Material with the potential of higher energy density	Lithium-ion battery	Lithium-sulphur batteries
Ultra-capacitors	Flywheels	Battery modelling and simulation
Battery charging system	Improving the life of low-cost, compact, lightweight batteries, etc	
Energy smart grid technology		
Energy smart meters and advanced metering infrastructure	Smart grid costs	Smart application integration platform
Forecast of energy consumption in the different sectors	Smart grid simulation	
Electric vehicles		
Development of potential DC fast chargers	Electric vehicle grid impact assessment	Electric vehicle technology technical and economic feasibility in SSA
Solar-powered electric vehicles	Fuel optimisation hybrid vehicle	Battery charging infrastructure for commercial and public applications, etc
Electrical air conditioning and heating systems for electric vehicles	Alternative source systems of in-vehicle electricity production	Battery/energy management and charging systems
Braking systems for electrical propulsion and traction systems		
CO_2capture and applications		
CO_2 direct air capture technologies	Low-temperature solid sorbent-based direct air capture (LT DAC)	High-temperature aqueous solution-based direct air capture (HT DAC)

and production technologies. Hence, well-coordinated, adequate, and sustainable R&D investments in CO_2, alternative energy, and transformation are required. The expected R&D outcomes include reduction in CO2 emission, increase in the applications of CO_2, affordable, environmentally friendly, and sustainable energy. New RE products and processes based on the region's peculiarities need to be developed for appreciable sustainable energy transition to occur. In addition, RE manufacturing capacity built simultaneously with R&D. Manufacturing infrastructure is critical to the transformation of the advances in R&D into end user's demand products. Global warming discovery, analysis, and predictions are products of science, engineering, and technology and equally same serve as solution platforms to the issue.

Presently, a lot is going in the deployment of energy storage technologies, smart grids, and general purpose technologies, such as information and communication technology (ICT) in the combat of CO_2 emissions and limiting warming to 1.5 °C (Bastida et al. 2019; Bruun et al. 2014; Kamal 1997; Lau et al. 2012; Loha et al. 2020; Mori 2012). However, every promising approach for CO_2 removal, capturing, and storing as part of climate change strategy to avoid dangerous levels of global warming has challenges. Hence, SSA should investment in domestic-based research, development, and demonstration on CO_2 removal, capturing, and storing approaches and other ways of reducing and using of CO_2. The identified areas that the region should consider for R&D include energy materials and storage, demand management, and conservation. It also includes the impact of price, technical improvements, physical and legal controls, and education and promotion on energy demand. The region should take advantage of on RE and CO_2 capturing emerging technologies and invest in R&D areas, as presented in Table 6. Considering the consequences of inadequate energy supply, the use of fossil fuel, and climate change in SSA, the region should play a leading role in the R&D and manufacturing of CO_2 and RE devices, systems, capturing, and production technologies.

Conclusion

The pathway towards energy sufficiency in SSA is compounded by the global quest for a zero-CO_2-driven economy. The disproportionality in the volume of CO_2 in the biosphere now and during the pre-industrial era is wide. The environment and health consequences of this occurrence have been established, and these include drought, extreme rainfall, flooding, high temperatures, cyclones, etc. Although SSA contributes insignificantly to global emissions, the region is vulnerable to climate change due to its low economic and technological advancement, and high reliance on natural resources. The increase in climate change triggered events in the region attest to this vulnerability claim. The study and analysis of energy reports, research articles, and several other sources of energy information and tools show that:

i. Low economic activities in SSA resulted in a 7.1% global share of CO_2 emission.
ii. Despite the low CO_2 emission, the region is highly vulnerable to climate change due to low economic and technological growth and high dependence on natural resources for agricultural production.
iii. South Africa and Nigeria are the highest emitters of CO_2 in the region; health and environment are always traded off for energy.
iv. The energy sector has the highest share of CO_2 emission.
v. CO_2 outlook shows that CO_2 emission is on the increase.
vi. Global warming of about 0.5℃ and anthropogenic global warming of between 0.8 and 1.2 °C locally.
vii. Global warming is continuous at a rate of 0.2 °C per decade.
viii. The global warming of 1.5 °C will be reached between 2030 and 2053.
ix. That the relation between energy consumption, CO_2 emissions, and GDP is unidirectional; causality running from energy consumption to GDP and CO_2.

In conclusion, this study sees the deployment of R&D and infrastructural capacity development in RE as the key ways of salvaging the huge energy deficit and continuous deterioration of power infrastructure in SSA. These sustainable CO_2 emissions mitigating steps are devoid of environmental safety and human health compromise characteristic of fossil-driven economy thus can stimulate a zero-CO_2-driven economy.

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References

Abd AA, Naji SZ, Hashim AS, Othman MR (2020) Carbon dioxide removal through physical adsorption using carbonaceous and non-carbonaceous adsorbents: a review. J Environ Chem Eng 8(5):104142. https://doi.org/10.1016/j.jece.2020.104142

Abid M (2016) Impact of economic, financial, and institutional factors on CO2 emissions: evidence from Sub-Saharan Africa economies. Util Policy 41:85–94. https://doi.org/10.1016/j.jup.2016.06.009

Acheampong AO, Adams S, Boateng E (2019) Do globalization and renewable energy contribute to carbon emissions mitigation in Sub-Saharan Africa? Sci Total Environ 677:436–446. https://doi.org/10.1016/j.scitotenv.2019.04.353

Adzawla W, Sawaneh M, Yusuf AM (2019) Greenhouse gasses emission and economic growth nexus of sub-Saharan Africa. Sci Afr 3:e00065. https://doi.org/10.1016/j.sciaf.2019.e00065

AfDB (2012) The solutions for a changing climate: the African development bank's response to impacts in Africa. Retrieved from https://www.afdb.org/en/documents/document/the-solut

ions-for-a-changing-climate-the-african-development-banks-response-to-impacts-in-africa-30097
Agrawal S, Yamamoto S (2015) Effect of Indoor air pollution from biomass and solid fuel combustion on symptoms of preeclampsia/eclampsia in Indian women. Indoor Air 25(3):341–352. https://doi.org/10.1111/ina.12144
Al-mulali U, Binti Che Sab CN (2012) The impact of energy consumption and CO2 emission on the economic growth and financial development in the Sub Saharan African countries. Energy 39(1):180–186. https://doi.org/10.1016/j.energy.2012.01.032
Aljazeera (2019) East Africa struggles with heavy rains as thousands displaced. Retrieved from https://www.aljazeera.com/news/2019/11/east-africa-struggles-heavy-rains-thousands-displaced-191129061914721.html
Amegah AK, Jaakkola JJ (2016) Household air pollution and the sustainable development goals. Bull World Health Org 94:215–221. https://doi.org/10.2471/BLT.15.155812
Ang JB (2008) Economic development, pollutant emissions and energy consumption in Malaysia. J Policy Model 30(2):271–278. https://doi.org/10.1016/j.jpolmod.2007.04.010
Apergis N, Payne JE (2009) Energy consumption and economic growth in Central America: evidence from a panel cointegration and error correction model. Energy Econ 31(2):211–216. https://doi.org/10.1016/j.eneco.2008.09.002
Baloch MA, Danish K, KhanUlucak SUDZS (2020) Analyzing the relationship between poverty, income inequality, and CO2 emission in Sub-Saharan African countries. Sci Total Environ. https://doi.org/10.1016/j.scitotenv.2020.139867
Barua S, Acharya D, Kiran K, Khadka TR, Murugavelu V, Singaravelo D, Arun PR (2020) Carbon footprint assessment and mitigation strategies for sustainable development. Int J Strat Energy Environ Plan 2(2):55–79
Bastida L, Cohen JJ, Kollmann A, Moya A, Reichl J (2019) Exploring the role of ICT on household behavioural energy efficiency to mitigate global warming. Renew Sustain Energy Rev 103:455–462. https://doi.org/10.1016/j.rser.2019.01.004
Bruun S, Jensen LS, Khanh VVT, Sommer S (2014) Small-scale household biogas digesters: an option for global warming mitigation or a potential climate bomb? Renew Sustain Energy Rev 33:736–741. https://doi.org/10.1016/j.rser.2014.02.033
Bunn C, Läderach P, Quaye A, Muilerman S, Noponen MRA, Lundy M (2019) Recommendation domains to scale out climate change adaptation in cocoa production in Ghana. Clim Serv 16:100123. https://doi.org/10.1016/j.cliser.2019.100123
CFI (2020) Cointegration. Retrieved from https://corporatefinanceinstitute.com/resources/knowledge/other/cointegration/
Chakamera C, Alagidede P (2018) Electricity crisis and the effect of CO2 emissions on infrastructure-growth nexus in Sub Saharan Africa. Renew Sustain Energy Rev 94:945–958. https://doi.org/10.1016/j.rser.2018.06.062
Chen S-T, Kuo H-I, Chen C-C (2007) The relationship between GDP and electricity consumption in 10 Asian countries. Energy Policy 35(4):2611–2621
Clay N, King B (2019) Smallholders' uneven capacities to adapt to climate change amid Africa's 'green revolution': case study of Rwanda's crop intensification program. World Dev 116:1–14. https://doi.org/10.1016/j.worlddev.2018.11.022
Corfee-Morlot J, Parks P, Ogunleye J, Ayeni F (2019) Achieving clean energy access in Sub-Saharan Africa. Retrieved from Financing Climate Futures: Rethinking Infrastructure, OECD, UN Environment and the World Bank Group: https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=13&cad=rja&uact=8&ved=2ahUKEwjnoInB4a_nAhUNZMAKHQ9GBrYQFjAMegQIBBAB&url=https%3A%2F%2Fwww.oecd.org%2Fenvironment%2Fcc%2Fclimate-futures%2Fcase-study-achieving-clean-energy-access-in-sub-saharan-africa.pdf&usg=AOvVaw3VzygJHzNhrzCFzntrVtPU
Curry J, Webster PJ (1998) Thermodynamics of atmospheres and oceans, vol 65, 1st edn. Academic Press, United States
Das I, Jagger P, Yeatts K (2017) Biomass cooking fuels and health outcomes for women in Malawi. EcoHealth 14(1):7–19. https://doi.org/10.1007/s10393-016-1190-0
Diedhiou A (2019) Global warming in Africa: "it's time to propose solutions developed by Africans. Retrieved from https://ideas4development.org/en/auteur/15464/
Drechsler C, Agar DW (2020) Intensified integrated direct air capture—power-to-gas process based on H2O and CO2 from ambient air. Appl Energy 273:115076. https://doi.org/10.1016/j.apenergy.2020.115076
Ebhota WS (2019) Power accessibility, fossil fuel and the exploitation of small hydropower technology in sub-saharan Africa. Int J Sustain Energy Plan Manag. https://doi.org/10.5278/ijsepm.2019.19.3
Ebhota WS, Eloka-Eboka AC, Inambao FL (2014) Energy sustainability through domestication of energy technologies in third world countries in Africa. In: Paper presented at the Industrial and Commercial Use of Energy (ICUE) 2014 International Conference. https://ieeexplore.ieee.org/document/6904197
Ebhota WS, Inambao FL (2015) Domestic turbine design, simulation and manufacturing for sub-saharan africa energy sustainability. In: Paper presented at the 14th international conference on sustainable energy technologies—SET 2015, Nottingham, UK
Ebhota WS, Inambao FL (2016) Design basics of a small hydro turbine plant for capacity building in sub-Saharan Africa. Afr J Sci Technol Innov Dev 8(1):111–120. https://doi.org/10.1080/20421338.2015.1128039
Ebhota WS, Inambao FL (2017) Smart design and development of a small hydropower system and exploitation of locally sourced material for pelton turbine bucket production. Iran J Sci Technol Trans Mech Eng. https://doi.org/10.1007/s40997-017-0134-9
Ebohon OJ, Ikeme AJ (2006) Decomposition analysis of CO2 emission intensity between oil-producing and non-oil-producing sub-Saharan African countries. Energy Policy 34(18):3599–3611. https://doi.org/10.1016/j.enpol.2004.10.012
Economist (2018) A burning issue in Africa: Africa's big carbon emitters admit they have a problem. The Economist Newspaper Limited
Fasihi M, Efimova O, Breyer C (2019) Techno-economic assessment of CO2 direct air capture plants. J Clean Prod 224:957–980. https://doi.org/10.1016/j.jclepro.2019.03.086
FloodList (2019a) DR Congo—600,000 Affected by Floods in 12 Provinces, Says UN. Retrieved from https://floodlist.com/africa/dr-congo-floods-december-2019
FloodList (2019b) Uganda—More Fatalities After Floods in Central and Eastern Regions. Retrieved from https://floodlist.com/africa/uganda-floods-central-eastern-region-december-2019
Fodha M, Zaghdoud O (2010) Economic growth and pollutant emissions in Tunisia: an empirical analysis of the environmental Kuznets curve. Energy Policy 38(2):1150–1156. https://doi.org/10.1016/j.enpol.2009.11.002
Friedrich J, Damassa T (2014) The history of carbon dioxide emissions. Retrieved from https://www.wri.org/blog/2014/05/history-carbon-dioxide-emissions
Glasure YU, Lee A-R (1998) Cointegration, error-correction, and the relationship between GDP and energy: the case of South Korea and Singapore. Resour Energy Econ 20(1):17–25
Glueckauf E (1951) The composition of atmospheric Air. In: Byers HR, Landsberg HE, Wexler H, Haurwitz B, Spilhaus AF, Willett HC, Houghton HG, Malone TF (eds) Compendium of meteorology: prepared under the direction of the committee on the

compendium of meteorology. American Meteorological Society, Boston, MA, pp 3–10

Halicioglu F (2009) An econometric study of CO2 emissions, energy consumption, income and foreign trade in Turkey. Energy Policy 37(3):1156–1164. https://doi.org/10.1016/j.enpol.2008.11.012

Hickman JE, Scholes RJ, Rosenstock TS, Pérez García-Pando C, Nyamangara J (2014) Assessing non-CO2 climate-forcing emissions and mitigation in sub-Saharan Africa. Curr Opin Environ Sustain 9–10:65–72. https://doi.org/10.1016/j.cosust.2014.07.010

IEA (2014) Africa energy outlook: a focus on energy prospects in Sub-Saharan Africa. Retrieved from London

IEA (2017a) CO2 emissions from fuel combustion highlights. Retrieved from International Energy Agency (IEA), Paris, France: https://www.iea.org/publications/freepublications/publication/CO2EmissionsfromFuelCombustionHighlights2017.pdf

IEA (2017b) Energy access outlook: from poverty to prosperity. Retrieved from Paris, France: https://www.iea.org/publications/freepublications/publication/WEO2017SpecialReport_EnergyAccessOutlook.pdf

IEA (2019) SDG7: Data and projections—access to affordable, reliable, sustainable and modern energy for all. Retrieved from https://www.iea.org/reports/sdg7-data-and-projections/access-to-electricity

IEA (2020) CO_2 emissions from fuel combustion. Retrieved from https://www.iea.org/subscribe-to-data-services/co2-emissions-statistics

IMF (2019) Real GDP growth: annual percent change. Retrieved from https://www.imf.org/external/datamapper/NGDP_RPCH@WEO/OEMDC/ADVEC/WEOWORLD

Inglesi-Lotz R, Dogan E (2018) The role of renewable versus non-renewable energy to the level of CO2 emissions a panel analysis of sub- Saharan Africa's Big 10 electricity generators. Renew Energy 123:36–43. https://doi.org/10.1016/j.renene.2018.02.041

IPCC (2014) Climate change 2014: impacts, adaptation, and vulnerability. Part A: global and sectoral aspects. Contribution of working group II to the fifth assessment report of the intergovernmental panel on climate change United Kingdom and New York, NY, USA: Cambridge University Press

IPCC (2015) Intergovernmental panel on climate change. climate change 2014: mitigation of climate change. The Intergovernmental Panel on Climate Change (IPCC), Shanghai, China: Cambridge University Press

Ito K (2017) CO2 emissions, renewable and non-renewable energy consumption, and economic growth: evidence from panel data for developing countries. Int Econ 151:1–6. https://doi.org/10.1016/j.inteco.2017.02.001

Johansen S (1995) Likelihood-based inference in cointegrated vector autoregressive models. Oxford University Press, Oxford

Johansen S (1988) Statistical analysis of cointegration vectors. J Econ Dyn Cont 12(2):231–254. https://doi.org/10.1016/0165-1889(88)90041-3

Johansen S, Juselius K (1990) Maximum likelihood estimation and inference on cointegration-with applications to the demand for money. Oxford Bull Econ Stat 52(2):169–210

Joos F, Spahni R (2008) Rates of change in natural and anthropogenic radiative forcing over the past 20,000 years. Proc Natl Acad Sci 105(5):1425–1430. https://doi.org/10.1073/pnas.0707386105

Jovanovic B (2018) When is there a Kuznets curve? Some evidence from the ex-socialist countries. Econ Syst 42(2):248–268. https://doi.org/10.1016/j.ecosys.2017.06.004

Kamal WA (1997) Improving energy efficiency—the cost-effective way to mitigate global warming. Energy Convers Manag 38(1):39–59. https://doi.org/10.1016/0196-8904(96)00012-X

Kammila S, Kappen JF, Rysankova D, Hyseni B, Putti VR (2014) Clean and improved cooking in Sub-Saharan Africa. Retrieved from Washington, D.C.: World Bank Group: https://documents.worldbank.org/curated/en/164241468178757464/Clean-and-improved-cooking-in-Sub-Saharan-Africa-a-landscape-report

Kumar D, Kumar D (2016) Chapter 6—societal responsibility and economic viability. In: Kumar D, Kumar D (eds) Management of coking coal resources. Elsevier, Amsterdam, pp 193–259

Lau LC, Lee KT, Mohamed AR (2012) Global warming mitigation and renewable energy policy development from the Kyoto Protocol to the Copenhagen Accord—a comment. Renew Sustain Energy Rev 16(7):5280–5284. https://doi.org/10.1016/j.rser.2012.04.006

Le T-H, Nguyen CP, Su TD, Tran-Nam B (2020) The Kuznets curve for export diversification and income inequality: evidence from a global sample. Econ Anal Policy 65:21–39. https://doi.org/10.1016/j.eap.2019.11.004

Lee C-C, Chang C-P (2008) Energy consumption and economic growth in Asian economies: a more comprehensive analysis using panel data. Resour Energy Econ 30(1):50–65. https://doi.org/10.1016/j.reseneeco.2007.03.003

Loha C, Karmakar MK, Chattopadhyay H, Majumdar G (2020) Renewable biomass: a candidate for mitigating global warming. In: Hashmi S, Choudhury IA (eds) Encyclopedia of renewable and sustainable materials. Elsevier, Oxford, pp 715–727

Lotfalipour MR, Falahi MA, Ashena M (2010) Economic growth, CO2 emissions, and fossil fuels consumption in Iran. Energy 35(12):5115–5120. https://doi.org/10.1016/j.energy.2010.08.004

Mahadevan R, Asafu-Adjaye J (2007) Energy consumption, economic growth and prices: a reassessment using panel VECM for developed and developing countries. Energy Policy 35(4):2481–2490

Maji IK (2019) Impact of clean energy and inclusive development on CO2 emissions in sub-Saharan Africa. J Clean Prod 240:118186. https://doi.org/10.1016/j.jclepro.2019.118186

Masih AMM, Masih R (1996) Energy consumption, real income and temporal causality: results from a multi-country study based on cointegration and error-correction modelling techniques. Energy Econ 18(3):165–183. https://doi.org/10.1016/0140-9883(96)00009-6

Masih AMM, Masih R (1998) A multivariate cointegrated modelling approach in testing temporal causality between energy consumption, real income and prices with an application to two Asian LDCs. Appl Econ 30(10):1287–1298. https://doi.org/10.1080/000368498324904

Mason-D'Croz D, Sulser TB, Wiebe K, Rosegrant MW, Lowder SK, Nin-Pratt A, Robertson RD (2019) Agricultural investments and hunger in Africa modeling potential contributions to SDG2—Zero Hunger. World Dev 116:38–53. https://doi.org/10.1016/j.worlddev.2018.12.006

Matewos T (2019) The state of local adaptive capacity to climate change in drought-prone districts of rural sidama, Southern Ethiopia. Clim Risk Manag. https://doi.org/10.1016/j.crm.2019.100209

Mori S (2012) An assessment of the potentials of nuclear power and carbon capture and storage in the long-term global warming mitigation options based on Asian Modeling Exercise scenarios. Energy Econ 34:S421–S428. https://doi.org/10.1016/j.eneco.2012.03.017

Mueller V, Sheriff G, Dou X, Gray C (2020) Temporary migration and climate variation in eastern Africa. World Dev. https://doi.org/10.1016/j.worlddev.2019.104704

Muhammad B (2019) Energy consumption, CO2 emissions and economic growth in developed, emerging and Middle East and North Africa countries. Energy 179:232–245. https://doi.org/10.1016/j.energy.2019.03.126

Munir Q, Lean HH, Smyth R (2020) CO2 emissions, energy consumption and economic growth in the ASEAN-5 countries: a cross-sectional dependence approach. Energy Econ 85:104571. https://doi.org/10.1016/j.eneco.2019.104571

Murry DA, Nan GD (1994) A definition of the gross domestic product-electrification interrelationship. J Energy Dev 19(2):275–283
Nachmany M, Fankhauser S, Townshend M, Collins T, Landesman T, Matthews A, Setzer J (2014) The globe climate legislation study: a review of climate change legislation in 66 countries. Globe International and the Grantham Research Institute, London School of Economics, London
OECD (2020) Gross domestic product (GDP). Retrieved from https://data.oecd.org/gdp/gross-domestic-product-gdp.htm
Olale E, Ochuodho TO, Lantz V, El Armali J (2018) The environmental Kuznets curve model for greenhouse gas emissions in Canada. J Clean Prod 184:859–868. https://doi.org/10.1016/j.jclepro.2018.02.178
Ozturk I, Acaravci A (2013) The long-run and causal analysis of energy, growth, openness and financial development on carbon emissions in Turkey. Energy Econ 36:262–267. https://doi.org/10.1016/j.eneco.2012.08.025
Pao H-T, Yu H-C, Yang Y-H (2011) Modeling the CO2 emissions, energy use, and economic growth in Russia. Energy 36(8):5094–5100. https://doi.org/10.1016/j.energy.2011.06.004
PCC (2014) Climate change 2014: mitigation of climate change. Contribution of work-ing group III to the fifth assessment report of the intergovernmental panel on climate change. Retrieved from Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.: file:///C:/Users/ENGRWI~1/AppData/Local/Temp/ipcc_wg3_ar5_summary-for-policymakers.pdf
Roberts D (2017) These uses of CO_2 could cut emissions—and make trillions of dollars
Rodríguez-Mosqueda R, Rutgers J, Bramer EA, Brem G (2019) Low temperature water vapor pressure swing for the regeneration of adsorbents for CO2 enrichment in greenhouses via direct air capture. J CO2 Util 29:65–73. https://doi.org/10.1016/j.jcou.2018.11.010
Rogelj J, Shindell D, Jiang K, Fifita S, Forster P, Ginzburg V, Vilariño MV (2018) Mitigation pathways compatible with 1.5 °C in the context of sustainable development. In: Global Warming of 1.5 °C Global Warming of 1.5 °C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty USA: IPCC
Saboori B, Sulaiman J, Mohd S (2012) Economic growth and CO2 emissions in Malaysia: a cointegration analysis of the Environmental Kuznets Curve. Energy Policy 51:184–191. https://doi.org/10.1016/j.enpol.2012.08.065
Sanz-Pérez ES, Fernández A, Arencibia A, Calleja G, Sanz R (2019) Hybrid amine-silica materials: determination of N content by 29Si NMR and application to direct CO2 capture from air. Chem Eng J 373:1286–1294. https://doi.org/10.1016/j.cej.2019.05.117
Shepard D (2019) Global warming: severe consequences for Africa New report projects greater temperature increases. Retrieved from https://www.un.org/en/contact-us/index.html
Stanzel P, Kling H, Bauer H (2018) Climate change impact on West African rivers under an ensemble of CORDEX climate projections. Clim Serv 11:36–48. https://doi.org/10.1016/j.cliser.2018.05.003
Stephenson M (2018) Chapter 5—geology and the reduction of emissions. In: Stephenson M (ed) Energy and climate change. Elsevier, Amsterdam, pp 91–121
Steynor A, Leighton M, Kavonic J, Abrahams W, Magole L, Kaunda S, Mubaya CP (2020) Learning from climate change perceptions in southern African cities. Clim Risk Manag 27:100202. https://doi.org/10.1016/j.crm.2019.100202
Tiwari AK, Kyophilavong P, Albulescu CT (2016) Testing the stationarity of CO2 emissions series in Sub-Saharan African countries by incorporating nonlinearity and smooth breaks. Res Int Bus Finance 37:527–540. https://doi.org/10.1016/j.ribaf.2016.01.005
UIG (2016) Carbon dioxide (CO_2) properties, uses, applications CO_2 gas and liquid carbon dioxide. Retrieved from https://www.uigi.com/carbondioxide.html
UN (2015) Resolution adopted by the General Assembly on 25 September 2015. Paper presented at the United Nations New York. https://daccess-ods.un.org/access.nsf/GetFile?OpenAgent&DS=A/RES/70/1&Lang=E&Type=DOC
UNEP (2012) Climate change challenges for africa: evidence from selected eu-funded research projects. Retrieved from United Nations Environment Programme, Nairobi.: https://www.afdb.org/en/documents/document/the-solutions-for-a-changing-climate-the-african-development-banks-response-to-impacts-in-africa-30097
Wasti SKA, Zaidi SW (2020) An empirical investigation between CO2 emission, energy consumption, trade liberalization and economic growth: a case of Kuwait. J Build Eng 28:101104. https://doi.org/10.1016/j.jobe.2019.101104
Watanuki K (1997) Evolution of the earth's atmosphere; variation of CO2 concentration and climatic changes. Energy 22(2):109–114. https://doi.org/10.1016/S0360-5442(96)00128-4
Worldbank (2019) CO_2 emissions (kt)—Sub-Saharan Africa. Retrieved from https://data.worldbank.org/indicator/EN.ATM.CO2E.KT?locations=ZG
Worldbank (2020) GDP (current USD). Retrieved from https://data.worldbank.org/indicator/ny.gdp.mktp.cd
Worldmeter (2019a) CO_2 Emissions. Retrieved from https://www.worldometers.info/co2-emissions/
Worldmeter (2019b) CO_2 Emissions by Year. Retrieved from https://www.worldometers.info/co2-emissions/co2-emissions-by-year/
Worldmeter (2019c) Global GDP (Gross World Product) 1960–2017. Retrieved from https://www.worldometers.info/gdp/#gdpyear
Worldmeter (2019d) Global GDP this year. Retrieved from https://www.worldometers.info/gdp/#top20
Yildirim E, Aslan A, Ozturk I (2014) Energy consumption and gdp in asean countries: bootstrap-corrected panel and time series causality tests. Singap Econ Rev 59(02):1450010. https://doi.org/10.1142/s0217590814500106
Yoo SH (2006) The causal relationship between electricity consumption and economic growth in the ASEAN countries. Energy Policy 34(18):3573–3582. https://doi.org/10.1016/j.enpol.2005.07.011
Yu ESH, Choi J-Y (1985) The causal relationship between energy and gnp: an international comparison. J Energy Dev 10(2):249–272
Zaidi S, Ferhi S (2019) Causal relationships between energy consumption, economic growth and CO_2 emission in sub-saharan: evidence from dynamic simultaneous-equations models. Mod Econ 10:2157–2173. https://doi.org/10.4236/me.2019.109136
Zhang X-P, Cheng X-M (2009) Energy consumption, carbon emissions, and economic growth in China. Ecol Econ 68(10):2706–2712. https://doi.org/10.1016/j.ecolecon.2009.05.011