3.Cost, environmental impact and the resilience of renewable energy under a changing climate in Africa

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Abstract

The heavy reliance on fossil fuels in Africa to attain and sustain economic prosperity and the attendant negative environmental consequences have now been ubiquitously recognized as an undeniable threat to achieving SDG Goal 13 – Climate Action: taking urgent actions to tackle climate change and its variegated impacts on our planet. Presently, Africa is the most vulnerable region to the impacts of climate change. Severe climate-induced environmental and economic challenges have triggered endemic poverty which has blurred the horizon of the continent's development trajectories. This paper aims to examine the cost, environmental impact and resilience of renewable energy under a changing climate in Africa. The descriptive quantitative method of data analysis was employed using secondary data summarized and presented in charts and tables. Findings show that renewable energy sources are abundantly available, but poorly and inadequately exploited in Africa. The evidence further confirmed that while Africa has the most abundant renewable energy resources, its renewable energy utilization is the least developed. It is further established that renewable energy technology costs in Africa have decreased significantly since 2010 with the cost of solar and wind-generated electricity per kilowatt-hour in 2021 being lower than those of fossil fuels. While it is estimated that almost all renewable energy sources have exclusively positive environmental effects, the negative effects associated with some can be mitigated through careful choice and utilization. We recommend that investment in renewable energy in Africa should be accelerated and funded to address the current climate and environmental challenges facing Africa, African national governments should address the key issue of cost in the energy transition process and policy reforms by internalizing the environmental and economic costs of different energy types in the transition agenda.

Keywords: Renewable Energy, Climate Change, Levelised Cost of Energy, Energy Transition, Environmental Impact.

Introduction

In recent years, and while striving to attain Goal 8 of the UN-SDG which seeks to promote sustained, inclusive, and sustainable economic growth, full and productive employment, and decent work for all, almost every nation resorted to the use of high-intensity fossil fuels as the primary source of energy for economic growth and prosperity. Barney and Franzi (2002) argue that energy is responsible for at least half the industrial growth in a modern economy while representing less than one-tenth of the cost of production. However, the process of converting and using fossil fuels involves a combustion process that produces environmentally harmful greenhouse gases (GHGs) producing global warming and exacerbating the impact of climate change. For this reason, fossil fuels constitute a potent threat to Goal 13 - Climate Action: taking urgent actions to tackle climate change and its variegated impacts on our planet.

With most countries in Africa resource-rich and highly dependent on fossil energy and lacking access to clean energies due to poor technological development and slow penetration of energy conversion technologies, there is a high tendency for the same policy of reliance on fossil fuels to continue with the dire consequence of increasing greenhouse gas emissions. Carbonization arising from the intense usage of fossil fuels for transportation, industry, building, and agriculture accentuates the risk of global warming as the Earth is already about 1.1°C warmer than it was in the late 1800s, and emissions continue to rise (UN, 2023). Hence, there is now an increasing need to mitigate climate change to make the Earth a livable planet.

Unarguably, Africa is the most vulnerable region to climate change and, by far, the worst hit by the variegated negative impact of environmental challenges confronting the world. The high and growing pace of environmental degradation in Africa is attributed to anthropogenic activities (IPCC, 2014; Stern, 2006). Anthropogenic activities refer to the human activities causing pollution (World Bank, 2018; IPCC, 2014). According to the Global Citizen Report (2023), climate change is impacting Africa the hardest in the following ways: (a) Almost a quarter of a billion Africans will face water scarcity by 2025, (b) 5 of the 10 countries most impacted by climate change are in Africa, according to the 2021 Global Climate Risk Index (c) Tropical storms in Southern Africa displaced half a million people in just three months this year, (d) 46 million people do not have access to enough food in the Horn of Africa and Sahel Region, (e) Hundreds of billions of locusts swarmed East Africa in 2020, (f) 86 million Africans could be forced to leave their homes in 2050, and (g) 1 in 3 deaths from extreme weather happen in Africa.

Furthermore, Africa's vulnerability to climate change has been linked to endemic poverty which clogged the wheel of the continent's development trajectories. According to Bailey (2009), people's climate and environmental vulnerability are inextricably linked with poverty, as poor people tend to live in poorly constructed homes, often in communities exposed to environmental hazards such as floods, landslides, or droughts, and in areas lacking basic health services or infrastructure. Poor people also tend to have fewer assets to use and/or sell to cope in the aftermath of an environmental or natural disaster, and they also generally lack access to social safety nets. It is therefore not a sheer coincidence that the African countries with high climate risk index are also ranked low in the human development index (for example, Mozambique and Zimbabwe with the two highest climate risk indexes in Africa are also ranked 181st and 150th respectively on global HDI ranking), thereby highlighting the nexus between vulnerability to climate change and the quality of human life as measured by HDI.

Consequently, this study becomes imperative against the backdrop of the need for Africa to achieve substantial and more sustainable progress in the journey to the attainment of Sustainable Development Goals (SDGs) after so many years of trailing the blaze. One veritable way to address the global climate crisis is through transitioning to renewable energy use. However, evidence shows no African country ranks among the world's top 30 in energy transition (AfDB,2023). Thus, one of the fundamental fields of action for energy transition in Africa is derisking and promoting private sector investment because the investments required to meet Africa´s growing demand for renewable energy are far greater than the funds available from public sources (IRENA, 2021). Therefore, when private investment in the renewable energy sector in Africa is considered, there is a crucial need for the assessment of the cost and benefits of renewable energy sources, the environmental impacts of renewable energy and the need to consider its resiliency in terms of its ability to survive and quickly recover from extreme and unexpected disruptions. A high energy system resilience is of utmost importance to modern societies that are highly dependent on continued access to energy services (Jasilunas *et al,* 2021).

Following the introduction, this paper is structured as follows: Section 2 focuses on the conceptual review and review of literature related to the study by highlighting the different types of renewable energy sources and the need for transitioning to renewable energy, while Section 3 dwells on the theoretical framework and methodology adopted for the study. We consider the cost of the various types of renewable energy in Section 4 by examining the cost of solar, hydropower and biomass renewable energy sources. Section 5 centres on the impact of the different renewable energy sources on the environment by assessing the positive and negative environmental impact, while Section 6 assesses the state of climate resilience and readiness in Africa by considering some key parameters. Section 7 closes the paper with a conclusion and recommendation.

Conceptual Framework and Review of Literature

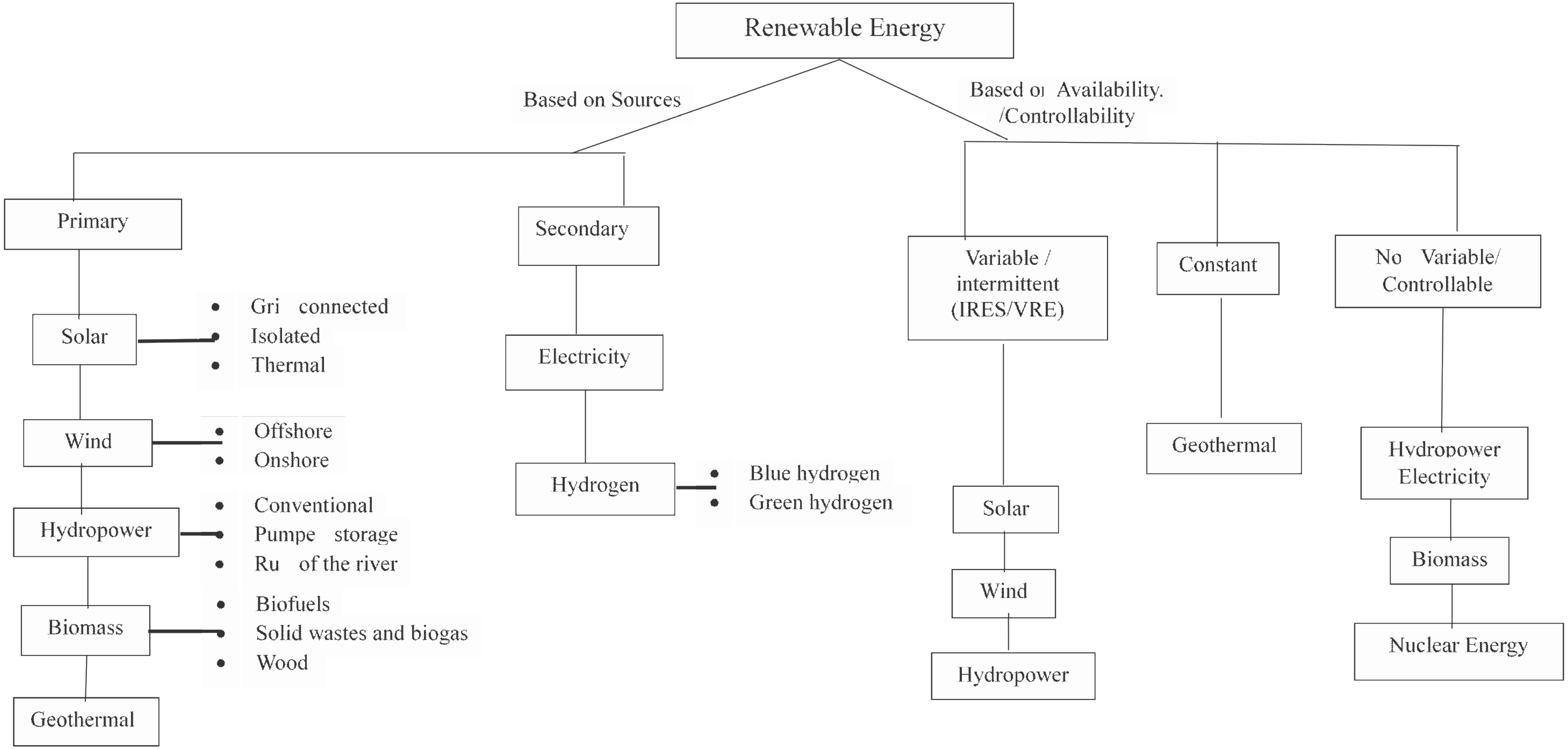
Types of Renewable Energies

Renewable energy is energy that is derived from natural resources. To achieve carbon neutrality, the global share of renewable energy is projected to increase from 14% in 2018 to approximately 74% in 2050, requiring an eightfold annual increase (Osman *et al*, 2022). Renewable energy is obtained from sources that are essentially inexhaustible and the most important feature of this source of energy is that they can be harnessed and utilized without the release of harmful pollutants such as greenhouse gases (GHGs) that are potential sources of global warming and climate change. It is well established that the activities of developed nations are mostly accountable for climate change, but the developing nations are those suffering more due to the inability to cope as a result of poverty and low technological development (Odjugo, 2010).

According to categorization obtained from the review of relevant literature, renewable energy technologies, as depicted in Fig. 1, are classified primarily into (i) solar energy, also known as photovoltaic energy, (ii) wind energy, (iii) geothermal energy, (iv) biomass energy, and (v) hydropower energy. (Bortoluzzi *et al*., 2021; Farrell *et al*., 2019). Solar energy is also known as photovoltaic (PV) energy, and it is solely generated from sunlight (Bortoluzzi *et al*., 2021; Farrell et al., 2019). Solar energy includes solar photovoltaic grid-connected, solar photovoltaic isolated, and thermal solar energy (Bortoluzzi *et al*., 2021; Karunathilake *et al*., 2019; Pang *et al.,* 2022). This energy source is one of the most rapidly expanding clean sources of global energy production. (ii) Wind energy is the utilization of wind power to generate electricity for residential and industrial use (Konneh *et al*., 2019; Ren and Lutzen, 2017). A wind turbine is utilized for the conversion of wind energy to electricity. The wind operation can primarily be used as a small-scale wind energy system, which supplies specific regions, and a wind-connected energy grid system, which makes it possible to construct electricity grids similar to wind farms (Bortoluzzi *et al*., 2021; Yazdani *et al*., 2018).

Wind and solar energies are two sources of clean energy, but they are weather-dependent. Thus, it is essential to consider weather changes when choosing such energy sources (Campos-Guzmán *et al*., 2019). It is important to note that solar and wind energy are regarded as variable renewable energy (VRE), or intermittent renewable energy sources (IRES) because they are not dispatchable due to their fluctuating nature. The penetration of intermittent renewables in most power grids is low: global electricity generation in 2021 was 7% wind and 4% solar. However, in 2021 Denmark, Luxembourg and Uruguay generated over 40% of their electricity from wind and solar (Global Energy Review, 2022).

(iii) Geothermal energy is heat from the hot interior of the earth or near the earth's surface. Geothermal energy from deep underground is used to generate electricity. The near-constant temperature of the earth near the earth's surface is used in geothermal heat pumps for heating and cooling buildings (EIA, 2023). Geothermal energy can provide industrial-scale electricity and heat (Rani et al., 2019). Given its vast geological features, Africa has a huge potential for producing geothermal energy, but the potential is currently largely unutilized. (iv) Biomass energy is derived from both plant and animal sources; it is a source of renewable energy derived from non-fossilized plant materials. The energy is produced through the combustion of wood, agricultural residues such as crop and animal waste, and other organic feedstocks (Osman *et al*., 2019a). Biomass pyrolysis produces biochar that can be used effectively for climate change mitigation as a readily available negative emission technology; this is in addition to the renewable energy produced from the process in the form of excess heat (Fawzy et al., 2022; Osman *et al*., 2022). Energy from waste can be considered a subset of biomass energy when waste derived from animal, human, or vegetable sources is considered (Akor *et al*., 2021; Al-Wahaibi *et al*., 2020; Osman *et al*., 2019b). Figure 1 provides a schematic framework for the classification of renewable energy based on a review of relevant literature on renewable energy.



NOTE: Hydropower electricity can be classified as either constant or controllable Renewable Energy depending on:

- Pumped storage system
- Small hydropower plants
- Cascaded reservoir hydropower plant
- **Figure** : A schematic framework for the classification of renewable energy sources

Source Authc s Design (2023)

According to the United States Energy Information Administration (2023), biomass energy is categorized into three main types, namely: (a) biofuels which include ethanol, biodiesel, renewable diesel, and other biofuels that are mostly used for transportation, (b) municipal solid wastes and biogas which biomass (or biogenic) materials and non-biomass combustible materials (mainly plastics and other synthetic materials made from petroleum). MSW or garbage is burned in waste-to-energy plants to generate electricity, and (c) wood which is made up of, first, residues from forestry operations and lumber, paper, and furniture mills for use as industrial process heat and to generate electricity and, second, fuel wood and wood pellets for space heating and cooking in homes and businesses.

(v) Hydropower is obtained by converting the potential energy of water into kinetic energy (Çolak and Kaya, 2017). Hydroelectricity is generated by constructing dams on rivers. Water at a greater altitude is precipitated onto the hydro-turbine, which generates electricity. Hydroelectricity generates approximately 1150 gigawatts globally and is the largest renewable energy source (Rahman *et al*, 2022). Compared to other RE sources, hydropower generates electricity with the highest conversion efficiency, which is about 90%. Hydropower contributes 20% of electricity generation worldwide. Hydropower systems can be modified to meet the loading requirement with maximum capacity factor, thus there are various types of hydropower such as pumped storage systems, small hydropower plants, and cascaded reservoir hydropower plants (Tze-Zhang *et al*, 2022).

General Overview of Climate Change Impact in Africa

Climate change is long-term shifts in temperature and weather patterns and it represents one of the major threats to Africa achieving the Sustainable Development Goals, especially the quest for Goal 13 – Taking Climate Action. The Intergovernmental Panel on Climate Change (IPCC) report 2018 highlighted the grave consequences of a temperature increase above 1.5°C, especially for Africa. According to the Intergovernmental Panel on Climate Change (2007), climate change refers to a change in the state of the climate that can be identified (e.g., by using statistical tests) by changes in the mean and /or the variability of its properties, and that persists for an extended period typically decades or longer. Although the length of time it takes the changes to manifest matters, the level of deviation from the normal and its impacts on the ecology are paramount. This prompted Ayoade (2003) to state that secular variations in climate occurring throughout 100 to 150 years may not qualify as a climate change if conditions will quickly reverse later, but a climate change usually takes place over a long period of at least 150 years with clear and permanent impacts on the ecosystem.

On a per capita basis, Africa contributes the least to global climatic change. This is primarily because of the region's overall low levels of industrial development (May and Caron 2009). Less than 3% of the world's total emissions of greenhouse gases emanate from the African continent. The rich countries dominate the overall emissions account; collectively, they are responsible for approximately 7 out of every 10 tonnes of CO2 that have been emitted since the start of the industrial era, with those emissions being highly concentrated in a small group of countries (UNDP 2007). The top 10 emitters are responsible for over 60%; the top five emitters (China, India, Japan, the Russian Federation and the United States) account for more than 50%; and the United States is the largest emitter, accounting for around 20% of the total (UNDP 2007).

Highlighting the severity of climate change on the African continent, the Global Citizen Report (2023) identified 7 more devastating facts about how climate change is impacting Africa the hardest: (1) Almost a quarter of a billion Africans will face water scarcity by 2025, (2) 5 of the 10 countries most impacted by climate change are in

Africa, according to the 2021 Global Climate Risk Index (3) Tropical storms in Southern Africa displaced half a million people in just three months this year, (4) 46 million people do not have access to enough food in the Horn of Africa and Sahel Region, (5) Hundreds of billions of locusts swarmed East Africa in 2020, (6) 86 million Africans could be forced to leave their homes in 2050, and (7) 1 in 3 deaths from extreme weather happen in Africa.

Figure 2 below shows the recent warming levels of the globe and Africa from 2014 to 2018 based on research by the African Centre of Meteorological Applications for Development (2019).

and there is a clear indication that Africa is warming faster than the rest of the world on average.

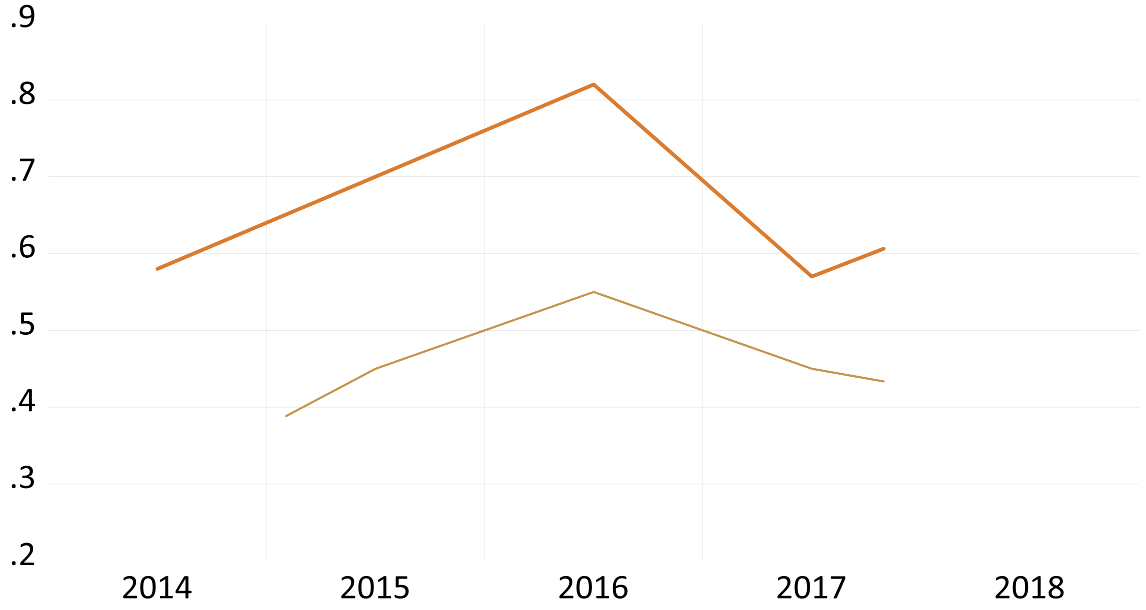


Figure 2: Recent Warming Levels of the Globe and Africa

Source: Authors' Design (2023)

Table 1 depicts the 10 warmest years on record over Africa and tit is clear that there is a general warming trend at the continental level. For example, of the 10 warmest years on record in Africa, 9 warmest years have been observed in the last 10 years (Table 4). Based on NOAA data, the warming rate over the past 69 years is about 2.14 °C/century. Considering the past 28 years, the warming rate is 3.57 °C/century (Figure 1). With this warming trend, Africa may reach 2 °C warming above the 1981-2010 average in the next few decades.

Table 1: 10 Warmest Years on the Record over Africa

Year	Anomaly with respect to 1981-2010 (^{O} C)
2010	+0.90
2016	+0.83
2015	+0.71
2018	+0.70
2017	+0.60
2014	+0.59
2005	+0.56
2009	+0.55
2013	+0.51
1998	+0.41

Source: African Centre of Meteorological Applications for Development (2019)

During year 2018, temperature anomalies exhibited varying warming levels over the different sub-regions of Africa. Over Northern Africa, the average temperature anomaly was 0.84 C warmer than the long-term mean. As such, the year 2018 was ranked as the 3rd warmest year on record in this region since 1950. The rate at which temperature has been increasing in this region over the period; 1950-2018 and 1990-2018 was found to be 2.3 °C and 4.29 C per century, respectively (ACMAF, 2019).

The Need for Transitioning to Renewable Energy Sources in Africa

Almost 80% of the global population lives in countries that are net importers of fossil fuels (IRENA 2022). Ironically, renewable energy resources are available in all nations, waiting for their full potential to be exploited. The International Renewable Energy Agency estimates that by 2050, 90% of the world's energy can and should come from renewable sources (IRENA 2018).

However, the excessive use of fossil fuels and non-renewable energy sources by developed and emerging economies to propel industrial and economic growth contributes to global warming by emitting large quantities of greenhouse gases and mitigating the perilous impacts of greenhouse gas emissions from energy production and consumption is crucial to combating climate change to achieve the UN Net Zero in line with the Paris Agreement which is seeking to reduce global GHG emissions by 45% by 2030 and reach net zero by 2050. The urgency to combat climate change and achieve sustainable development strengthens the global renewable energy transition momentum in an era of global environmental degradation. A sustainable energy future is within reach due to the development of green buildings, green energy and power use in industry, green transportation, decreased costs of renewable energy, increased energy efficiency and continued technological advancements, and informed policymaking (Osman *et al* 2022).

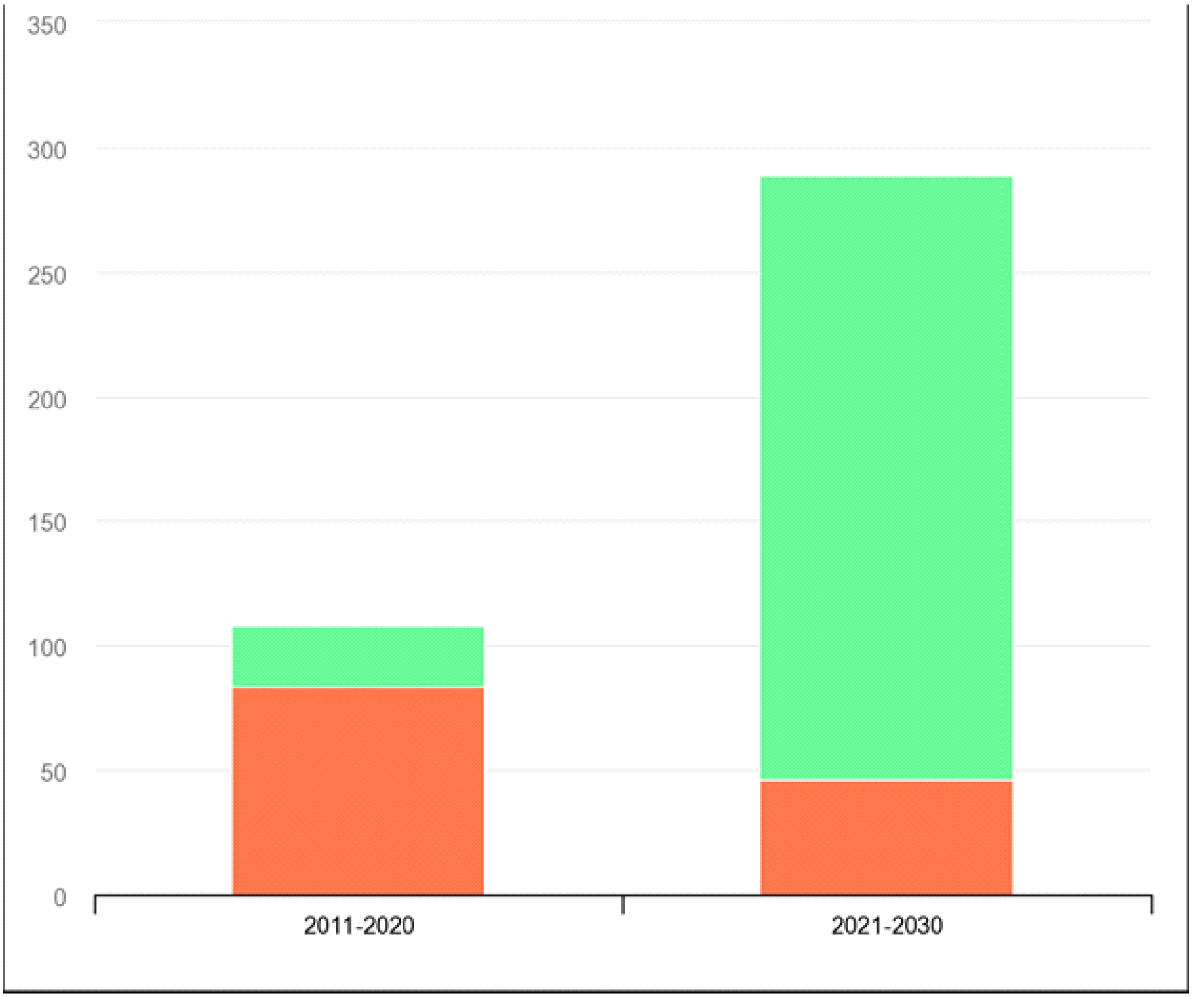


Figure 3*:* Power Generating Capacity Additions in Africa in Sustainable Africa Scenario 2011-2030
Source: International Energy Agency (2022), **Note: Green** – Fossil fuels, **Orange** – Renewable

The global shift from fossil-based energy systems is gaining substantial traction, but it must accelerate to contribute to global sustainable development. African countries need to do more to incorporate renewable energy into their energy mix to make the energy transition more seamless. According to the development and research on the use of renewable energy in critical sectors (Karunathilake *et al* 2019), renewable energy can be used to replace fossil-fuel energy in four key sectors, namely: construction industry, power plants, transportation, and the industrial sector. The benefits of deploying renewable energy in these sectors include but are not limited to saving money and protecting the environment from the danger of fossil fuel emissions; they are cleaner, reliable, versatile, and lower in costs compared to fossil fuel alternatives. Renewable energy has the potential to provide electricity to the 600 million Africans currently deprived of it, create jobs, and stimulate industrialization.

Theoretical Framework

Theoretical Framework

The theoretical framework of this study is based on an extended version of the Environmental Kuznets curve (EKC). According to EKC, as an economy develops production levels and carbon emissions increase together. However, at a higher level of economic development input mix changes because of the availability of clean technologies such as renewable energy, thereby reducing carbon emissions (Grossman and Kruger, 1991). The baseline equation is based on the model used by Holtz-Eakin and Selden (1995), Chandran and Tang (2013), Kasman & Duman (2015), Bilgili *et al.* (2016) and Majeed (2018).

$$(\text{Environmental Degradation})_{it} = f(\text{GDP, GDP2})_{it} \qquad (1)$$

This study revisits EKC incorporating the role of renewable energy in explaining environmental degradation. The use of renewable energy leads to environmental improvement as it is the cleanest form of energy and does not lead to emissions and resource depletion. Solar and wind energy are the cleanest form of energy. Unlike fossil fuels, renewable energy is inexhaustible. The role played by renewable energy in mitigating environmental degradation has been explored by Bilgili *et al.* (2016) and Zoundi (2017) among others.

With exponential population growth and poor rural conditions, rural-urban migration takes place. The reasons behind rural-urban migration are the provision of facilities such as education, jobs, and medical among others. This rural-urban migration puts pressure on limited resources available in urban areas amplifying overexploitation and environmental degradation. Urbanization puts pressure on water resources to meet the demands of an increasing population. Therefore, urbanization coupled with a rapidly increasing population leads to overexploitation of water resources for drinking, domestic, sanitation, and hygiene. In such a scenario, demand for food, transportation, and energy increases, thereby overburdening the environment.

Methodology

The study employed descriptive quantitative analysis using secondary data and data-based evidence from a wide range of sources. The method of data analysis is the descriptive method which involves presenting, organizing and summarizing the data sets with the aid of such tools as charts, trend graphs, tables and figures to analyse the data set relevant to the period of review. The quantitative aspect employed such parameters as the means, frequency distribution, and simple percentages to explore observable trends in our variables of interest. The sources of data employed in our analysis are as follows: The data set on renewable energy indicators was obtained from the International Renewable Energy Agency (IRENA), the World Resources Institute (WRI), and the International Energy Agency (IEA) databases; data on climate change indicators and data on the environmental impact of renewable energy usage were sourced from the Intergovernmental Panel on Climate Change (IPCC), the Global Centre on Adaptation (GCA) and IMF Climate Change and the African Centre of Meteorological Applications for Development (ACMAD).

Cost of Renewable Energies

In this section, we attempt to analyse the cost of only three renewable energy sources – solar, hydropower, and biomass renewable energies. Other sources of renewable energy are not considered because the current state of renewable energy technology in Africa has not supported the development of other renewables such as wind, nuclear, and geothermal (except in Kenya where geothermal is 53% of renewable energy) energy.

Table 2 and Table 3 show the renewable energy installed prices and the levelized cost of electricity. The levelized cost of electricity (or the levelized cost of energy) is a measurement used to assess and compare alternative methods of energy production. All renewable energy prices were reduced in 2021, except for geothermal and hydroelectric energy. The cost of solar and wind-generated electricity per kilowatt-hour in Europe in 2021 would be four to six times less than that of fossil fuels in 2022. Given the crisis in fossil fuels, the new renewable capacity added in 2021 could reduce electricity generation costs by $55 billion in 2022. Between January and May of 2022, wind and solar generation alone in Europe prevented at least $50 billion in fossil fuel imports.

Table 2: Renewable Energy Installed Prices

Renewable Source	Overall investment cost ($/kilowatt)	Overall investment cost ($/kilowatt)	
	2010	**2021**	**Change (%)**
Bioenergy	2714	2353	-13
Geothermal	2714	3991	47
Hydropower	1315	2135	62
Solar Photovoltaics	4808	857	-82
Concentrated Solar Power	9422	9091	-4
Onshore wind	2042	1325	-35
Offshore wind	4876	2858	-41

Source: International Renewable Energy Agency (IRENA) (2022)

Table 3*:* Levelized Cost of Energy ($/kilowatt)

Renewable Source	Levelized cost of electricity (LCOE)* ($/kilowatt)	Levelized cost of electricity (LCOE) ($/kilowatt)	
	2010	**2021**	**Change (%)**
Bioenergy	0.078	0.067	-14
Geothermal	0.050	0.068	34
Hydropower	0.039	0.048	24
Solar Photovoltaics	0.417	0.048	-88
Concentrated Solar Power	0.358	0.114	-68
Onshore wind	0.102	0.033	-68
Offshore wind	0.188	0.075	-60

Source: International Renewable Energy Agency (IRENA) (2022)

***Note:** The levelized cost of electricity (LCOE) is defined as the price at which the generated electricity should be sold for the system to break even at the end of its lifetime. It is calculated by first taking the NPV of the total cost of building and operating the power-generating assets and then dividing the result by the total electricity generation over its lifetime.

Africa has more than 39% of the world's renewable energy potential, more than any other continent and these renewable energy sources are mainly derivable from three major sources, namely: solar, biomass and hydropower.

Cost of Solar Energy

By 2021, over 843 gigawatts of solar photovoltaic systems had been installed worldwide, representing a 21-fold increase in solar energy since 2010. In addition, 133 gigawatts of newly installed systems were established during 2021 alone, which was a 13% increase from 2020. These new capacity additions were the highest among all renewable energy sources that year (IRENAa, 2022).

Solar energy costs must be quantified to promote the benefits and future of renewable energies. The levelized cost of energy (LCOE) of crystalline and amorphous silicon photovoltaic panels in different local climates was the subject of one study. The LCOE and lifetime of the crystalline silicon panels were $0.143 (21 years), $0.138 (32 years), $0.172 (25 years), and $0.159 (40 years) for mid-altitude desert, humid subtropical, humid continental, and maritime climates, respectively (Flowers et al., 2016). The amorphous silicon panels had LCOE values and life spans of $0.141 (17 years), $0.201 (14 years), and $0.227 (17 years) for mid-altitude desert, humid subtropical, and maritime climates, respectively. The study identified crystalline silicon panels as the most viable due to their low degradation rates. Another research studied the LCOE of bifacial solar farms considering land and module costs. The research suggested that for places with limited and expensive land, solar panels should be laid flat to maximize land utilization (Osman, *et al.*,2023).

Solar PV module prices declined by around 80% between 2009 and 2015 (Figure 11). In 2011, price declines accelerated as oversupply created a buyer's market. The price declines then slowed between 2013 and 2015 as manufacturer margins reached more sustainable levels and trade disputes set price floors in some markets. During Q1 2015, solar PV module prices continued declining by about 15% for crystalline modules and by a slower 4% for thin-film modules. Module prices stabilized during Q3 and Q4 2015, with crystalline modules increasing slightly. Thin-film module prices continued their downward trend and decreased by 3% during Q2, Q3 and Q4 2015. During early 2016, thin-film prices have stayed around USD 0.5/W. During 2015, weighted average country-level module prices ranged from around USD 0.52 to USD 0.72/W

Finally, the implications for Africa from these observations and analysis are significant. They highlight that a large gap can exist between what a hypothesized “efficient” cost structure in African countries may look like and what is achievable on the ground given local market maturity, structural cost factors and the impact of the regulatory framework. There is a tendency among many commentators and researchers to be overly optimistic about what average solar PV installed costs may look like in Africa (and indeed elsewhere), particularly for small-scale projects and residential systems, as deployment grows. The difficulties of rapidly establishing an efficient cost structure given all of the challenges involved can be large. This is not to say that they are unreasonable assumptions for a longer-term, more established market situation, but that there often is a tendency to underestimate initial levels (IRENA, 2023).

Cost of Hydropower Energy

Hydropower remains the lowest-cost source of electricity globally, and Africa is no exception. Hydropower production costs depend on the construction, equipment, operation, and maintenance expenses. Micro hydropower plants are necessary for rural and underdeveloped areas to have access to electricity. The cost of micro hydropower plants utilizing locally manufactured equipment was quantified in Nepal. The results showed that the average price per kilowatt at Crossfow and Pelton sites were $505/ kilowatt and $605/kilowatt, respectively (Butchers et al., 2022). The generator, penstock, and turbine sub-systems account for almost half of the total costs of the hydropower plant sub-systems. The initial cost of a micro-hydropower plant is around 6 cents/hour, while solar and wind plants cost 10 cents/hour and 7 cents/hour, respectively (Elbatran *et al.,* 2015). The cost of starting up a mi-hydropower plant is divided into civil works (40%), turbine and generator (30%), control equipment (22%), and management cost (8%). The initial costs of construction and equipment for

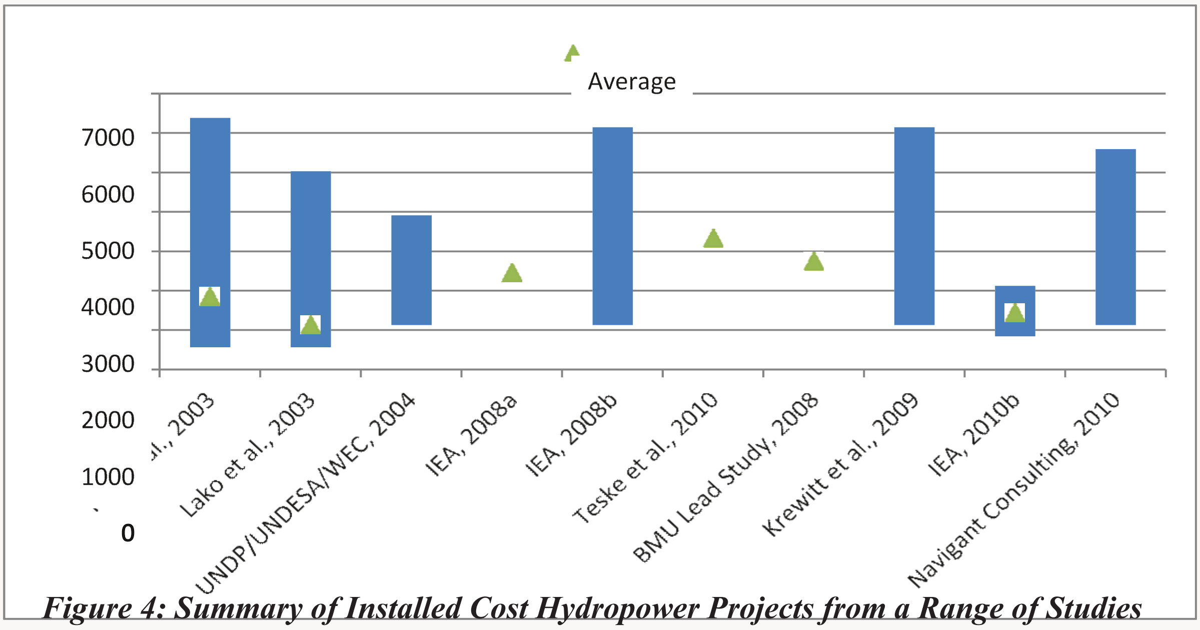


Figure 4: Summary of Installed Cost Hydropower Projects from a Range of Studies
Source: IRENA (2021).

Figure 4 summarises several studies that have analysed the costs of hydropower plants. A large, comprehensive cost analysis of over 2 155 potential hydropower projects in the United States totalling 43 GW identified an average capital cost of USD 1 650/kW, with 90 % of projects having costs below USD 3 350/kW (Hall, et al., 2003). In another study (Lako et al., 2003), 250 projects worldwide with a total capacity of 202 GW had an average investment cost of just USD 1 000/kW and 90 % had costs of USD 1 700/kW or less (Lako et al., 2003).

Cost of Biomass Energy

Figure 4*:* Summary of Installed Cost Hydropower Projects from a Range of Studies
Source: IRENA (2021).

Available low-cost biomass, such as agricultural by-products, provides highly competitive, dispatchable sources of electricity. However, transportation costs are responsible for the high price of biomass. In Switzerland, research has been conducted on the transport of biomass, including firewood, woodchips, and solid and liquid manure, along various transport chains. The results revealed that transportation costs ranged from 24 Swiss francs/ton of dry matter for the transport of slurry by underground pipe to 340 Swiss francs/ton of dry matter for transporting coniferous wood by farmers (Schnorf *et al.*, 2021).

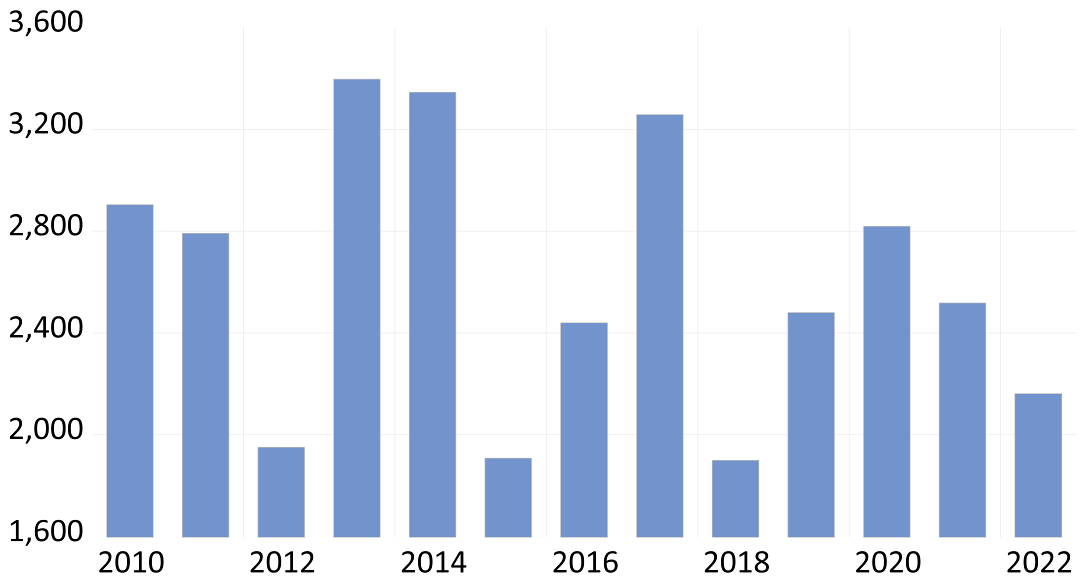


Figure 5: Average Installation Cost of Bioenergy Plants Worldwide from 2010 to 2022 (in US dollars per kilowatt) **Source:** Statista (2023)

Figure 5 shows the global average cost of installing bioenergy plants from 2010 to 2022 in US$ per kilowatt and it indicates that the average cost of installing bioenergy plants in 2022 is 2,162 US dollars per kilowatt installed. The trend shows that there are sharp fluctuations in cost over the years with the highest cost being recorded in 2013 with $3.397 installation cost per kilowatt. Although there are many possible factors influencing cost of biomass energy, the main three drivers are equipment cost from the factory gate to the delivery site, total installed project cost (including fixed financing cost) and the levelized cost of electricity (LCOE) generated. According to IRENA (2023), the LCOE of biomass-fired power plants range from 6 to 29 cents per kWh based on capital costs and feedstock costs. Where low-cost feedstocks are available and capital costs are modest, biomass can be a very competitive power generation option, according to the analysis, and where low-cost agricultural or forestry residues and wastes are available, biomass can often compete with conventional power sources. Even where feedstocks are more expensive, the LCOE range for biomass is still more competitive than for diesel-fired generation, making biomass an ideal solution for off-grid or mini-grid electricity supply.

Impact of Renewable Energy on the Environment

According to the World Health Organization, nearly 99% of the world's population breathes unhealthy air, and more than 13 million people die annually from preventable environmental causes, including air pollution (World Health Organization, 2022). Primarily, the combustion of fossil fuels generates fine particulate matter and nitrogen dioxide. In 2018, air pollution from fossil fuels caused daily health and economic losses of approximately $8 billion (United Nations a, 2018). Switching to renewable energy sources, such as solar and wind, aids in combating climate change, air pollution, and health problems (Osman *et al,* 2023).

Table 4 examines the environmental impact of renewable energy deployment on the environment. The table summarizes the environmental benefits and hazards of continuous and expanding use of renewable energy in various regions and time periods.

Table 4: Environmental Impact of Increasing Renewable Energy Sources

Project Title	**Year**	**Environmental Impact**	**Region**	**References**
Heterogeneous impacts of renewable energy and environmental patents on carbon dioxide emission—Evidence from the BRICS (Brazil, Russia, India, China, and South Africa)	2019	+	BRICS (Brazil, Russia, India, China and South Africa)	Cheng *et al* (2019)
Social, economic, and environmental impacts of renewable energy systems	2009	-	Uttaranchal state, Tehri Garhwal district, Jaunpur block, India	Akella *et al* (2009)
Environmental impacts of high penetration renewable energy scenarios for Europe	2016	+	Europe	Berrill *et al* (2016)
Does nuclear and renewable energy improve the environment? Empirical evidence from the USA	2016	+	USA	Baek (2016)
Impact of renewable energy consumption, globalization, and technological innovation on environmental degradation in Japan: application of wavelet tools	2021	+	Japan	Adebayo and Kirikkaleli (2021)
Economic and environmental benefits of increasing the renewable energy sources in the power system	2019	+	Egypt	Nassar *et al* (2019)

* **Note:** "+" represents a positive impact, while "-" represents a negative impact.

Source: Adapted from Osman *et al* (2023).

Furthermore, on a general note, renewable energy utilization can be said to have little or no hazardous effect on the quality of environmental conditions. This perspective is corroborated in the literature as the extant literature of renewable energy highlights various mechanisms through which renewable energy helps to improve the quality of the environment. First, renewable energy does not emit pollutants and therefore the quality of the environment does not deteriorate. Second, renewable energy lowers environmental degradation because of the "substitution effect". That is, renewable energy is substituted with fossil fuels and the prospective emissions of fossil fuels are diminished (Bilgili *et al.*, 2016).

Third, renewable energy does not deplete unlike fossil fuels (Akella *et al.*, 2009; Tsoutsos *et al.*, 2005) and, therefore, does not burden the environment by freeing the resources from extraction and mining activities. Fourth, renewable energy improves the quality of the environment by generating dynamic effects through economies of scale and spillover effects. According to technological transfer theory, the "horizontal" or international perspective of technology transfer "enables developing countries to acquire, adapt, deploy and diffuse renewable energy technologies from overseas and further innovate as a result of the capabilities acquired through the technology transfer process".

Renewable energy sources "such as solar, wind, geothermal, biomass and small hydropower plant" ensure the sustainability of energy and are inexhaustible, unlike fossil fuels which deplete (Tsoutsos *et al*., 2005). Renewable energy ensures energy security and sustainability (Prandecki, 2014). Among renewables, solar energy is extensively available and has the potential to meet the growing energy demand and to slow down climate change as it does not produce emissions. Solar energy is the cleanest form of energy that has the least environmental impact. The solar energy capacity of the world has increased. Solar energy is not vulnerable to weather patterns. Solar energy does not lead to any gaseous emissions to air or generate liquid and solid waste thus improving the environment (Devabhaktuni *et al.,* 2013; Bhattacharyya, 2011; Solangi *et al.,* 2011).

In addition, renewable energy has spillover effects. Because of the decentralized nature of renewable energy, it increases job opportunities and can easily be applied with low maintenance cost which leads to spillover effects (IRENA, 2019). Dependence on imports of fossil fuels affects trade balance and leads to macro-economic instability whereas harnessing renewable energy reduces the vulnerability of the economy to external economic shocks. Renewable energy increases employment opportunities because of its decentralized nature. Off-grid solar units can be installed in rural communities and far-flung areas, which lack electrification. Off-grid units have ensured access to energy which improves businesses and employment opportunities (IRENA, 2016).

Furthermore, as found out by Asongu, Iheonu and Odu (2019), the fact that renewable decreases CO2 emissions is an indication that to mitigate CO2 emissions in Africa in the light of sustainable development goals (SDGs) about energy, sampled policies will need to tailor policies that favour the replacement of non-renewable resources of energy with renewable sources. Some policies that can be implemented in this direction include making environmentally conscious political decisions aimed at encouraging the use of green energy sources such as solar and wind power for electricity generation. Adopting green energy sources in the industry also reduces CO2 emissions as the industry is one of the leading contributors of CO2 emissions not just in Sub-Saharan Africa but also in the rest of the world. Governments should also study the feasibility of the use of electric cars in the region and the possible adoption of such cars for CO2 emissions to be reduced.

In contrast, some studies also argue that renewable energy can also negatively affect the quality of the environment. Combustible renewables and waste are not clean energy use. If they have a major share in renewable energy sources then emissions can increase (Jebli and Youssef, 2017). "Renewable energy sources, such as biofuels, solar, wind and geothermal energy, require a substantial amount of water and land". Given the limited availability of land and water resources, renewable energy resources will increase the ecological footprint, thereby degrading the environment (Al-Mulali *et al*., 2016). Using a sample of 58 countries from 1980 to 2009, Al-Mulali *et al*., (2016) confirm that renewable energy increases ecological footprint by increasing the inefficiency of land and water use and therefore degrade the environment.

In conclusion, there seems to be no consensus regarding the impact of renewable energy on emissions and the consequent impact on the environment, however, the existing evidence on the positive effects of renewable energy on the environment outweighs the evidence of its harmful effects. Therefore, the current study occupies a unique position in the literature by contributing to the existing debate of the energy-environment nexus, as the availability of renewable energy sources is not constrained like fossil fuel which depletes and degrades the environment. Moreover, renewable energy ensures energy sustainability and security as well.

An Assessment of Climate Resilience in Africa

Resilience is an important and desirable feature of an efficient energy system and an energy system is said to be efficient when it possesses the ability to withstand the gradual long-term changes in climate patterns and continue operation after severe disruptions. According to the African Development Bank (2023), "Of all continents, Africa is least responsible for climate change. It has contributed only a minute part (far less than 4%) of the Greenhouse gas emissions that are responsible for the climate emergency the world faces today. Yet, Africa faces a more arduous battle than the rest of the world to tackle the impacts of climate change and to make itself resilient to climate change. Climate resilience is about successfully coping with and managing the impacts of climate change while preventing those impacts from growing worse. A climate-resilient society would be low-carbon and equipped to deal with the realities of a warmer world.

Today, Africa remains one of the most vulnerable and the least climate-resilient regions in the world. This is manifest across all corners of the continent. In the Horn of Africa, millions are threatened as a historic drought looms. In the Sahel, climate change is fueling insecurity because of increasingly scarce resources. And Southern Africa is experiencing lethal rain and floods. Action has never been more urgent. These climate change-induced challenges cut across many countries and subregions of the continent and have triggered a wide range of socio-economic challenges including considerably slowing down Africa's economic growth trajectory with average annual losses in GDP per capita growth of 5–15 per cent in 1986–2015. These losses stem largely from differences in economic structure and exposure to climate change. The economic cost is projected to be much higher in the next few decades. The future climate-induced macroeconomic risk for African countries was estimated to be higher than the rest of the world under two Representative Concentration Pathways – RCP 2.8 and RCP 8.5.

Carleton *et al* (2020) submit that Beyond macroeconomic impacts, climate change has significant impacts on socioeconomic outcomes. For instance, the average global risk of mortality from high temperatures amounts to an additional 85 deaths per 100,000 people in 2100, but the effect is worse in Africa. In Ghana and Sudan, for instance, high temperatures could be responsible for an additional 160 and 200 deaths per 100,000, respectively, in 2100.High-temperature projections for that year would raise the prevalence of child-wasting among children under the age of five by 37 per cent in West Africa and by 25 per cent in Central Africa and East Africa (Baker and Anttila-Hughes, 2020).

In addition, the risk of climate-change-related conflicts such as fighting over scarce water resources, are increasing (IDMC, 2021). A 1°C higher temperature is associated with a greater risk of conflict in Africa of about 11 per cent since 1980.In 2020, 30 million people worldwide became internally displaced as a result of weather-related disasters, including 4.3 million in Africa, the highest level since 2012-suggesting that climate-related disasters lead primarily to internal rather than international migration, particularly in developing countries (IMF, 2020). Extreme weather events account for 89 per cent of all disease displacement in most African countries, they lead to higher rural-urban migration because of the effects on agriculture. Further, internally displaced people struggle to find safety in camps, tents, and makeshift shelters, often for uncertain and prolonged periods. Lacking privacy for daily activities such as bathing, sleeping, and dressing, the camps become an ungoverned place for increased sexual violence. Many women and girls have reported heightened exposure to gender-based and sexual violence when living in makeshift camps with very little protection (Desai and Mandal, 2021).

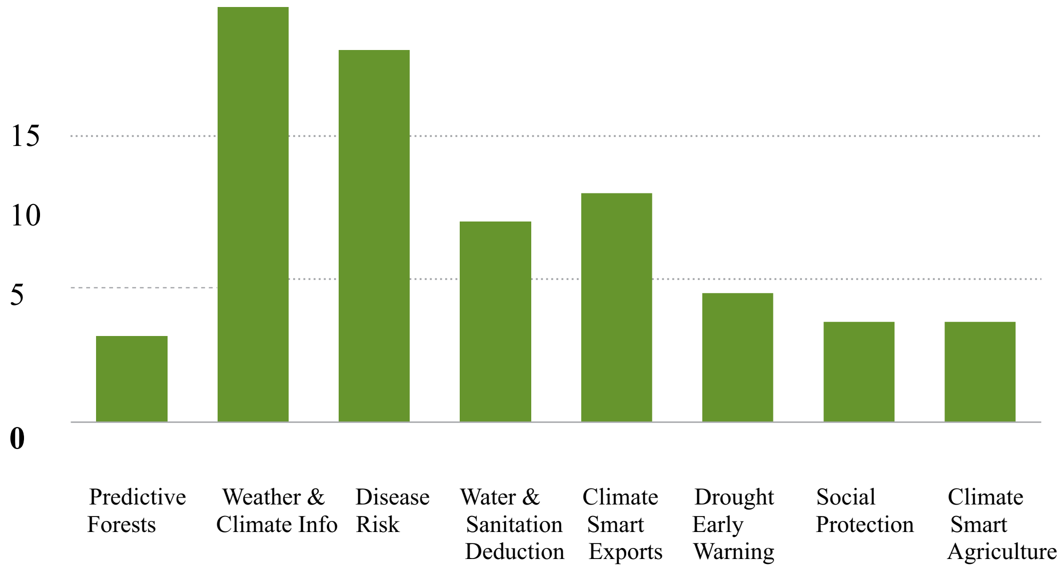


Figure 6: Cost-benefit ratios for Climate-resilient Options in Africa

Source: Adapted from Global Center on Adaptation (2021).

Note: The figure shows averages of a range of indicative benefit–cost ratios reported in the source. These ratios are highly site- and context-specific, and future uncertainty about the scale of climate change could affect them greatly.

It is evident that Africa has a low adaptive and climate-resilience capacity and there is an increasing need to build efficient and cost-effective climate resilience to cover not only adaptation investments and costs but also losses and damages associated with residual damage and adaptation deficits. Considering the high vulnerability and low readiness of African countries (problems worsened by the impacts of the COVID-19 pandemic) and the limited contribution of Africa to climate change, Africa can become climate-resilient by adopting several strategies for climate change mitigation and adaptation. Social protection to support poor people during climate shocks also increases beneficiaries' resilience by minimizing associated losses as well as investments in resilient infrastructure, with measures to complement and upgrade the infrastructure to reduce the negative impacts of climate change on economic growth compared with a business-as-usual scenario of investments in standard infrastructure. Investing in resilient infrastructure also reduces inequality. Bridging the huge energy gap in Africa is one of the most viable strategies to improve Africa's low level of climate resilience and climate readiness. IEA (2019) states that as extreme weather events become more frequent and intense, the installation of residential and workplace climate control systems is important for building climate resilience among households and businesses requiring modern energy, but such efforts are held back by Africa's low modern energy production and consumption.

Conclusion and Recommendation

This paper examines the cost and the environmental impact of renewable energy deployment in Africa as well as

Africa's climate change resilience and readiness under a changing global climate. We show that about 80% of the world's population resides in countries that are regarded as net importers of fossil fuels, leaving approximately 6 billion people susceptible to geopolitical shocks and energy crises. We consider the different types and forms of renewable energy that could be deployed for efficient and cost-effective energy transition. In contrast, renewable energy sources are available in all nations, but their full potential is not being adequately realized. Ironically, Africa has the most abundant renewable energy resources, but it has the least developed renewable energy utilization. By 2050, approximately 90% of the world's energy will come from renewable sources. Excluding geothermal and hydropower-derived energy, renewable energy technology costs in Africa (just like the rest of the world) have decreased significantly since 2010. In Africa, the cost of solar and wind-generated electricity per kilowatt-hour in 2021 was four to six times less than that of fossil fuels in 2022. With prices declining, new power supply based in renewable energy sources has a significant portion of the future to supply 65% of the world's total electricity by 2030 and to decarbonize 90% of the electricity industry by 2050. This is anticipated to stem the tide of carbon emissions thereby contributing to climate change mitigation and to the attainment of the UN Net Zero Agenda by 2050.

In explaining the impact of renewable energy sources on the environment, consideration is given to all renewable energy sources, including solar, wind, hydropower, geothermal, and biomass. Each renewable energy source has different environmental impacts depending on the renewable energy source type, location, scale, and implementation method. While almost all renewable energy sources have positive environmental effects, the negative effects can be mitigated through careful choice and utilization of renewable energy sources. Wind, hydropower, biomass, and geothermal energy were found to have the greatest environmental effects, while solar energy had the least effect on the environment and climate change. Among all regions, Africa is the least climate-resilient as extreme weather and climate fluctuations continue to cause immense socioeconomic damages resulting in huge economic losses and precipitous decline in GDP. The climate readiness of Africa is low in all ramifications compared to the rest of the world. Hence, renewable energy adoption is necessary for expanding and establishing renewables to reduce reliance on fossil fuels and save the environment, while climate-resilient options including bridging the huge energy gap in Africa will provide efficient and cost-effective strategies to enhance climate resilience in Africa.

To effectively achieve net-zero emissions by 2050, renewable energy sources must be solidly established in Africa by 2030 by ensuring the acceleration of its massive renewable energy resources. Africa must be given time to transit and be allowed to use natural gas as its transition fuel. Investment in renewable energy in Africa should be accelerated while financial and technical assistance is to be rendered to them given that the energy transition in Africa is estimated to cost $100 billion annually between 2020 to 2050. It will be to Africa's benefit in terms of environment and economics to abandon the current overreliance on fossil fuels and invest more in renewable energy. National governments in Africa need to address key issues in the energy transition process which include – strategies for building a sustainable energy future for Africa, deregulation of the energy sector, utilizing gas as a transition fuel, sectoral challenges, local contents, the roles of national oil companies in the transition, etc. Policy reforms need to be geared toward encouraging fair conditions for all energy forms in terms of internalizing the environmental and economic costs of different energy types. An appropriate and market-determined energy pricing structure is fundamental to the emergence of a sustainable energy future in Africa.

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