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Renewable Energy Transition from the Lens of Technological Advancement and Financial Flows in Sub-Saharan Africa

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Abstract

The upsurge in economic activities prompted by the desire to increase productivity and attain development has increased energy demand in developing countries. Accordingly, energy production in Sub-Saharan Africa is dominated by fossil sources. As a result, CO_2 emissions have increased in the region. To mitigate this, the UN in 2015 came up with a clean and affordable energy declaration by 2030, which has triggered interest from scholars, analysts, and policymakers. Thus, this study is directed to examine the influence of key renewable energy drivers on renewable energy production in Sub-Saharan Africa as a way of assuaging global warming and maintaining environmental sustainability. We found scant literature in this area, particularly that which featured novel drivers such as installed capacity, international financial flows for clean energy, research and development in technology, and institutional quality. The study conceptualized institutional quality with Principal Component Analysis (PCA) and made a methodological contribution by using Method of Moments Quantile Regression to estimate a panel dataset from the period 2014 to 2023. The study found installed capacity as the main significant instrument driving renewable energy production in SSA. Additionally, except in a few countries, shocks in institutional quality contributed insignificantly to improving renewable energy, whereas positive shocks in research and development in technology hurt renewable energy production in all quantiles. For policy implications, we advocate for a conscious and concerted energy policy that will increase installed capacity and institutions that will instill appropriation of international financial flows with sufficient attention to research and development.

Index-words: *Renewable Energy Production, Transition, Fossil Energy, Institutional Quality, Installed Capacity, SSA.*

I. Introduction

As global energy demand dominated by fossil sources continues to expand due to a surge in economic activities, there is a seamless corresponding increase in carbon emissions. The growing demand for mineral resources required for human economic and social activities might increase mining activities and require higher energy input in producing and developing countries [1]. [2] reports a global energy demand increase of 2.2% in 2024, faster than the past decade. It further noted that the increase results from increased electricity demand by 4.3%, while 80% of this increase is accounted for by emerging and developing economies. CO_2 emissions from fossil energy sources and cement in 2024 increased by 0.8%, summing to 37.4bn tons [3]. This increase contributed to the atmospheric CO_2 concentration of 422.5 ppm in the same period, three ppm higher than in 2023 and 50% higher than the pre-industrial period [2]. CO_2 emissions from fuel in Africa in 2022 were 1,262.252 metric tons, with South Africa emitting 394.069 metric tons [2]. Thus, current global economic and climate conditions require an urgent transition to a low-carbon energy

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system [4]. Renewable energy must supply 70-85% of the World's electricity in 2050, and investment into energy technologies and energy efficiency must be multiplied by a factor of 4-10 to limit global warming to 1.5 ℃ [5].

Africa contributes negligibly to the changing climate with only about 2 to 3% global CO2 emissions, yet stands as the most vulnerable region in the World [6]. This is because Africa lacks the resources to buffer itself and recover from the colossal effects of global warming. Transiting from fossil energy use to the use of low-carbon sources of energy unequivocally becomes Africa's solution to global warming. To support this view, [7] promote renewable energy use as an essential step in combating climate change and promoting sustainable development. Consequently, renewable energy adoption has taken center stage in global energy discourse and national policies since the United Nations clean energy declaration in 2015. This shift is intended to reduce greenhouse gas emissions and their attendant health and ecological consequences. The adoption of renewable energy systems is essential for combating greenhouse gas emissions and achieving Sustainable Development Goals. Nevertheless, these changes may not be enough to achieve the specific objectives of affordable and clean energy and global warming in Africa [8]. This is because Africa is slow in transitioning from fossil to clean energy use.

Failure to improve environmental quality could result in a rise in global temperature, which in turn will exacerbate global warming [9]. Accordingly, both humans and animals will be exposed to varying degrees of diseases, which may result in displacement, reduced longevity, reduced food production, economic growth, and environmental degradation. Thus, the focus of the 2015 UN treaty on affordable and clean energy is to mitigate greenhouse gas emissions and maintain a 2 ℃ annual global average temperature [10].

Previous studies, such as [11], focused on public-private partnership in reducing carbon emission, [12] [13] evaluated the connection between industrialization and carbon emission in Sub-Saharan Africa. [14] examined the determinants of electricity production from renewable energy sources other than hydroelectricity in some East African countries. [15] focused on drivers of renewable energy in developing and developed countries. From the EU, [16] investigated the determinants of renewable development. [17] studied the role of renewable and non-renewable energy sources on the development of Sub-Saharan Africa. [18] have highlighted the indicators of renewable energy production in Turkiye, focusing on renewable consumption; [19] explored the role of fossil and renewable energy in determining environmental sustainability. Similarly, [20] estimated the effect of renewable and non-renewable energy and the use of technology in environmental sustainability; the study of [21] concentrated on the factors responsible for renewable energy distribution and disparity across countries; the study of [22] evaluated renewable energy development in Sub-Saharan Africa, focusing on challenges and opportunities. [23] examined the drivers of renewable energy generation in a developing country like Pakistan as a means of environmental sustainability. [24] considered the usefulness of renewable energy in sustainable agricultural production, focusing on the solar-powered irrigation system.

Despite laudable effort in literature to explore drivers of renewable energy and sustainable development, in Sub-Sahara Africa, developed, developing and emerging economies, no substantial effort has been made to considered the crucial impact of novel variables such as institutions, research and development in technology, international financial flows for clean energy and renewable energy installed capacity on renewable energy production as a trajectory to sustainable development. To provide more insight into the renewable energy transition in Sub-Saharan Africa and environmental sustainability, this study seeks to examine policy variables that may boost the transition from fossil to clean energy. Given the economic, social, and political similarities of the countries under consideration, the study makes a methodological contribution by employing methods that consider cross-sectional dependency and the nature of available data. Thus, this study is set to investigate the effect of institutional quality captured by principal component analysis (PCA), international financial flows, and research and development on technology and installed capacity, and renewable energy production as a means of swift change from fossil fuel to renewable energy use and attaining sustainable development. It will further address the following research questions: how do institutional quality, installed capacity of renewable energy, international financial flows, and research and development in technology drive renewable production in SSA?

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Evaluating the progress of fossil energy transformation to clean energy 10 years after the UN declaration and 5 years to the 2030 deadline for affordable and clean energy, and how much impact this has made on sustainable development in SSA, is the motivation for this study.

This study is useful in three ways: (1) the research findings will inform policy decisions on novel driving mechanisms of renewable energy production to foster sustainable development in SSA. (2) It will boost renewable energy literature, thereby contributing to knowledge. (3) The study will reveal to SSA countries the need to meet the UN deadline for clean and affordable energy in 2030.

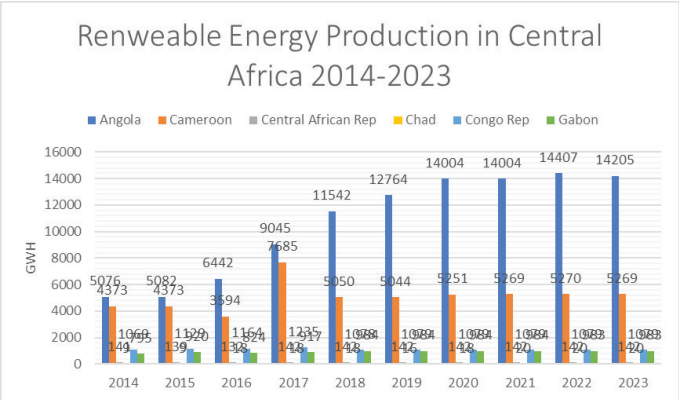
The remainder of this study is arranged as follows: A brief literature review is followed by presentation of data and methodology, result presentation, discussion, and policy implications of the paper.

A. Facts on renewable energy production in SSA

Though Africa is rich in land and energy resources, its population is projected to grow to nearly 2.5 billion people in 2050, 80% of whom are in Sub-Saharan Africa [25]. The region's electricity demand is expected to rise with its increasing population in 2050 and with the projected structural transformation in manufacturing [26]. Despite the abundance of energy resources and recorded progress to modern energy in Sub-Saharan Africa, access to energy remains low. In 2020, about 571 million people in the region did not have access to electricity, while 923 million lacked access to clean cooking fuels and technology; and these figures have increased due to a surge in population [27]. At the moment, Africa's effort to achieve critical sustainable goals, principally energy goals such as access to clean and affordable energy, is weakening and far behind 2030 targets [28]. Africa as a whole and Sub-Saharan Africa are characterized by high population rates and rising income levels; meanwhile, they have the lowest level of access to electricity in the World [29] [30]. Inaccessibility, high cost of electricity, and clean cooking fuels and technology in Sub-Saharan Africa are attributed to a slow response to renewable energy transition programs and low production of renewable energy. Electricity growth in SSA in the last 40 years is half the growth of other developing countries, resulting from lingering energy challenges ranging from poor connectivity to high cost [31]. Electricity shortages bring huge costs to Sub-Saharan Africa, slowing annual economic growth by 2–4% of GDP [32].

Investment in renewable energy is the way out of energy poverty in Sub-Saharan Africa. A huge and concerted investment effort in renewable energy, taking advantage of abundant energy resources, has to be made to achieve sustainable energy development in the region. Only 1.7% of global investment in renewable energy from 2010 to 2020 went into Sub-Saharan Africa; 60% of USD 90 billion energy investment in 2021 in Africa went into fossil energy [33] [34]. Of the 29% share of renewables in power generation in 2019 in the region, 24% was from hydropower, with only 5% from other sources of renewables, and since 2010, only 0.8% of the globally added capacity of onshore wind turbines have been installed in Africa [28].

B. Trend of renewable energy production in Sub-Saharan Africa 10 years after the UN clean energy declaration and 5 years to 2030



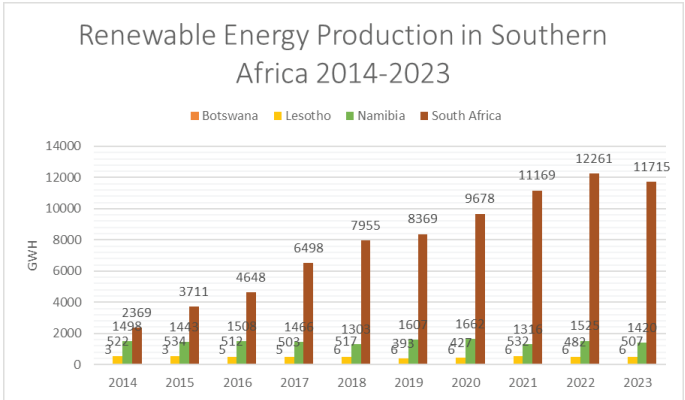
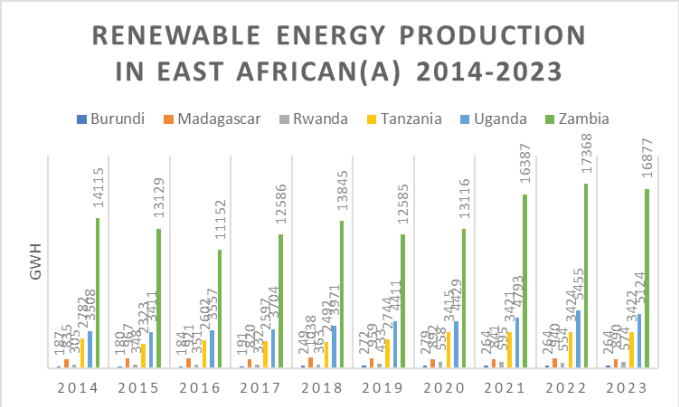


Figure 1: Renewable energy production in Central and Southern Africa; Source: Author's construction from International Renewable Energy Agency Statistics (2024). www.irena.org/Data

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Figure 1 shows that Angola generated the highest amount of renewable energy in Central Africa. Its highest power generation was 14407 GWh in 2022 (with a decline in 2023) and lowest in 2014 (5076 GWh). It had an average production of 10657.1 GWh and a 9331 GWh increase, representing a 64.8% increase. Similarly, Chad generated the lowest renewable energy in the region, from 9 GWh in 2014 to 20 GWh in 2023. It generated an average of 16.6 GWh, and its generation increased by 11 GWh, translating to 55%.

In the Southern African region, South Africa was the highest renewable power generator. With a decline in 2023, it generated 12261 GWh in 2022 and 2369 GWh in 2014. Average generation in South Africa was 7837.3 GWh and an increase of 9892 GWh, representing an 80.1% increase. Botswana's power generation was lowest in the region. It generated 3 GWh in 2014 and 6 GWh in 2023. Annual average generation was 5.2 GWh, and a 50% increase in generation.



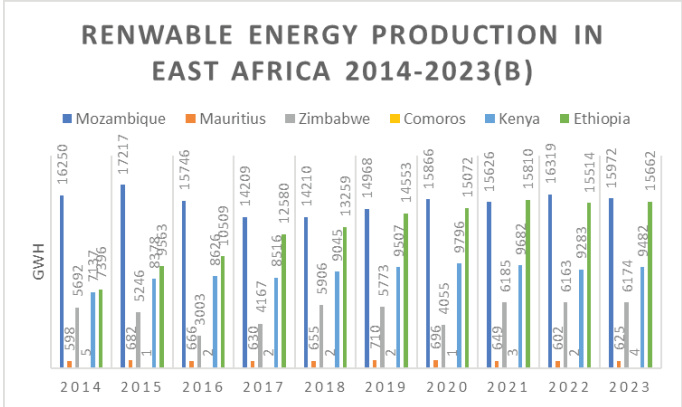
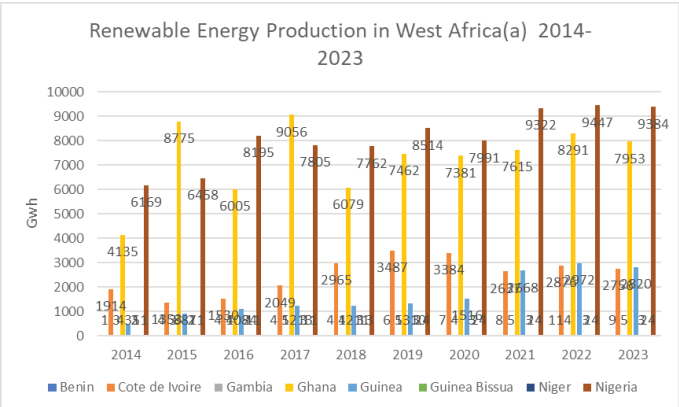


Figure 2: Renewable Energy Production in East Africa. Source: Author's construction from International Renewable Energy Agency Statistics (2024). www.irena.org/Data

Figure 2 indicates that Zambia generated the highest renewable power in East Africa, with 17,368 GWh in 2022, which declined to 16,877 GWh in 2023. Notably, 14,115 GWh was generated in 2014. Zambia is the highest renewable power generator in Sub-Saharan Africa. Its annual average generation was 14116 GWh with an 18.7% increase from 2014 to 2023. Comoros generated the lowest amount of renewable energy in East Africa. It generated 5Gwh in 2014 and 4 GWh in 2023, with an average of 2.4 GWh annual generation and a 20% decrease in generation.



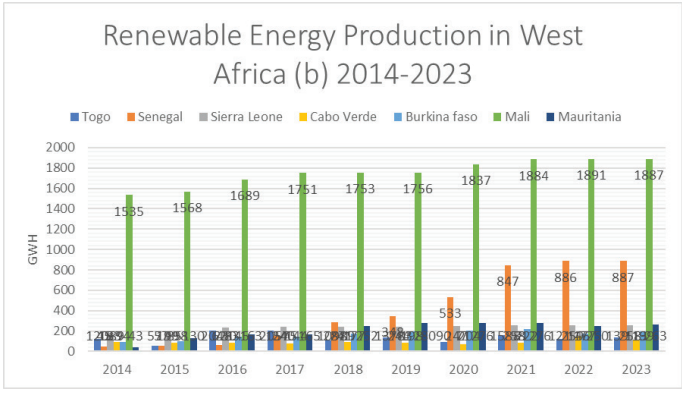


Figure 3: Source: Renewable Energy Production in West Africa. Authors' construction from International Renewable Energy Agency Statistics (2024). www.irena.org/Data

Figure 3 reveals that Nigeria generated 6169 GWh of power in 2014 and 9384 GWh in 2022, making it the highest renewable energy power in West Africa. On average, it produced 8104.7 GWh and a 34.2% increase in generation. Nigeria also had a decline in generation in 2023 from 9447 GWh in 2022 to 9384 GWh in 2023. Guinea-Bissau is the lowest energy producer in West Africa, with an average generation of 2.7 GWh.

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In general, Zambia is the highest producer of renewable energy in Sub-Saharan Africa. Other countries with high generation of renewable energy include: Mozambique, Ethiopia, Kenya, Mali, and Ghana. Comoros, Botswana, Benin, Gambia, Guinea-Bissau, and Chad are countries with the lowest renewable energy generation in SSA.

II. Literature review

A. Empirical literature

In this section, we first consider a cluster of related studies on renewable development, consumption, and drivers of renewable production in Sub-Saharan African, developed, and developing countries. Subsequently, other relevant and related clusters of studies on renewable energy and environmental sustainability will be presented.

B. Drivers and development of renewable production and consumption

[35]examined determinants of electricity production from renewable energy, excluding hydroelectricity in East Africa from 1998 to 2019. It was a panel study of 5 East African countries that employed the pool mean group estimation method. Several factors were considered, among which were GDP per capita growth, population growth, energy consumption per capita, and energy import, which increased renewable energy production in both the long run and the short run. Political instability, electricity production from gas, CO2 oil, and coal were also found to have reduced renewable energy production. Upon review of this paper, this study decided to increase the number of East African countries, the period of studies, and introduce a new set of variables. Using a large sample size of 177 developing and developed countries, [15] examined the determinants of renewable energy from 1990 to 2020. The study employed the fixed effect model with country and time fixed effects. The study identified GDP, oil price, access to electricity, CO2, and methane emissions as significant drivers of renewable energy, both in production and consumption of renewable energy. Further, [16] considered the determinants of renewable energy development in 27 EU countries from 2011 to 2020.

The random effect GLS regression was adopted to find that economic development and employment of advanced technology, active political and economic freedom, and geographical location drive the RE sector, whereas unemployment, level of corruption, and democracy puncture RE deployment [36]. The role of renewable energy in global energy transformation was the focus of [37]. The study used data from a renewable energy map scenario, which found that renewable energy sources could drive two-thirds of global primary energy supply by 2050. This is at variance with the 24% projection from the reference scenario. According to this study, energy transition in Africa is constrained by challenges despite its energy potential. Similarly, the study of [22] on sustainable energy development in Sub-Saharan Africa used Ward's hierarchical clustering method, classification and regression tree analysis, and distance-weighted least squares method. They found energy sector development varying greatly among Sub-Saharan African countries, while their exposure to climate change affects energy sector development. [38] Rummaged the power of electricity to promote sustainable development in the Philippine rural areas. They evaluated 500 households on two Islands. Results indicate that communities with less than 24 hours of electricity still preferred the conventional fuel for lighting and were not productive, while other communities with 24 hours of access to electricity were productive but found electricity unaffordable. The implication of this outcome is that an affordable and regular electricity supply improves production and discourages the use of traditional fuel energy.

In a similar study, [39] focused on the determinants of renewable energy for sustainable development in the Philippines. The study spans from 1990 to 2022 and utilizes the Vector Error Correction estimator. Outcomes indicate a significant direct correlation between CO2 emission, electricity consumption, fossil fuel consumption, GDP, and renewable energy consumption. [19] utilized a panel vector autoregressive model to investigate the determinants of renewable energy consumption in 6 developed countries of Asia from 2000 to 2020. The study revealed that electricity consumption, foreign direct investment flows, and economic growth positively impacted renewable energy consumption, whereas fossil fuel consumption adversely affected renewable energy consumption. A possible reason for this indirect relationship could be attributed to insufficient renewable energy production and affordability. To identify factors that influence renewable generation in Pakistan, [23] utilized the Partial Least Squares Structural Equation method to analyze questionnaires drawn

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from academia. The study identified both drivers and barriers to energy development. Findings reveal a lack of good governance as the most significant barrier to renewable energy production.

Further, it is shown that public acceptance is the major driver of renewable energy, whereas environmental effects are the least. In a Sub-Saharan African study, [40]examined factors that influence renewable energy consumption from 1998 to 2014. The study employed the panel ARDL estimator. From the 23 sampled nations, findings show that gross domestic product per capita and education positively and significantly influenced renewable energy consumption in the long run, whereas CO2 emission and life expectancy were found to significantly reduce renewable energy consumption in the long run. [41] studied energy transition focusing on its connotation, mechanisms, and effects. It indicates that energy transition will lead to the reconstruction of the energy system beyond the energy sector through implicit and explicit transitions as dual connotations essential for energy transition. Accordingly, explicit transition captures energy utilization type, structure, form, transportation mode, and spatial pattern, whereas implicit transition captures shift in energy security, geographical structure, energy justice, energy power, and energy governance.

In a study focused on the impact of China's green financial development on sustainable development from 2008 to 2020, [42] used the two-stage ordinary least squares estimator to find that green finance, renewable development, and green GDP are essential drivers of sustainable development. [43] Examine the influence of renewable energy consumption, non-renewable energy consumption, and GDP on the sustainable development of 20 high-income countries. Using the Pool Mean Group estimator, the study found a statistically significant relationship between renewable energy consumption and sustainable development, while non-renewable energy consumption significantly impedes sustainable development in high-income countries. According to [44], in a study that sought to find drivers of renewable energy penetration and its impact on power sector decarbonization in China, the US, UK, and Germany from 1995 to 2018, it found electricity consumption to be a contributor to renewable electricity generation in China, while electricity productivity and output productivity are major negative contributors. Meanwhile, electricity productivity and output productivity were found to be major drivers of renewable electricity generation in the US, UK, and Germany. (Vanegas Cantarero, 2020) found affordable technology, citizens' participation in renewable energy planning, and strong democratic institutions as significant and main propellers of renewable energy development in developing countries. [45] focused on investigating the determinants of hybrid energy system integration in developing countries. The study highlighted government support and community organizations as the main channels of grid electrification in developing nations. [46] concluded mini tidal power and salt gradient power as the Ocean resources most suitable for coastal power development and sustainability in Sub-Saharan Africa. A study by [47] on some selected countries, the period 2000 to 2019, highlights the positive association between renewable energy adoption and human development involving education, health, and income. Focusing on renewable energy development in South Africa, Egypt, and Nigeria, [48] identified technology and human development as key drivers of renewable energy development. Additionally, [49] found institutional quality, GDP per capita growth, population growth as main determinants of renewable energy in Egypt, whereas oil price, CO2 emission, renewable technical innovation, energy import, and adaptation have no effect on renewable energy development. [50] assert that renewable energy development does not hinder economic growth in both developing and developed countries, rather renewable energy strengthens economic growth in developed countries. [51] identified foreign direct investment, GDP, and financial development as significant enhancers of renewable energy production in Jordan, while CO2 emission weakens energy production in that country.

C. Renewable energy & environmental sustainability

[19] explored the role of fossil and renewable energy on environmental sustainability in OECD countries from 1990 to 2019. The study utilized the CS-ARDL to estimate the long-run effect of fossil fuel and renewable energy on carbon emissions. The study's outcome shows that fossil fuel and GDP increased carbon emissions in both the long run and the short run, while RE reduced carbon emissions. [17] evaluated the impact of renewable, non-renewable, and natural resources on sustainable development in 28 Sub-Saharan African countries

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from 1990 to 2019. The Augmented mean group and common correlated effects mean group estimation reveal that renewable energy and natural resources have insignificant improvement in sustainable development, as fossil fuel significantly hurts sustainable development. We found mixed findings in these studies. While fossil fuels increased carbon emissions in the study of [19], they significantly degraded the environment in [17]. The differences in these findings may be attributed to economic and estimation technique differences.

The study of (Mentel et al., 2022) focused on the impact of research and development and renewable energy on CO2 emissions in 26 countries between 1995 and 2015. The full modified OLS estimation indicates that R&D and renewable energy significantly worsen carbon emissions, as FDI and GDP significantly improve CO2 emissions. [11] modeled the effect of renewable energy and public-private partnership investment on the environment in E7 countries from 1995 to 2018. They employed the MMQR to find that renewable energy production can mitigate CO2 emission in the lower and upper quantiles, but couldn't in the middle quantile. On the contrary, PPPI mitigated carbon emissions in all quantiles of the countries considered. [12] investigated the relationship between industrialization and carbon emissions in Sub-Saharan Africa. The study focused on 28 countries from 2003 to 2021 and used the GMM estimator. The outcome reveals that industrialization directly impacts carbon emissions through the moderating influence of trade openness. In QUAD countries, [20] studied the effect of RE and NRE usage and technological improvement on environmental sustainability.

With the use of MMQR, it was discovered that renewable energy production and technological innovation improved environmental sustainability, while non-renewable energy usage and economic growth depleted the sustainable environment. [52] related environmental tax and income inequality to sustainable development in 92 countries across the globe from 1994 to 2020. With MMQR estimators, the study reveals that global inequality is reduced through environmental tax, which in turn influences sustainable development. [53] evaluated the effect of environmental concerns and income inequality on environmentally friendly purchases in the US from 2010 to 2017. The study utilized a Two-Way fixed effect estimator to find that environmental concerns positively impact inconspicuous, environmentally friendly products like energy-saving equipment. Income inequality is found to exert a negative influence on inconspicuous environmentally friendly products, but with a more direct impact on conspicuous products like electric vehicles. Further findings include a positive interactive influence of environmental concerns and income inequality on inconspicuous environmentally friendly products. [54] examined how renewable consumption impacts the environment in the presence of education in OECD countries. The study covered the period from 1990 to 2015 using the continuously updated, fully modified, and bias-corrected estimators. Findings show that natural resource availability and foreign direct investment hampered environmental quality, while renewable energy improved economic growth.

Similarly, [55] used the MMQR to find that natural resources increased CO2 in MINT countries with low renewable energy consumption, but had no significant effect in countries with modest and high renewable energy consumption due to sustainable usage of natural resources. [56] studied solar green roofs' contribution to SDGs, their efficiency, and their contribution to environmental conservation. The study found green roofs and solar gardens to be more economical, having the capacity to reduce the cost per kilowatt. [57] did a study on 24 Sub-Saharan African countries to investigate the impact of energy consumption and population growth on persistent emissions from the period 2000 to 2022 using the random and fixed effect methods. Increased energy consumption reduced carbon emissions, while population growth reduced the positive impact of energy consumption on emissions. To examine the impact of urbanization on residential emissions in China from the period 2000 to 2015, [58] employed the panel threshold regression method. Results indicate that urbanization positively promotes residential CO2 emission in the 30 provinces studied. Results further show that the magnitude of impact depends on the stage of income and the energy structure of the residents. [59] estimated the impact of banking sector development and low energy investment on environmental sustainability in Japan from the period 1974 to 2022, utilizing the Fourier Non-linear ARDL. The study highlighted that a reduced banking sector and economic growth deteriorate environmental sustainability, whereas increased investment in low-carbon energy and trade openness enhance environmental

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sustainability. (Yahong et al., 2023) adduced that energy poverty, population, and trade enhanced CO2 emissions in Asian developing countries from the period 2006 to 2017, thereby reducing environmental quality. In G 20 countries, [53] reveal that agriculture significantly induced CO2 emission, while renewable energy consumption reduced CO2 emission. [60] found increased energy use, economic growth, industrialization, and urbanization as direct drivers of CO2 emission in 23 developing countries across the 1995 to 2018 period. [61] reports that increasing material efficiency and reducing emission intensities attract a cumulative negative effect of 73.2% and 23.6% on CO2 emission, respectively, while their combined effect is 79.5% reduction. [62] provided insight on the effectiveness of modern and combustible renewable energy on the ecological footprint in Africa from the period 2006 to 2020. The study highlighted economic progress as an effective agent of ecological progress, whereas renewable energy impedes ecological progress. [63] offered an answer to the relationship between renewable energy consumption and sustainable development in Central Asia from the period 1993 to 2019 using the seemingly unrelated regression. Renewable energy consumption exhibited an inverted U relation with carbon intensity both in downstream countries and in the entire region [64].

D. Gap in literature

From available literature, we found scanty studies on drivers of renewable energy production, particularly those focused on as many as 37 countries of SSA, representing all the regions. Most importantly, this study found no study on SSA considering novel variables such as Installed Capacity, Research and development on technology, international financial flow for clean energy, and institutional quality. This study also filled a methodological gap by utilizing the novel MMQR estimator, which will partition the countries according to their production capacities.

III. Methodology

A. Data and methodology

This study examines the drivers of renewable energy production in 37 Sub-Saharan African countries as a means of transitioning from fossil fuels to renewable energy sources. The sample was selected to ensure the representation of countries from the entire Sub-Saharan African region. Consequently, the data range and choice of countries are largely dependent on the consistency and availability of data. Novel variables such as institutional quality derived from principal component analysis, installed capacity, research and development in technology, and international financial flows for clean energy development are considered crucial propellers of renewable energy production in the countries, while the study controls for public financial flows. Data for the study covers the period from 2014 to 2023.

Table 1: Description of variables and sources

Variables	Ellipsis	Description	Unit of measurement	Source	'A priori Expectation
Renewable energy Prod	LREPRO	Total renewable energy production	GWh	Renewable energy statistics. IRENA	NA
Installed capacity	LINCAP	The maximum net generating capacity of a power plant using renewable energy sources to produce electricity	MW	Renewable energy statistics. IRENA	+
Research and development in Tech.	LREDEV	Annual articles published in scientific and technical journals	Per million people	OWID	+
Int. Financial Flows	LINTFL	Financial flows to developing countries for clean energy development and production	USD	Renewable energy statistics. IRENA	+
Public Financial Flows	PUBFL	General final government consumption expenditure	Percentage of GDP	WDI	+
Institutional Quality	INQLY	World Governance Indicators	PCA	WDI	+
Sampled Countries: Angola, Benin, Botswana, Burkina Faso, Burundi, Carbo Verde, Cameroon, Central Africa, Chad, Comoros, Congo Rep, Cote d' Ivore, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea Bissau, Kenya, Lesotho, Madagascar, Mali, Mauritania, Mauritius, Mozambique, Namibia, Niger, Nigeria, Rwanda, Senegal Sierra Leone, South Africa, Tanzania, Togo, Uganda, Zamibia, Zimbabawe.					

Source: Author's construction

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B. Method of data analysis and model specification

The study covers 37 Sub-Saharan countries employing the methods of moment quantile regression. Previous studies, such as [65] [52] [20] [11], adapted the MMQR considering their peculiar studies and areas of study. Initially, [66] introduced the concept of quantile regression in the context of panel data. Consequently, [67] introduced the method of moment quantile regression to capture the fixed effect of cross-sectional data. Adopting MMQR offers several advantages to this study. It will place Sub-Saharan African countries in quantiles, making it easy to assess their level of renewable energy production, and establishing the relationship between renewable energy production and the novel structural determinants. Second, it offers a richer characterization of the relationships by considering the entire conditional distribution, addressing the problem of uneven distribution [68]. A unique feature of MMQR is its insight for handling non-crossing estimates without giving invalid responses [52]. Third, quantile regression has the potential to capture data outliers when the dataset is non-parametric, minimal or no correlations, non-normality assumptions, and contains individual fixed effects across the conditional distribution [65]. Further, MMQR is used when dealing with heteroscedasticity, homogeneity, and heterogeneity conditions as well as appealing to both non-linear and asymmetric estimations [52].

The location scale model of quantile regression is employed to express the relationship between the exogenous variable X and he conditional quantile of the dependent variable as follows

$$Q_y(\tau / X) \tag{2}$$

This is usually assumed to follow a linear functional form shown in equation 3

$$Q_y(\tau / X) = X\beta(\tau) \tag{3}$$

Following [67], the conditional quantiles of equation 2 are estimated for a locational scale model of the form

$$y_{it} = \alpha_i + X'_{it}\beta + (\psi_i + \mathrm{T}'_{it}\lambda)\varepsilon_{it} \tag{4}$$

with y_{it} as the dependent variable, X_{it} is an endogenous variable distributed independently and identically for any fixed i and is time dependent t, (α, β, ψ, λ) are parameters to be estimated, ε_{it} are distributed independently and identically among cross sections and orthogonal to X_{it}. $P(\psi_i + \mathrm{T}'_{it} > 0) = 1$ and T is a k-vector of identifiable components of X that are differentiated transformations [52] [20] [11] [69].

The generic form of the MMQR equation is stated as follows:

$$Q_y(\frac{\vartheta}{X_{it}}) = (\alpha_i + \psi_i q(\vartheta)) + X'_{it}\beta + T'_{it}\lambda q(\vartheta) \tag{5}$$

With $Q_y(\frac{\vartheta}{X_{it}})$ the quantile distribution of the criterion Renewable energy production (REPRO), X_{it} represents the vector of the predictor variables installed capacity of renewable energy (INCAP), Research and development in technology (REDEV), international financial flows (INTFL), Public financial flows (PUBFL), and Institutional quality (INQLY). The scalar coefficient $\alpha i(\vartheta) \equiv \alpha i + \psi_i q(\vartheta)$ is the quantile-ϑ fixed effect for an individual country or the distributional effect at ϑ. The distributional effect contrasts with the normal fixed effect because it is not a location shift. The distributional effect is the time invariant of distinct characteristics, which, like other variables, are permitted to have diverse impacts on different regions of the conditional distribution of Y [67].

C. Theoretical review and framework

This study is anchored on Schumpeterian theory of development (as cited in [70]). According to Schumpeter, a product can be enhanced using both material and immaterial productive forces. While productive factors include the traditional factors of production, immaterial components include technical factors and social organization factors.

In its simplest form, Schumpeter's model is represented as follows:

$$\mathrm{Q} = f\ [\mathrm{k}, \mathrm{r}, \mathrm{L}, \mathrm{u}, \nu) \tag{1}$$

Q = output, k = Schumpeterian concept of produced means of production

r = natural resources, L = labour force, u = society's fund of technical knowledge, and ν = facts of social organization.

Adapting the Schumpeterian model Q = f [k, r, L, u, ν),

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The basic operational equation for this study follows:

$$\mathrm{Re}\, pro_{it} = \delta_i + \vartheta_1 Lincap_{it} + \vartheta_2 L\,\mathrm{Re}\, dev_{it} + \vartheta_3 L\,\mathrm{int}\, fl_{it} + \vartheta_4 Pubfl_{it} + \vartheta_5 Inqly_{it} + \varepsilon_{it} \quad (6)$$

while the study controls for public finance.

D. Econometric framework

To adequately estimate the above model, a systematic econometric methodological framework is required. Achieving the objectives of this will require proper diagnostic checks on the characteristics of the variables. Several diagnostic and post-estimation checks, such as descriptive and correlation analysis, cross-sectional dependency and slope heterogeneity, unit root and cointegration, are necessary.

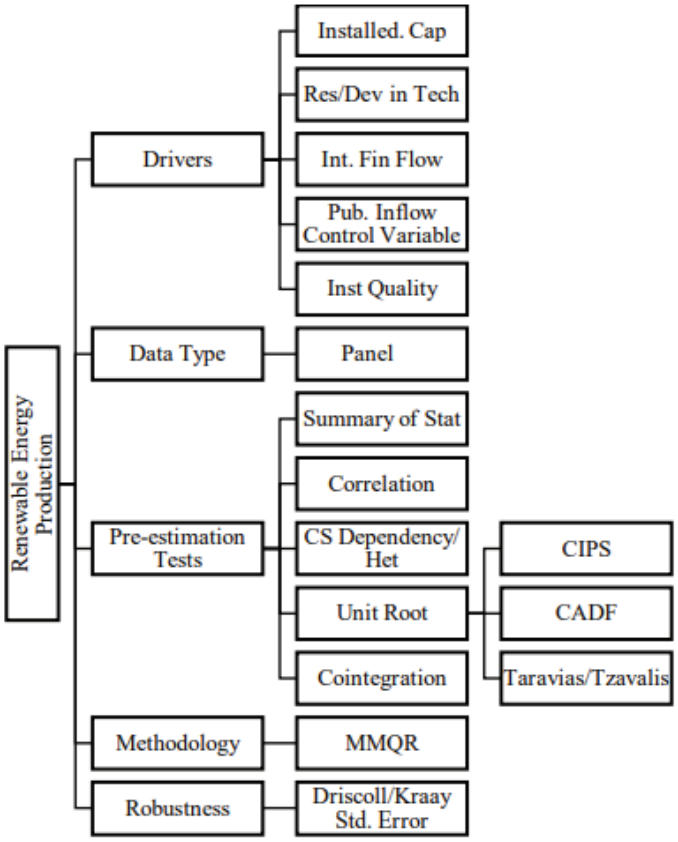


Figure 3: Methodological Framework.
Source: Authors' Conceptualization

E. Cross-sectional dependency and heterogeneity

This test is necessary to ensure that country similarities do not influence the study's outcome. Country similarities are experienced when the error terms of the cross sections are related, which may arise from common shocks and unobserved components of variables [71]. Practically, nations are linked through several links such as economic, political, border sharing, social activities, and trade [54]. When sufficient evidence of cross-sectional dependency in the dataset is ignored, the decrease in estimation efficiency can be so large that the pooled least squares estimator may provide an insignificant gain. Again, the dependency test result determines the unit root test type. For a balanced panel, [72] has proposed the following:

$$CD = \sqrt{\frac{2T}{N(N-1)\left(\sum_{i=1}^{N-1}\sum_{j=i+1}^{N} \hat{p}_{ij}\right)}} \quad (7)$$

In a panel data model, such as

$$y_{it} = \alpha_{it} + \beta_{it} X_{it} + \varepsilon_{it} \quad (8)$$

The null hypothesis assumes that the error term (ε_{it}) is independent and identically distributed over time and across units, i.e. $Cov(\varepsilon_{it}, \varepsilon_{ij}) = 0$. However, the alternative hypothesis is that the error term may correlate across units. $(Cov(\varepsilon_{it}, \varepsilon_{ij}) \neq 0)$ Whereas the null hypothesis assumes no cross-sectional dependence, the alternative hypothesis assumes that panels are affected by shocks from other panels, which translates to cross-sectional dependence.

F. Unit root

The presence of cross-sectional dependency and heterogeneity demeans the use of first-generation unit root criteria. Several unit root criteria that use orthogonalization-type procedures to asymptotically eliminate cross-sectional dependence of series have been proposed [73] [74] [75]. Instead of building unit root tests on deviations from estimated factors, standard panel unit root tests are now constructed on the simple averages of the individual cross-sectionally augmented ADF statistics represented as (CADF), and an improved version of the *t-bar* test proposed by [76], denoted as CIPS [77], respectively, as follows;

$$\Delta y_{it} = \alpha_i + \varphi_i y_{it-1} + \rho_1 \bar{y}_{t-1} + \partial_i \Delta \bar{y}_t + \varepsilon_{it} \quad (9)$$

Another possibility is to consider the cross-sectional augmented version of IPS based on

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$$CIPS(N,T) = tbar = N^{-1}\sum_{i=1}^{N} ti(N,T) \quad (10)$$

where $ti(N,T)$ is the cross-sectionally augmented Dicky-Fuller statistic for the ith cross-section unit given by the t-ratio of the coefficient y_{it-1} in the CADF regression [77].

Furthermore, the study added a unit root test to check for stationarity of the variables in the face of structural breaks. Structural breaks can misrepresent unit root results as efficient when in reality, they are spurious [78]. [79] The unit root test is used to check for structural breaks. This test tolerates a unit root in the presence of one or more structural breaks in the intercepts or linear trends of the individual variables. The panel data method provides a unique viewpoint to investigate if the presence of unit roots can be incorrectly attributed to the existence of structural breaks, which is not obtained using the single series approaches. The test allows for a short panel experiment. While the null hypothesis assumes that all panel time series are unit root processes, the alternative hypothesis assumes that some panel series are stationary processes.

G. Cointegration

Once the stationarity of variables is confirmed, a natural follow-up is to ascertain the long-run relationship among the variables. To avoid spurious results from first-generation cointegration tests, the study employed the Pedroni and Westerlund cointegration criteria. Thus, the Pedroni test has the advantage of accommodating both homogeneous and heterogeneous panels. It can also be carried out with or without a constant and/or time trend [80]. Additionally, the test can include common time dummies to address simple cross-sectional dependency as follows;

$$\bar{y} = \frac{1}{N}\sum_{i=1}^{N} yit \quad (11)$$

[81]The cointegration test is based on the Durbin-Watson principle to evaluate long-run cointegrating association among variables using the Durbin-Watson panel and DH group statistics [54]. The advantages of the Westerlund criterion include its robustness and the assumption of some cointegrating panels, as opposed to Pedroni's all-cointegrating panels.

IV. Results

Table 2: Summary of statistics

Variable	Mean	Std. dev	Min.	Max
REPRO	1643.620	3589.604	1.000000	14407.00
INCAP	387.1	932.1361	1.000000	4091.000
REDEV	20.9101	32.03718	0.632249	129.3039
INTFL	44.90730	106.7941	0.010000	951.8800
PUBFL	15.62511	8.323198	3.587513	36.14305
INQLY	0.123321	0.640378	-1.154117	1.558621

Source: Authors' regression output

Table 2 presents the descriptive statistics of the dataset. The mean of renewable energy is 1643.62 GWh, and its standard deviation of 3589.60 GWh shows at least a definite average growth of renewable electricity production, but varies significantly among the Sub-Saharan African countries. The maximum renewable energy production of 14407 GWh indicates a significant improvement in renewable energy production in some countries, like Zambia, Nigeria, and Uganda, whereas the minimum value of 1.00 GWh explains very low renewable energy in some countries, such as Benin and Guinea-Bissau. Installed capacity has a mean of 387 MW and a standard deviation of 932.136. This shows a diverse amount of installed capacity of renewable energy in the region. The maximum installed capacity of 4091 MW and the minimum of 1.0 MW suggest a great variation among the countries. The mean and standard deviation of research and development in technology are 20.91101 and 32.03718, respectively. This suggests that the average level of research activity in the region is low and has a high variance. This is confirmed with 0.63225 annual research in some countries compared to 129.304 in other countries. International financial flows for renewable energy development in the region also vary significantly, with an average of $44.91 and a standard deviation of $106, respectively. International financial flow to some countries rose to $951.88 M, while some were as low as $ 0.01 M. Public finance in the region also varies significantly, with a mean of 15% of GDP as public expenditure and a deviation of 8.3%. The 36% maximum and 3.5% minimum show that public expenditure is significantly high in some countries and significantly low in other countries. With an average of 0.12, a minimum of -1.15, and a maximum of 1.5, respectively, Sub-Saharan

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Africa has a relatively low institutional quality for developing renewable energy. The -1.5 value suggests countries with very weak institutions, while the 1.5 value shows countries with strong institutions.

Table 3: Correlation matrix

Variable	LREPRO	LINTFL	PUBFL	INQLY	LREDEV	LINCAP
LREPRO	1.0000					
LINTFL	0.3121	1.0000				
PUBFL	-0.0602	-1.1443	1.0000			
INQLY	-0.3807	-0.4093	0.0752	1.0000		
LREDEV	0.1851	0.1359	0.1582	-0.0583	1.0000	
LINCAP	.9762	0.3471	-0.758	-0.3952	0.2636	1.0000

Source: Author's regression output

The correlation matrix is presented in Table 3. It reveals a positive but relatively weak association between LREPRO and LINTFL, and LREDEV, as well as a negative and moderate association between LREPRO and PUBFL, and INQLY. The matrix, however, shows a strong and positive correlation between LREPRO and LINCAP.

Table 4: Cross-sectional dependency and heterogeneity tests

Cross-Sectional Dependency					
LREPRO	LINCAP	LREDEV	LINTFL	PUBFL	INQLY
29.699***	57.166***	34.2***	1.363	5.938***	3.82***
Slope Heterogeneity Test					
Delta	3.456***	*Adj.*	6.331***		

Source: Author regression output; Note *** p<0.01, ** p<0.05, * p<0.1

The cross-sectional dependency test is shown in Table 4. From the test, we reject the null hypothesis of cross-sectional dependency and subscribe to the alternative of no cross-sectional dependency, suggesting that error terms are not correlated across the cross-sectional units. The slope heterogeneity test using both the delta and adjusted delta indicates the presence of heterogeneity, meaning that the relationship between the dependent and independent variables is not the same across all the groups or periods.

Table 5: Pedroni and Westerlund cointegration tests

Pedroni	Westerlund
Modified Phillips–Perront(8.6678)***	Variance ratio (3.0493)***
Phillips–Perront(-4.7344)***	
Augmented Dickey–Fuller t(-5.7259)***	

Source: Authors regression output; Note: *** p<0.01, ** p<0.05, * p<0

With the order of integration ascertained, the cointegration test becomes essential to confirm the long-run relationship among the variables, which is necessary for consistent and unbiased long-run estimation. The Pedroni and Westerlund test reveals that the three criteria, including the variance ratio, confirmed cointegration among the variables.

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Table 6: CIPS and CADF unit root tests

CIPS			CADF	
Variables	**Level**	**First Diff.**	**Levels**	**First Diff.**
LREPRO	(-2.539) ** -2.16	-	(-2.184) ** -2.16	-
LINCAP	-	(-2.499) ** -2.16	-	(-2.762) ** -2.16
LREDEV	(-3.318) ** -2.16	-	(-3.390) ** -2.16	-
INTFL	(-3.386) ** -2.16	-	-	(-4.823) ** -2.16
PUBFL	(-2.819) ** -2.16	-	-	(-2.427) ** -2.16
INQLY	(-2.350) ** -2.16	-	-	(-2.361) ** -2.16

Source: Author regression output; Note: *** p<0.01, ** p<0.05, * p<0.1 with c values in parenthesis

The CIPS unit root test shows that LREPRO, LREDEV, INTFL, PUBFL, and INQLY demonstrated stationarity and significance at the level, while LINCAP contained a unit root process but demonstrated stationarity and significance after transformation at first difference. The CADF test, on the other hand, indicates that only LREPEO and LREDEV were stationary and significant at the level, while LINCAP, INTFL, PUBFL, and INQLY contained unit processes at the level but were stationary and significant at first difference. Both criteria confirmed the stationarity and significance of LINCAP after transformation. It further confirmed the stationarity and significance of all variables at a 5% confidence level.

Table 7: Taravias and Tzavalis panel unit root test with structural breaks

Variable	Z Stat	Bootstrap Breaks	Val.
LREPRO	-0.0477	-0.1153	-
ΔLREPRO	-0.5824**	-0.3968	2021
LINCAP	-0.0161	-0.0319	-
ΔLINCAP	-0.3526**	-0.1428	2021
LREDEV	-0.0388**	-0.0383	2018
INTFL	-11.0645***	-2.1360	2022
PUBFL	-0.9122	-2.0511	-
ΔPUBFL	-2.6114***	-1.7642	2020
INQLY	-0.4625***	-0.2356	2018

Source: Authors regression output; Note: *** p<0.01, ** p<0.05, * p<0.1

Table 7 presents the panel unit root test with structural breaks. We found a majority of the breaks occurring during and after the COVID-19 pandemic, with breaks in institutional quality, research, and development in technology occurring before the pandemic. The result further indicates that unit root processes are mostly contained in Renewable Energy production, Installed capacity of renewable energy, and public finance. However, the series became stationary after the transformation.

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Table 8: Method of moments Quantile Regression

	Lower Quantile		Medium Quantile		Upper Quantile				
LREPRO	0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90
LINCAP	1.143***	1.166***	1.169***	1.168***	1.170***	1.162***	1.155***	1.115***	1.053***
	(0.0364)	(0.0266)	(0.0155)	(0.0124)	(0.0126)	(0.0164)	(0.0180)	(0.0162)	(0.0198)
LREDEV	-0.282***	-0.152***	-0.0961***	-0.0952***	-0.0940***	-0.141***	-0.171***	-0.168***	-0.132***
	(0.0617)	(0.0451)	(0.0262)	(0.0210)	(0.0213)	(0.0278)	(0.0305)	(0.0274)	(0.0334)
LINTFL	-0.00932	-0.00528	-0.00196	0.00433	0.00589	0.00640	-0.00487	-0.0159	-0.0185
	(0.0286)	(0.0209)	(0.0121)	(0.00974)	(0.00988)	(0.0129)	(0.0141)	(0.0127)	(0.0155)
PUBFL	0.0130***	0.00575*	0.00659***	0.00751***	0.00629***	0.00678***	0.00372	0.00355*	0.00400
	(0.00468)	(0.00342)	(0.00199)	(0.00159)	(0.00162)	(0.00211)	(0.00231)	(0.00207)	(0.00254)
INQLY	0.00683	0.00413	0.0323	0.0339*	0.00167	-0.0127	0.00439	0.00784	-0.0272
	(0.0553)	(0.0404)	(0.0235)	(0.0188)	(0.0191)	(0.0249)	(0.0273)	(0.0245)	(0.0300)
Constant	-0.0390	0.0296	0.0170	0.0435	0.0966**	0.204***	0.369***	0.539***	0.716***
	(0.116)	(0.0847)	(0.0492)	(0.0395)	(0.0400)	(0.0521)	(0.0573)	(0.0514)	(0.0628)
Ps R2	79	82	82	82	82	81	80	79	77

LREPRO= log of Renewable Energy Production; LINTFL= log of International financial flows for renewable energy production; PUBFL Public expenditure; LINCAP= log of installed capacity; INQLY= Institutional quality; LREDEV= log of research and development. Standard errors in parentheses
Source: Author regression output; Note: *** p<0.01, ** p<0.05, * p<0.1

The study's outcome in Table 8 reveals that the installed capacity of renewable energy is a highly significant and increasing function of renewable energy production in all quantiles of sub-Saharan Africa. It shows an average improvement of 1.5% on renewable energy given any 1% addition to install capacity across all quantiles. This outcome is supported by [48] [20] [16] [4] [82], who identified technology and technological improvement as pivotal in driving renewable energy and environmental sustainability in QUAD, 27 EU, and developing countries. The study adopts these results on the assumption that the state of technology determines the installed capacity of a nation. On the contrary, shock to research and development in technology has a significant damping effect on renewable energy production in all of sub-Saharan Africa. It stands that 1% upsurge in the number of persons involved in research and development translates to an average of a 0.1% slump in renewable energy production across the quantiles. Again, our result is reinforced by (Mentel et al., 2022), who found research and development detrimental to environmental sustainability in 26 countries. Except for a few in the medium and upper quantiles, institutional quality enhanced renewable energy production in SSA. 1% increase in institutional quality has an average insignificant positive impact of 0.008% on the renewable energy production of all the countries. The findings of [49] [23] strengthen our findings on countries of high renewable energy production and weaken them on countries of low production. International financial flows reveal mixed results. It strangulates renewable energy production in low and high renewable energy-producing countries but increases it in medium renewable energy-producing countries. 1% increase in international financial flow reduced renewable energy production in countries with low production capacity by 0.005% and 0.12% in countries with high production capacity. International financial flow, however, improved energy production by a modest 0.005% [83] [84].

From the foregoing, the study states that installed capacity meets the study's expectation, whereas research and development contradict the expectation. Both international financial flows and institutional quality conform to theory in some quantiles and show a contradiction in some quantiles. Possible explanations for such disconformity and agreement have been outlined in the discussion section.

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Table 9: Driscoll-Kraay standard error robustness test

Drisc/Kraay				
LREPRO	Coefficient	Std. Error t-Stat	Prob. Value	
LINCAP	1.155535***	.0112013	103.16	0.000
LREDEV	-.1723675***	.0107946	-15.97	0.000
LINTFL	-.0200135 *	.0096898	-2.07	0.069
PUBFL	.0042605***	.0006469	6.59	0.000
INQLY	.0053755	.0293989	0.18	0.859
CONS	.2595317***	.043345	5.99	0.000
R2	95.9	F stat. 79864.14	Prob. 0.0000	

Source: Authors regression output; Note: *** p<0.01, ** p<0.05, * p<0.1

The Driscoll-Kraay robustness outcome in Table 9 confirms the significant improvement in renewable energy production in all Sub-Saharan African countries via the installed capacity of renewable energy. It further confirms the significant drop in renewable energy in all countries despite a surge in research and development in technology. International financial flows improved renewable energy production only in countries in the medium quantile, whereas the financial flows hurt renewable energy production in low and high-energy-producing countries. Except for a few high renewable energy-producing countries, institutional quality significantly increased energy production in the region.

A. Discussions

The significant contribution of installed capacity to renewable energy production in Sub-Saharan Africa within this period could be attributed to the urge to respond to the UN 2030 clean energy declaration. It could also be ascribed to the need and quest for industrialization and development of the region. On the other hand, the significant downturn in energy production resulting from an upturn in research and development could be credited to an insufficient number of researchers, inadequate funding, and a lack of encouragement to researchers and research institutions. It could also be a function of the lack of implementation of research findings due to poor public management and weak institutions. Two possible reasons may be responsible for the insignificant improvement of energy production in the medium quantile, and the decline in the low and upper quantiles despite international financial flow for clean energy. First may be for reasons that border on misappropriation, and second may be insufficiency of the funds. Possible explanations for insignificant positive contribution and even downturn in renewable energy credited institutional quality could greatly be heaped on weak governance, poor rules and policy implementation, corruption, etc.

B. Conclusion

The study focused on evaluating drivers of renewable energy production in 37 Sub-Saharan African countries as a trajectory to meeting SDG 7 in 2030. The study introduced novel variables, including installed capacity of renewable energy, research and development on technology, international financial flows for clean and affordable energy, and institutional quality. Utilizing a novel method of estimation, we conclude that the installation capacity of renewable energy and institutional quality are major driving mechanisms of renewable energy production in SSA.

C. Recommendations

To migrate to clean and affordable energy in 2030, Sub-Saharan African nations will have to intensively stick to energy policies aimed at increasing their installed capacities. A pronounced way of achieving this will be a conscious investment in the renewable energy sub-sector, and a concerted commitment to de-emphasize fossil energy use. Strong institutions are required to secure energy installations and to ensure a robust legal environment for business transactions. Appropriation of international financial flows into renewable energy projects can also be enhanced via quality institutions. Renewable energy policies should be extended to increase the magnitude of research and development in technology in the region.

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D. Limitations

Given the multidimensionality of renewable energy and sustainable development, this study did not cover all areas. For instance, factors such as international influences, international remittances, and culture are relevant factors that could drive renewable energy in Sub-Saharan Africa. This study could not capture all Sub-Saharan African countries due to consistency and data availability. A study that will capture all the Sub-Saharan countries and all African countries will boost renewable energy literature in the region, even though this present study is very relevant, having studied 37 out of the region's 49 countries.

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Declaration of Interest Statement:
The authors have no conflict of interest.

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