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Globalization, non-renewable energy consumption and carbon dioxide emissions in Sub-Saharan Africa

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Abstract **-** This study examines the effects of globalization and non-renewable energy consumption on carbon dioxide emissions within the framework of the Environmental Kuznets Curve (EKC) hypothesis in Sub-Saharan Africa (SSA). The research focuses on 21 countries using panel data covering the 1990-2022 period. Two estimation techniques are employed: Panel-Corrected Standard Errors (PCSE) and Feasible Generalized Least Squares (FGLS) for robustness checks and a comparative analysis across SSA sub-regions. The variables of interest include carbon emissions (measured in metric tons per capita), non-renewable energy consumption (measured in kg of oil equivalent per capita), and the multidimensional globalization index from the KOF Swiss Economic Institute. The results reveal that only the EKC hypothesis applied to globalization, with a turning point equal to 3.9, is validated in SSA. The EKC hypotheses applied to non-renewable energy and to the interaction variable (non-renewable energy and globalization) are not convincingly confirmed, as their turning points in the non-linear relationships exhibit high variability and a wide confidence interval. Only the globalization index confirms the EKC hypothesis across the Western, Central, Eastern, and Southern sub-regions of SSA.

JEL Classification
F18, Q43, Q53, O55, C23

Keywords
Globalization
Non-renewable energy
Carbon emissions
Sub-Saharan Africa
PCSE method
FGLS estimation

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INTRODUCTION

The issue of CO_2 emissions has been the subject of particular attention since global warming and other environmental problems (pollution, deforestation, loss of biodiversity, etc.) have become prominent (IPCC, 2018; Barua and al., 2022). As CO_2 emissions are caused by the consumption of non-renewable energy, trade, transport logistics and industrialisation, analyzing the relationship between globalization, non-renewable energy and CO_2 emissions aims to improve the quality of the environment, which is becoming a major concern for nations and the world (IPCC, 2018). CO_2, one of the main GHGs, contributes to the phenomenon of climate change and its impacts. Therefore, to address climate change, it becomes imperative to understand its contributing factors (one of which is carbon dioxide (CO_2) emissions). The sources of carbon emissions are mainly from the burning of fossil fuel in a productive system with active power generation, transport, residential, and industrial sectors (IPCC, 2018). Non-renewable energy, economic growth, and globalization are the identifed drivers of carbon emissions (Dogan and Aslan, 2017; Shahbaz and Sinha, 2018; Murshed and Dao, 2020; Parker and Bhatti, 2020; Adeleye and al., 2021b; Eregha and al., 2021; Shakib and al., 2022; Awan and Azam, 2022*).* Non-renewable energy consumption refers to the use of energy sources that do not regenerate on a human timescale and are generally derived from fossil or nuclear resources. The non-renewable energy includes: (i) Fossil fuels: Oil (Used for transport, heating and electricity generation.), Coal (Mainly used for electricity generation and in certain industries) and Natural gas (Used for heating, electricity generation and as a raw material in the chemical industry), (ii) Nuclear energy (Uses uranium or plutonium as fuel to generate electricity through nuclear fission).

These components not only alter the earth's atmosphere but also emit varieties of pollutants that negatively affect human health (Atasoy, 2017; IPCC, 2018; Barua and al., 2022). Hence, with the danger posed by increasing emissions, most developing economies are primarily saddled with the seemingly impossible task of curbing emissions amidst achieving steady economic growth and unhindered energy supply. Environment degradation, is precipitated by the enormous amount of carbon dioxide produced by the use of renewable and non-renewable energy sources in a bid to produce goods and services for human's consumption (Akadiri and al., 2020; Liu and al., 2020; Rahman, 2020; Aluko and al., 2021; Mughal and al., 2021). Globalization, in the positive sense, promises less restriction in the movement of people, capital, goods and services, technology and culture etc., from one country to another enhancing harmony among people globally (Dong and al., 2018; Sasana and al., 2018; Bataka, 2021). Though, Rahman (2020) and Farooq and al. (2022) report that globalization affects the quality of the environment in various ways. Such an increase in trade and production rises carbon dioxide emission, it also allows for transfer of technology, which does reduce carbon dioxide emission in the long run.

Globalization refers to the process of increasing integration among economies, societies, and cultures on a global scale. This phenomenon leads to an intensification of trade, financial exchanges, human mobility (migration, tourism), and cultural exchanges between different parts of the world, driven in particular by advances in communication and transportation technologies. Consequently, scholars need to account for the many facets of globalization. Composite indicators, such as the KOF

Globalisation Index, are prime examples of this, as they allow different variables, measuring different aspects of globalization to be combined into a single index. Several composite indicators measuring globalization have been proposed. The KOF Globalization Index, introduced by Dreher (2006) and updated in Dreher et al. (2008), measures globalization across economic, social and political dimensions for almost every country in the world since 1970. It has become the most widely used globalization index in the academic literature (Potrafke, 2015). The revised version of the KOF Globalization Index distinguishes between de facto and de jure globalization. Whilst de facto globalization measures actual international flows and activities, de jure globalization measures policies and conditions that, in principle, enable, facilitate and foster such flows and activities. In terms of *economic globalization*, de facto trade is determined on the basis of trade in goods and services. De jure trade covers customs duties, taxes and trade restrictions. *Social globalization* comprises three segments, each with its own de facto and de jure component. Interpersonal contact is measured within the de facto segment on the basis of international telephone connections, tourist numbers and migration. Within the de jure segment, it is measured based on telephone subscriptions, international airports, and visa restrictions. Information flows are determined within the de facto segment based on international patent applications, international students, and trade in high-technology goods. The de jure segment measures access to TV and the internet, freedom of the press, and international internet connections. Cultural proximity is measured in the de facto segment based on trade in cultural goods and international trademark registrations. The de jure segment focuses on civil rights (freedom of citizens), gender equality, and public spending on school education. *Political globalization* pertains to the de facto segment, measured based on the number of embassies and international non-governmental organisations (NGOs), as well as participation in UN peacekeeping missions. The de jure segment includes variables focusing on membership of international organisations and international treaties.

The use of the KOFGL Globalization index is justified by its ability to capture globalization in its multidimensional aspect, going beyond the purely economic indicators traditionally used, such as foreign direct investment or the degree of trade openness. By integrating economic, social, and political components, this index makes it possible to grasp broader channels of influence likely to affect CO_2 emissions, particularly through technological diffusion, institutional interactions, and changes in consumer behavior. Thus, KOFGL offers a more comprehensive and representative measure of the globalization phenomenon under study.

The empirical evidence in favour of climate change mitigation and environmental sustainability is diverse. However, several studies suggest that environmental sustainability can be achieved by reducing carbon dioxide emissions through energy efficiency (Murshed and al., 2022a; Khan and al., 2022), the use of renewable energy (Murshed and al., 2022b; Hamid and al., 2022a), the adoption of nuclear energy (Nathaniel and al., 2021a, b), globalization (Jahanger and al., 2023; Rehman and al., 2022a) and overall domestic consumption. Exploring various factors that exacerbate environmental degradation, the literature review draws on the link between globalization and carbon dioxide emissions (He and al., 2021; Rahman, 2020; Liu and al. (2020); Asongu and al., 2020), as well as panel data (Achuo and al. (2024); Shahbaz and al. (2019a,b); Adeleye and al. (2021a); Neagu and Teodoru (2019)) and time series frameworks (Okoye and al. (2021); Shaheen and al. (2020); Ma and al. (2019); Lin and Raza (2019)).

The objective of this study is to contribute to the empirical debate on whether the use of non-renewable energy, globalization index, and their interaction drive carbon dioxide emissions in Sub-Saharan Africa (SSA). To achieve this, we employ panel data including per capita carbon dioxide emissions, per capita non-renewable energy, the globalization index, the indicator of interaction between non-renewable energy and globalization, and a set of control variables for the period 1990-2022. The study has five subsidiary objectives generally linked to the Environmental Kuznets Curve hypothesis (EKC): (1) Check if the non-renewable energy-Kuznets hypothesis is evident; (2) investigate whether the globalization-Kuznets hypothesis is verified; (3) Check if the interacting variable (combining non-renewable energy consumption and Globalization index) EKC hypothesis holds; (4) determine the turning points and (5) assess whether the results differ significantly from one sub-region to another in Sub-Saharan Africa. To achieve these objectives, we deploy a blend of two estimation techniques: the panel-Corrected Standard Errors (PCSE), and the Feasible Generalized Least Squares (FGLS) for the robustness checks, and the Sub-Saharan Africa subregions comparison analysis. This is one of the main studies to adopt this approach.

Our paper contributes to the literature within the framework of the EKC hypothesis in various ways. Previous literature has focused more on the nonlinear effect of income per capita on CO_2 emissions per capita, than on the nonlinear effects of other variables on CO_2 emissions. Henceforth, the potential nonlinear relationships between globalization, non renewable energy consumption and the CO_2 emissions are compared to those of the benchmark linear model. Thus, the validity of the turning points computed for the nonlinear relationships is analyzed and discussed. Certainly, to the best of our knowledge, few or no studies have undertaken to assess the impact of non renewable energy consumption in globalization (interacting variable) on CO_2 emissions, focusing on SubSaharan Africa and its subregions, using the PCSE and FGLS techniques. This is a significant contribution because the idiosyncrasies of a region (including its economic development) expectedly affect the nature of the globalization, non renewable energy consumption, and CO_2 emissions nexuses. Results uncovered from such an examination will improve our understanding of these phenomena. For the most part, our results are consistent, with significant differences across subregions.

The rest of this study is structured as follows: the first section presents the stylized facts; the second section reviews the literature; the third section outlines the data and methodology; the fourth section analyzes and discusses the results.

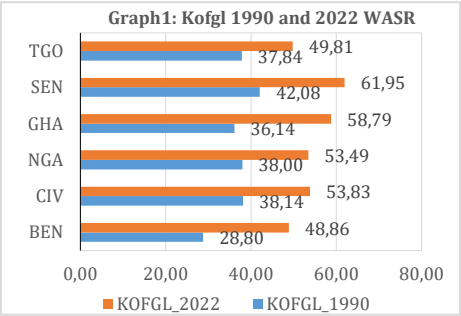
1. STYLIZED FACTS

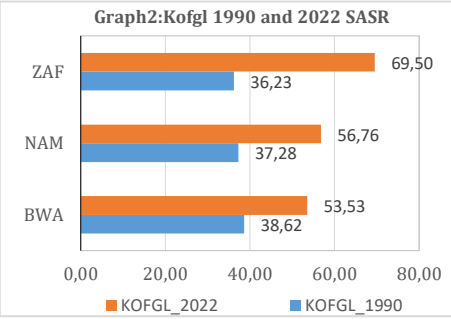
Graphs 1 to 10 present the stylized facts for 1990 and 2022 regarding CO_2 (metric tons per capita) and KOFGL (range from 0 to 100), for countries across the four regional categories of SSA, as well as the regional average for CO_2 emissions and the KOFGL.

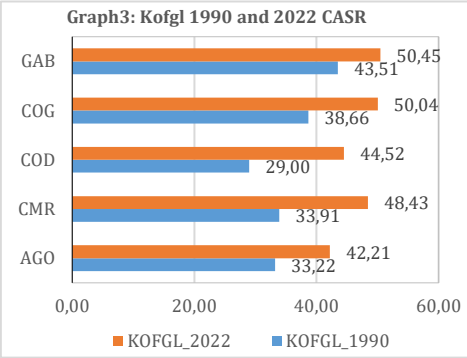
The stylized data on CO_2 emissions are indicative values representing average per capita CO_2 emissions (in metric tons) for 1990 and 2022, for countries across the four regional categories of Sub-Saharan African. In general, Southern Africa region (SASR) has higher values due to the mining industry and fossil fuels. In Central Africa region (CASR), these per capita emissions have been declining. With the exception for the CASR, CO_2 emissions in the regions of sub-Saharan African (SSA) are on the rise. Only four countries (COD, GAB, NGA and ZWE) reported a decrease in per capita CO_2 emissions in 2022 compared with the 1990s.

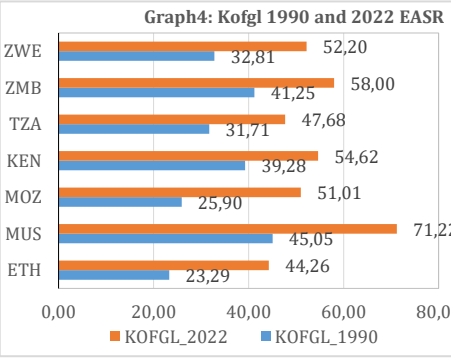
This decrease can be explained by:

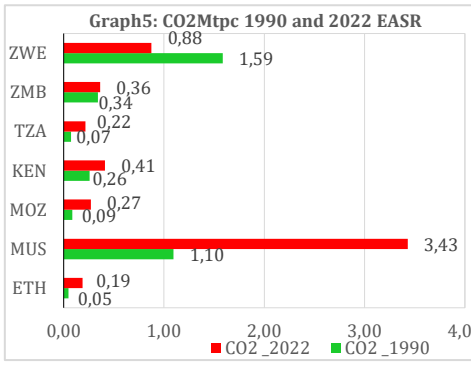
- The reduction of certain industrial and economic activities in a post-conflict or recessionary context, as in the DRC, is a significant factor. The country has experienced armed conflict and political unrest that have slowed industrial and extractive economic activity, temporarily reducing emissions. The closure of highly polluting factories or the reduction of production in certain heavy sectors have contributed to this decrease. In Gabon, the implementation of rigorous forest protection policies and the more sustainable development of its natural resources are helping to reduce its carbon footprint. Both Gabon and the DRC have vast tropical rainforests that act as carbon sinks. Conserving these forests can offset, or even reduce, net CO_2 emissions. If the population increases but total emissions remain stable or decrease, per capita emissions can fall. The development of non-polluting sectors, through a transition to service economies or light agriculture rather than heavy industry, promotes emissions reduction. The same applies to the adoption of policy measures aimed at limiting these emissions, particularly through commitments made under the Paris Agreement, incentives for emission reductions, and sustainable forest management.
- In Nigeria (NGA), despite strong industrial development, fluctuations in oil production, crises, and economic reforms may have temporarily influenced the decline in CO_2 emissions. However, recent efforts to diversify the economy and promote renewable energy are beginning to bear fruit.
- In Zimbabwe (ZWE), the prolonged economic crisis of the 2000s and industrial relocations impacted fossil fuel consumption. Recent policies promoting renewable energy have also played a role.

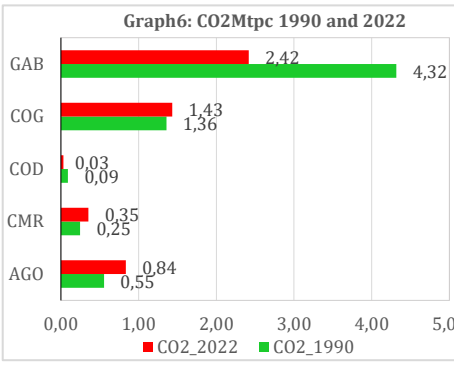


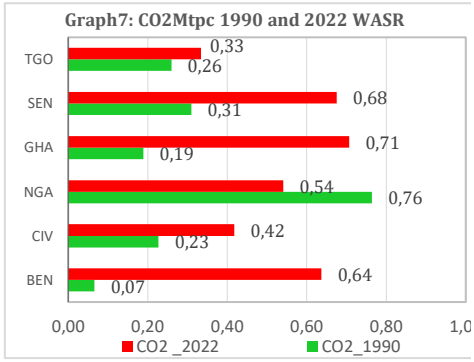


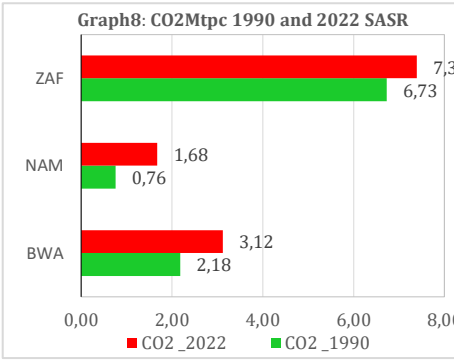


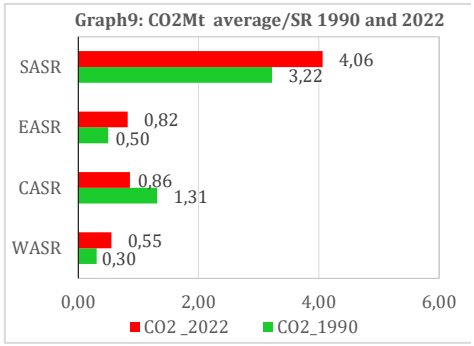


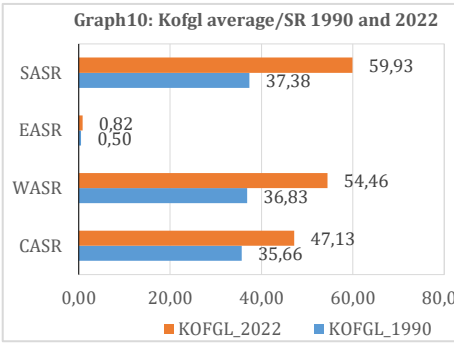












Source : author, on excel. Note: WASR, CASR, EASR and SASR refer to the sub-regions of West, Central, East and Southern Africa respectively.

KOFGL is a composite index measuring economic, social and political globalisation. The indices generally range from 0 to 100, with an upward trend linked to increasing globalization. This trend is more pronounced in the Southern Africa region than in other regions of sub-Saharan Africa (West, Central and East Africa). The values are stylized, based on the general trends observed in these sub-regions.

2. LITERATURE REVIEW

It is important to recall that the present study examines the relevance relationship between globalization, non-renewable energy consumption and CO_2 emissions (a proxy indicator of environmental degradation). Several studies highlighted in this section, have explored different factors aggravating environmental degradation, with varying results, partly due to the scope, the analytical technique, and the choice of control variables. Therefore, without claiming to be exhaustive, the literature on carbon dioxide emissions is reviewed, as well as panel data and time series frameworks.

2.1. Carbon dioxide (CO_2) emissions and globalization studies

Empirical analyses on globalization and carbon dioxide emissions have revealed inconsistent results that are attributable to differences in empirical techniques, variables selection or combination, geographic scope, and timing, among others. For example, He and al. (2021) find that globalization decreases carbon dioxide emissions in the top 10 energy transition economies. Similarly, Rahman (2020) finds an inverse relationship between carbon dioxide emissions and globalization among the top 10 electricity-consuming countries. Liu and al. (2020) report an inverted U-shaped relationship between carbon emissions and globalization for G7 countries. Afridi and al. (2019) report that trade openness as a proxy for globalization, has a negative impact on carbon emissions among South Asian Association for Regional Cooperation (SAARC) economies. Similarly, Asongu and al. (2020) report a modulation of the effect of globalization (trade openness) on carbon dioxide emissions in 44 Sub-Saharan Africa (SSA) countries. Acheampong and al. (2019) find that foreign direct investment mitigates carbon dioxide emissions in SSA. On the contrary, Jun and al. (2021) find a positive association between globalization and carbon dioxide emissions in some South Asian economies. Moreover, Rafndadi and Usman (2019) find that globalization increases carbon dioxide emissions in the short run in South Africa, while reducing them in the long run. Haseeb and al. (2018) find a negative and insignificant relationship between globalization and carbon dioxide emissions in Brazil, the Russian Federation, India, China, and South Africa (BRICS), but Saud and al. (2018) find a negative and significant relationship between globalization and energy demand, which is the main driver of carbon dioxide emissions; again, the result shows unidirectional causality between globalization and energy consumption in China. On the other hand, Yuping and al. (2021) report evidence of globalization reducing carbon emissions, and globalization and renewable energy consumption jointly reduce emissions in Argentina. The findings of Cao and al. (2021) reveal that globalization reduces carbon dioxide emissions in OECD countries. Wang, Rasool and al. (2019) and Wang, Wang and al. (2019) also report unidirectional causality from globalization to carbon dioxide emissions in OECD countries. Khan and al. (2021) find that globalization through FDI can reduce environmental quality by increasing carbon dioxide emissions. Finally, Islam and al. (2021) report that globalization has a negative effect on carbon dioxide emissions in Bangladesh. These empirical findings further reveal an inadequate geographical distribution of the study covering the South Asian region (see Jun and al., 2021), despite the importance of these areas in relation to the effect of globalization and environmental degradation, with a population of more than 1 billion people.

2.2. Panel Data studies

The studies of Eurostat (2020) of 27 member countries, find that carbon emissions are a major contributor to global warming and are responsible for approximately 80% of all human-induced greenhouse gas emissions in the European Union (EU). Achuo and al. (2024) used a data panel of 39 developing African countries from 1996 to 2020 and the system Generalized Method of Moments approach to investigate the effect of resource rents on environmental pollution. The key findings reveal that resource rents significantly contribute to pollution emissions in the context of African economies. However, this relationship is divergent for alternative measures of natural resources and across sub-regional economic blocs. Shahbaz and al. (2019b) used cross-correlation techniques to find that globalization reduces carbon emissions based on a study of 87 countries from 1970 to 2012. The study validates the existence of the Pollution Haven Hypothesis (PHH) for the FDI-emissions and growth-emissions relationships. Adeleye and al. (2021a) used a panel of seven South Asian countries from 1990 to 2019 and three empirical techniques to show that economic growth and non-renewable energy exacerbate carbon emissions, while renewable energy exerts emission-reducing properties. Neagu and Teodoru (2019) use DOLS and FMOLS procedures to show that there is a long-run equilibrium relationship between growth, energy consumption, and greenhouse gas (GHG) emissions in 25 EU countries. The studies of Churchill and al. (2019) on G7 countries from 1870 to 2014 use a non-parametric approach to show that emissions, and research and development have time-varying characteristics. Nguyen and Kakinaka (2019) used panel cointegration techniques in 107 countries from 1990 to 2013 to reveal that renewable energy locks in carbon emissions in high-income countries. Similarly, Shahbaz and al. (2019a) use the generalized method of moments (GMM) technique to examine the association between FDI and carbon emissions for the Middle East and North Africa (MENA) region between 1990 and 2015. Based on the analysis of high, middle, and low-income countries, Azizalrahman and Hasyimi (2019) use the ARDL procedure to find that urbanization and energy consumption are the drivers of carbon emissions in high-income countries from 1973 to 2013. Using the quantile-by-quantile technique, Mallick and al. (2019) find that the poor do not contribute to carbon emissions in the case of BRICS member states from 1980 to 2014. Inglesi-Lotz (2018) uses a non-parametric procedure on the study of BRICS member states from 1990 to 2014 and finds that carbon emissions are reduced with changes in energy and carbon intensity. This result is similar to that of Mahalik and al. (2018) who find that, with the exception of Brazil, coal consumption causes carbon emissions in BRICS member states from 1980 to 2013. Similarly, using a non-parametric approach, Chang and al. (2019) on the analysis of 121 countries show that population growth, energy consumption, economic growth and carbon intensity are the main drivers of emissions from 2000 to 2014. Acheampong (2018) deploys GMM and panel vector autoregressive (PVAR) techniques on a study of 116 countries from 1990 to 2014 to show that there is a causal feedback relationship between emissions/growth and emissions/energy consumption. Moreover, on a study of 17 countries from 1971 to 2013, Sarkodie (2018) deployed fixed and random effects techniques to show that globalization and energy consumption cause carbon emissions in the Granger sense. In the study of 13 Asian countries from 1980 to 2010, Salim and al. (2017) deploy the augmented average group (AMG) approach to show that trade liberalization, urbanization, and renewable energy consumption reduce carbon emissions. The findings of Ozcan's (2013) work based on the FMOLS estimator revealed a U-shaped curve between CO_2 emissions and growth, with a

threshold of 8.23. Stern and Zha (2016) studied the EKC hypothesis for 50 Chinese cities over the period 2013-2014 using both growth rates and traditional EKC models. Overall, according to both approaches, the relationship between pollution and growth shows a U-shaped curve.

2.3. Time series studies

Covering the period from 2005 to 2016, Ma and al. (2019) employ a non-parametric procedure on the relationship between carbon emissions and energy consumption to conclude that economic growth is the main predictor of carbon emissions in China. This result is similar to that of Lin and Raza (2019), who reveal that energy intensity reduces carbon emissions in Pakistan for the period from 1978 to 2017. Similarly, Shaheen and al. (2020) using the ARDL technique, show that in the long run, energy consumption and gross domestic product (GDP) intensified carbon emissions in Pakistan from 1972 to 2014. Salahuddin and al. (2019) employed Zivot-Andrews breakpoint analysis to conclude that urbanization and globalization are the drivers of emissions in South Africa from 1980 to 2017. Similarly, Wang and al. (2019a, b) on China from 1995 to 2014 use ridge analysis to reveal that population, urbanization, and industrialization are driving carbon emissions.

From 1970 to 2017, Sarkodie and Strezov (2018) deploy the dynamic autoregressive distributed lag (ARDL) model to reveal that energy consumption is a positive predictor of carbon emissions in Australia. Using the ARDL approach on Nigeria from 1981 to 2017, Okoye and al. (2021) provide evidence of energy-led growth. On Iran from 2002 to 2013 and using dynamic ordinary least squares (DOLS) and vector error correction model (VECM) procedures, Shabani and Shahnazi (2019) conclude that growth, energy consumption, and information technology are the drivers of carbon emissions. Similarly, Li and al. (2019) use fixed and random effects models to conclude that urbanization, agro-technology, and information technology are the main drivers of carbon emissions.

In the study of Saudi Arabia from 1990 to 2015, Omri and al. (2019) use Fully Modified Ordinary Least Squares (FMOLS) and DOLS to conclude that trade openness, financial development, and foreign direct investment (FDI) are the main contributors to carbon emissions. In the same vein, Yang and al. (2018) use ARDL to find that trade openness and urbanization drive emissions in China from 1995 to 2014. Sarkodie and Strezov (2018) conclude using FMOLS and DOLS, that renewable energy blocks emissions in Australia from 1974 to 2013. Shahbaz and al. (2018) also use ARDL to find that globalization, energy consumption, and economic growth exacerbated emissions in Japan from 1970 to 2014. In Kuwait, Salahuddin and al. (2018) deploy ARDL, VECM, and DOLS to find that the main determinants of carbon emissions from 1980 to 2013 are FDI, energy consumption, and economic growth. Zhou and al. (2018) find that FDI induces more carbon emissions in China from 2003 to 2015 using the ARDL technique. Roy and al. (2017) deploy the ridge technique on India from 1990 to 2016 and conclude that energy consumption reduces carbon emissions. Mirza and Kanwal (2017) using VECM and ARDL procedures find a feedback relationship between emissions/growth and emissions/energy consumption in Pakistan from 1979 to 2009. However, Bukhari and Waseem (2017) find a unidirectional causal impact of energy consumption on emissions in Pakistan from 1972 to 2013 using the ARDL approach. Moreover, using the bounds and cointegration techniques of Bayer and Hanck (2013), Okoro and al. (2021) show that

economic growth induces gas activities in Nigeria. Similarly, Khan and al. (2018) deploy the FMOLS technique to find that financial development reduces emissions in India, Bangladesh, and Pakistan from 1980 to 2014.

From 1980 to 2020, Alam (2022) finds that trade and economic growth in Bahrain have a negative relationship with environmental deterioration. In the Oman study, Alam and al. (2022) show that energy consumption and financial development are positive determinants of emissions in Oman from 1972 to 2019, while Hamid and al. (2022b) reveal that foreign direct investment flows, economic growth, and capital investment increase carbon dioxide emissions from 1980 to 2019. Similarly, other time series studies have found significant socioeconomic indicators aggravating environmental degradation.

3. DATA AND METHODOLOGY

This section presents the data and methodology of the study.

3.1. Data

This present study focuses on 21 countries of the Sub Saharan Africa (SSA) and uses data for the period from 1990 to 2022. Two main data sources are used for the study, namely: (i) the World Development Indicators (WDI) of the World Bank and (ii) the data of *KOF Swiss Economic Institute*. The lists of countries sampled from SSA and its sub-regions are provided in Appendix 1, while the variable names, description, sources, and expected signs, are presented in Appendix 2. Appendices 3 and 4 provide relevant information on descriptive statistics and the correlation matrix, respectively.

In accordance with the relevant literature on the subject, the dependent variable that is used to address Environmental quality is *carbon dioxide emissions* (CO_2) measured in metric tons per capita. The main independent variables are *non-renewable energy consumption* (*EnU1*) measured as kg of oil equivalent per capita and *globalization index (KOFGL)*. It should be noted that the interaction variable (EnU_KOF) combines the non-renewable energy and globalization index. *Fossil fuel energy consumption (FEC)* is employed as another proxy indicator in the robustness check of the independent variable (non-renewable energy). Since the conjecture is that non-renewable energy consumption and globalization contribute to rising carbon emissions (Acheampong and al., 2019; Afridi and al., 2019; Asongu and al., 2020; Adeleye and al., 2021a, 2021b; Ansari and al., 2021), we expect positive coefficients. Three main control variables are used in this study, with direct relations to carbon emissions, we name: *Gross Domestic Product per capita (GDPpc)* at constant 2015 US$ (Chontanawat, 2020; Murshed and al., 2020; Adedoyin and al., 2021; Nathaniel and al., 2021a; Akam and al., 2021; Shaari and al., 2021), *annual population growth (POPga)* (Bhat 2018; Işık and al., 2019; Azizalrahman and Hasyimi, 2019; Salahuddin and al., 2019; Adedoyin and Bekun, 2020; Yasin and al., 2020) and *renewable energy consumption (REC)* (Feng and Chen, 2018; Balsalobre-Lorente and al., 2018; Sharif and al., 2019; Khan and al., 2020; Rahman and Velayutham, 2020).

3.2. Methodology

Recalling the relevance relationship between globalization, non-renewable energy, and CO_2 emissions (quality of environment), our baseline model with CO_2 emission is a linear function of independent and control variables, expressed as:

$$\boldsymbol{LCO2_{it}} = \alpha_0 + \alpha_1 POPga_{it} + \alpha_2 LGDPpc_{it} + \alpha_3 LREC_{it} + \gamma_1 LKOFGL_{it} + \beta_1 LEnU1_{it} + \varepsilon_{it} \quad (1)$$

To verify the first hypothesis on the existence of the non renewable energy Kuznets hypothesis, we include the squared term of non-renewable energy (EnU^2) in specification (1):

$$\boldsymbol{LCO2_{it}} = \alpha_0 + \alpha_1 POPga_{it} + \alpha_2 LGDPpc_{it} + \alpha_3 LREC_{it} + \beta_1 LEnU1_{it} + \beta_2 EnU^2{}_{it} + \mu_t \quad (2)$$

To check the second hypothesis on the evidence of the Kuznets curve for globalization in Sub-Saharan Africa, the squared term of the globalization index ($KOFGL^2$) is incorporated into specification (1):

$$\boldsymbol{LCO2_{it}} = \alpha_0 + \alpha_1 POPga_{it} + \alpha_2 LGDPpc_{it} + \alpha_3 LREC_{it} + \gamma_1 LKOFGL_{it} + \gamma_2 KOFGL^2{}_{it} + \eta_{it} \quad (3)$$

In order to verify whether Kuznets' hypothesis on non-renewable energy through the consumption of fossil fuels energy remains valid, linear and squared variables (FEC^2) are incorporated into specification (1).

$$\boldsymbol{LCO2_{it}} = \alpha_0 + \alpha_1 POPga_{it} + \alpha_2 LGDPpc_{it} + \alpha_3 LREC_{it} + \theta_1 LFEC_{it} + \theta_2 FEC^2{}_{it} + \tau_{it} \quad (4)$$

To test the hypothesis based on the Kuznets curve for the combined variables of globalization and non-renewable energy in Sub-Saharan Africa, the linear and quadratic terms of the interacting variable are incorporated into specification (1).

$$\boldsymbol{LCO2_{it}} = \alpha_0 + \alpha_1 POPga_{it} + \alpha_2 LGDPpc_{it} + \alpha_3 LREC_{it} + \varphi_1 EnU_KOF_{it} + \varphi_2 EnU_KOF^2{}_{it} + \xi_{it} \quad (5)$$

where $LCO2_{it}$ is per capita CO_2 emissions. EnU_KOF_{it} is the interacting variable that allows us to estimate the combined effect of non-renewable energy and globalization on CO_2 emissions. $EnU_KOF^2{}_{it}$ is the square of the interacting variable. *LEnU1* is the non-renewable energy per capita, and EnU^2 is the square of non-renewable energy per capita. *LKOFGL* is the globalization index, and $KOFGL^2$ is the square of globalization index.

The control variables are as: $LGDPpc_{it}$ is the per capita GDP ; $POPga_{it}$ is the annual population growth ; $LREC_{it}$ is the renewable energy consumption ; $LFEC_{it}$ is another proxy of the non-renewable energy employed for the robustness check purpose, and $FEC2_{it}$ is the squared term of fossil fuel energy consumption ($LFEC_{it}$). β_i , γ_i , θ_i *and* φ_i are the parameters to be estimated; ε_{it} , μ_{it} , η_{it} , τ_{it} *and* ξ_{it} are the error terms. The subscript *i (i = 1…N)* denotes the countries, and the subscript t *(t =1…, T)* denotes the period.

To evaluate the core hypothesis of the study, specifications (2) to (5) assume similarity for the parameters β_1, β_2 , γ_1 , γ_2 , θ_1 , θ_2 , φ_1 *and* φ_2 which depend neither on a specifc country nor on the time period. It is assumed that all countries take on the same shape of the functional relation of the CO_2 emissions and

non-renewable energy, CO_2 emissions and globalization, and CO_2 emissions and interaction variable paradox. More importantly, specifications (2) to (5) permit the evaluation of different forms of CO_2 emissions and non-renewable energy, CO_2 emissions and globalization, and CO_2 emissions and interaction variable relationships. For instance, with respect to:

LEnU1 (Non-renewable energy consumption)

No relationship	$if\ \beta_1 = \beta_2 = 0$ $there\ is\ no\ relationship$	
Linear Relationship	• $if\ \beta_1 > 0\ et\ \beta_2 = 0$ $positive\ linear$ ➢ Linear model	• $if\ \beta_1 < 0\ et\ \beta_2 = 0$ $negative$ linear
Nonlinear Relationship	• $if\ \beta_1 > 0$ et $\beta_2 < 0$ inverted U shaped ($EKC\ hypothesis$) ➢ Square model, $Turning\ Point$: $\hat{x} = \boldsymbol{exp}^{-(\beta_1/2\beta_2)}$	• $if\ \beta_1 < 0$ et $\beta_2 > 0$ $U\ shaped$

LKOFGL (Globalization index)

No relationship	$if\ \gamma_1 = \gamma_2 = 0$ $there\ is\ no\ relationship$	
Linear Relationship	• $if\ \gamma_1 > 0\ et\ \gamma_2 = 0$ $positive\ linear$ ➢ Linear model	• $if\ \gamma_1 < 0\ et\ \gamma_2 = 0$ $negative$ linear
Nonlinear Relationship	• $if\ \gamma_1 > 0$ et $\gamma_2 < 0$ $inverted\ U\ shaped$ (EKC hypothesis) ➢ Square model, $Turning\ Point$: $\hat{x} = \boldsymbol{exp}^{-(\gamma_1\ /\ 2\gamma_2)}$	• $if\ \gamma_1 < 0$ et $\gamma_2 > 0$ $U\ shaped$

LFEC (Fossil fuel consumption)

No relationship	$if\ \theta_1 = \theta_2 = 0$ $there\ is\ no\ relationship$	
Linear Relationship	• $if\ \theta_1 > 0\ et\ \theta_2 = 0$ $positive\ linear$ ➢ Linear model	• $if\ \theta_1 < 0\ et\ \theta_2 = 0$ $negative$ linear
Nonlinear Relationship	• $if\ \theta_1 > 0$ et $\theta_2 < 0$ inverted U shaped (EKC hypothesis) ➢ Square model, $Turning\ Point$: $\hat{x} = \boldsymbol{exp}^{-(\theta_1/2\theta_2)}$	• $if\ \theta_1 < 0$ et $\theta_2 > 0$ $U\ shaped$

EnU_KOF (Interacting variable)

No relationship	$if\ \varphi_1 = \varphi_2 = 0$ $there\ is\ no\ relationship$	
Linear Relationship	• $if\ \varphi_1 > 0\ et\ \varphi_2 = 0$ $positive\ linear$ ➢ Linear model	• $if\ \varphi_1 < 0\ et\ \varphi_2 = 0$ $negative$ linear
Nonlinear Relationship	• $if\ \varphi_1 > 0$ et $\varphi_2 < 0$ $inverted\ U\ s\square aped$ (EKC hypothesis) ➢ Square model, $Turning\ Point$: $\hat{x} = \boldsymbol{exp}^{-(\varphi_1/2\varphi_2)}$	• $if\ \varphi_1 < 0$ et $\varphi_2 > 0$ $U\ shaped$

Source: author's conception.

- **Estimation approach**

The cross-sectional dependence test is employed to identify the appropriate procedures to use at the beginning of the empirical analysis across the countries. The risk of cross- sectionally dependent panels is very high due to the close proximities of the units and given the possibility of sharing common features. In the event of Cross-Sectional Dependence (CSD) in the data, biased estimates and inferences will occur (Pesaran, 2004). To forestall such, the study engages the Pesaran (2004, 2007) test for Cross-Sectional Dependency (CSD) which can be applied to small and large panels. The null hypothesis of no Cross Sectional Dependence which can be rejected at the 1%, 5%, and 10% significance levels is formulated as:

$$CD = \sqrt{2T/N(N-N)}\,.\left(\sum_{i=1}^{N-1}.\sum_{k=i+1}^{N}\hat{\rho}_{i,k}\right)$$

To prevent erroneous findings in the case of cross-sectional dependence, the data is put through second-generation unit root testing. Pesaran's (2007) cross-sectional augmented Im, Pesaran, and Shin (CIPS) test is used. The CIPS test, which is the augmented variant of Im and al. (2003) unit root test, is expressed as:

$$CIPS(N,T) = \bar{T} = N^{-1}\sum_{i=1}^{N} t_i(N,T)$$

where *N* and *T* are the numbers of cross-sections and years, respectively. *CIPS (N, T)* is the unit root test for heterogeneous panels, while the term t_i is the ordinary least squares (OLS) t-ratios employed in cross-sectional averaged augmented Dickey-Fuller (ADF) regression. Thereafter we assess whether a long-run relationship exists among the variables using the second-generation panel cointegration tests proposed by Westerlund (2007). This technique is suitable in the presence of CSD in the data, and the null hypothesis of no cointegration can be rejected at the 1%, 5%, and 10% significance levels. Finally, given the presence of cross-sectional dependence in the data and cointegration among the variables, the Prais-Winsten regression model with Panel- Corrected Standard Errors (PCSE) which also controls for heteroscedasticity and serial correlation is used to estimate all the models. For robustness checks and to observe the consistency of the results, we deploy the Feasible Generalized Least Squares (FGLS) techniques. Given that both PCSE and FGLS techniques pertain to only the conditional mean of the dependent variable, we re-estimate again specifications (2) to (5) using the FGLS technique for the specific analysis of each sub-region (of the Sub Saharan Africa's sample) revealing the complexity of territorial dynamics. We recall that PCSE technique is a static panel data technique suitable for estimating long run analysis. It is applicable when the number of cross sections is less than the time dimension ($N < T$) and controls for cross sectional dependence, autocorrelation and heteroscedasticity.

4. EMPIRICAL ANALYSIS

The empirical results are disclosed in this section. Sub-section 3.1 presents the pre-estimation main information criteria, and the sub-section 3.2 is focused on the estimations results. Prior to discussing the empirical results, it is relevant to clarify the main information criteria used to assess the validity of the empirical estimations.

4.1. Main information criteria

The results from pre-estimations (CSD, Panel Unit Root, and cointegration tests) are presented in Tables 1, 1a and 2. The results of the Pesaran (2004) CD test reject

the null hypothesis of no cross-sectional dependence at the 1% significance level suggesting that any shock in one country may be transmitted to other Sub Saharan Africa countries. To examine the stationarity of the variables, the Pesaran (2007) second-generation unit root test that presumes "cross-sectional dependency" is deployed. The outcomes from both tests indicate that all the variables are stationary after the first difference. The Westerlund (2007) cointegration results (in table 2) indicate that a long- run association among the variables exist.

Table 1: Cross Sectional Dependence (CSD) test

Variable	CD-test	P-value
LCO_2	13.133	0.000
LKOFGL	74.887	0.000
LEnU1	54.468	0.000
LFEC	15.456	0.000
LREC	8.401	0.000
POPga	14.468	0.000
LGDPpc	27.948	0.000

Source: author, on Stata 17.

Table 1a: Stationarity tests of CIPS

Panel Unit Root Test (Pesaran, 2007)						Conclusion
Variable	Trend	Demean		Trend	Demean	
Level				1st Difference		
LCO_2	-4.701***	0.173		-14.991***	-14.545***	I(0) , I(1)
LKOFGL	-4.954***	-3.251***		-14.604***	-14.284***	I(0) , I(1)
LEnU1	-2.211**	1,534		-14.698***	-14.081***	I(0) , I(1)
LFEC	-3.530***	2.676		-14.665***	-14.091***	I(0) , I(1)
LREC	-1.625*	0.636		-14.701***	-14.372***	I(0) , I(1)
POPga	-0.307	-1.270*		-12.992***	-12.793***	I(0) , I(1)
LGDPpc	2.254	5.342		-11.464***	-10.197***	I(1)

*Source: author, on Stata 17. ***, ** and * explain level significance at 1%, 5% and 10%, respectively. Note: I(0) and) I(1) represent the stationarity decision in level and first differences for the variables, respectively. « L » is the natural logarithm, CO_2 is the carbon emission indicating the environmental quality, KOFGL is the globalization index, EnU1 is the non-renewable energy consumption, REC is the renewable energy consumption, FEC is the fossil fuel energy consumption, GDPpc is the the gross domestic product per capita, and POPga is the population growth (annual). The Panel Unit Root Test of CIPS (Pesaran, 2007) is performed using the multi-purt routine.*

The results from both CIPS tests indicate that all variables are stationary after the first difference. The Cross Sectional Dependence test (Pesaran, 2004) reject the null hypothesis(H0) of no cross section dependence at the 1% significance level.

Table 2: Westerlund (2007) cointegration test

	Statistic	P-value
Variance Ratio	-2.595***	0.004
Variance Ratio (with trend)	-1.472*	0.070
Variance Ratio (all panels)	-1.659**	0.048
Variance Ratio (all panels trend)	-1.542*	0.061

*Source: author, on Stata 17. Note: ***, ** and * explain level significance at 1%, 5% and 10%, respectively.*

The significance results of the cointegration test (Westerlund, 2007) at 1%, 5% and 10% levels, indicate the existing of long run relationship among the variables.

4.2. Estimations Results

This subsection analyzes the PCSE estimation results and the predictive turning points of this study. The choice of PCSE techniques is appropriate for the main estimation because they allow standard errors to be adjusted for heteroscedasticity and potential autocorrelation in panel data, thus improving the reliability of statistical inferences. The adjusted errors are robust to various forms of heteroscedasticity and autocorrelation, which are particularly useful in panel data where such concerns are common.

4.2.1. PCSE results analysis

Table 3 displays the results from estimating specifications (1) to (5) using the PCSE technique. Discussions here are restricted to the variables that address the core of the study. We name: globalization index, non-renewable energy, and the interacting variable between non-renewable energy and the Globalization index.

Table 3: PCSE estimation Results

Variables		Dependent variable: Environmental Quality (LCO_2)				
		(1)	(2)	(3)	(4)	(5)
Long run	LREC	-0.888*** (0.052)	-1.104*** (0.079)	-1.709*** (0.051)	-0.470*** (0.117)	-1.034*** (0.071)
	LGDPpc	0.026*** (0.003)	0.016*** (0.005)	-0.0001 (0.004)	0.006*** (0.003)	0.027*** (0.003)
	POPga	0.159*** (0.026)	0.0005 (0.025)	0.048 (0.056)	-0.024 (0.052)	0.232*** (0.054)
	LEnU1	1.105*** (0.054)	2.525*** (0.703)			
	EnU2		-0.1276** (0.053)			
	LKOFGL	1.641*** (0.295)		42.116*** (4.863)		
	KOFGL2			-5.403*** (0.650)		
	LFEC				1.5516*** (0.210)	
	FEC2				-0.08989** (0.042)	
	EnU_KOF					1.0707*** (0.111)
	EnU_KOF2					-0.0156*** (0.002)
	Constant	-9.992*** (1.380)	-6.744*** (2.373)	-75.583*** (8.963	-2.782*** (0.459)	-12.822*** (1.392)
R^2 (%)		72.50	76.46	59.84	75.33	59.84
Observations		692	692	692	692	692
Countries		21	21	21	21	21
Wald test		9253.26***	521.37***	1773***	9895.20***	1773***

*Source: author' computations on Stata 17. ***, ** and * explain level significance at 1%, 5% and 10%, respectively. Student error in (.).*

Specifications (2) to (5) indicate that the results in Table 3 confirm the strength of the substantial and positive long-run relationship between the variables of interest and the dependent variable. Nevertheless, the results are also convincing when fossil fuel energy consumption is used as another proxy indicator in the robustness check of the independent variable « non-renewable energy ». As expected, non-renewable energy upsurges environmental pressure in the Sub-Saharan Africa with a statistically significant relationship of 1% in the long run. This indicates that a unit increase in non-renewable energy use contributes positively to carbon emissions by 2.525 (see specification [2]). The result is similar to the works of Nasreen and al. (2017), Hunjra and al. (2020), and Adeleye and al. (2021a) who found that being reliant on non-renewable energy sources for meeting energy demand induces poor environmental quality (Murshed 2021; Murshed and al., 2022). Thus, Sub-Saharan Africa countries (at their early stage of development) are faced with the hazardous substance that deteriorates human health. Moreover, the square term of the non-renewable energy in relationship with CO_2 emissions is negative, but this relationship has not yet reached the threshold point which validates the inverted U-shaped EKC theory as shown in Fig. 1. This is an implication that SSA countries will attain a threshold point at which the deteriorating impact of dirty energy began to diminish. The predictive turning point is equal to 9.49, above the observed range of LEnU1(see table 3). Attaining this predictive turning point could be attributed to the population's awareness of cleaner energy and its importance in improving quality of life (Sarkodie, 2018).

This finding is in line with Chunyu and al. (2021) who found a positive monotonic energy-emissions relationship. Similarly, the effect of non-renewable energy consumption combined with globalization (EnU_KOF) is positive and statistically significant at 1% in SSA, revealing that a unit increase leads to a rise in CO_2 emissions of 1.070. However, the coefficient of the squared term is negative and significant, with a predictive inflection point above the limit of the EnU_KOF range, which could be reached in the future. This indicates an increasing positive linear relationship (see Figure 1).

With regard to the contribution of the LKOFGL, a unit increase in globalization leads to an increase in carbon emissions of 42.1 at a statistically significant level of 1%. Moreover, the square term of the globalization in relationship with CO_2 emissions is negative, and validates the EKC theory. As shown in Figure 1, the threshold (equal to 3.89) lies between 3.147 and 4.26 of the LKOFGL index (globalization), showing that at the turning point, carbon emissions begin to decline. This implies that in the early stages of its development, Sub-Saharan Africa experiences environmental unsustainability due to globalization. This environmental unsustainability decreases once the threshold is reached. Thus, in the early stages, the result supports the pollution haven hypothesis; thereafter, the halo effect sets in. Furthermore, the increasing positive effect may be due to the relocation of polluting firms from high-income countries, where regulations are strict, to low-income countries, where environmental regulations are less strict (Doytch and Uctum, 2016; Chang and al., 2019). The environmental pressure of globalization is not surprising, as the Sub-saharan Africa countries studied here are low-income countries where pollution is on the rise.

4.2.2. Computations procedure and analysis of Predictive turning points

In general, the various estimates show that non-renewable energy and the globalization index tend to increase CO_2 emissions, thereby damaging the quality of

the environment. As the effect of the square variables of non-renewable energy and globalization index is negative, their relationship with CO_2 emissions reveals the plausible existence of inflection points. These inflection points are computed by nullifying the first derivative of specifications (2) to (5). We have also computed predictive turning points of the interaction variable between non-renewable energy and globalization index, and the Fossil fuel energy consumption (LFEC) is employed as another proxy for the robustness checks of the independente variable. Results are in table 4. The procedure for computing predictive inflection points is expressed as:

- $\frac{\partial LCO2_{it}}{\partial LKOFGL_{it}} = \gamma_1 + 2\gamma_2 LKOFGL_{it} = 0 \quad => LKOFGL_{it} = -\frac{\gamma_1}{2\gamma_2}$
- $\frac{\partial LCO2_{it}}{\partial LEnU1_{it}} = \beta_1 + 2\beta_2 LEnU1_{it} = 0 \quad => \quad LEnU1_{it} = -\frac{\beta_1}{2\beta_2}$
- $\frac{\partial LCO2_{it}}{\partial EnU_KOF_{it}} = \varphi_1 + 2\varphi_2 EnU_KOF_{it} = 0 \; => EnU_KOF_{it} = -\frac{\varphi_1}{2\varphi_2}$
- $\frac{\partial LCO2_{it}}{\partial LFEC_{it}} = \theta_1 + 2\theta_2 LFEC_{it} = 0 \quad => \quad LFEC_{it} = -\frac{\theta_1}{2\theta_2}$

Table 4: Predictive Turning Points of LKOFGL, LEnU1, EnU_KOF and LFEC (Dependente Variable: LCO_2)

Variable	*Turning Point*	*Range*	*Std Error*	*C.I (95%)*
LKOFGL	3.897	[3.147, 4.260]	0.022	3.852 , 3.945
LEnU1	9.892	[5.338 , 8.048]	1.451	7.048 , 12.737
EnU_KOF	34.335	[19.427, 33.519]	1.260	31.864 , 36.805
LFEC	8.630	[0.494, 4.494]	2.762	3.216 , 14.044

Source: Author's computation on stata 17. Note: C.I is the confidence interval at 95%. EnU_KOF is the interactive variable between non-renewable energy and the Globalization index.

To reinforce the validity of Turning Point (TP) analysis in nonlinear relationship, it is essential to evaluate standard errors of the estimated value of the turning point (x < 10% of TP) and to ensure that confidence intervals do not contain insignificant values, such as zero, and remain narrow (ideally less than 20% of the estimated value of the turning point). These criteria ensure the robustness and reliability of the results. Thus, we have:

- *LKOFGL (Globalization index)*

The globalization (LKOFGL) index has a turning point at 3.9, which is within the range, relatively close to its limits. This high precision (extremely low standard error) reinforces the reliability of this threshold. The interpretation is that globalization significantly influences CO_2 emissions in this range. In fact, a rise of the index in the SSA likely corresponds to an increase in emissions. This is explained by the intensification of global trade, capital flows, and industrial activities fostered by globalization. However, beyond this threshold, the effects may become nonlinear or even decrease, possibly due to better technological integration and increased efficiency of industrial processes.

- *LEnU1 (Non-renewable energy consumption)*

The turning point equal to 9.9, is above the observed range, indicating uncertainty about the actual threshold at which the effect of non-renewable energy consumption on CO_2 emissions changes in nature. The high variability shows that

the impact of this variable is complex and can evolve with contextual factors such as energy efficiency and the technologies used. However, the clear trend is an intensification of emissions when non-renewable energy consumption reaches or exceeds this threshold, signaling an increased environmental risk. This finding underscores the need for policies aimed at reducing dependence on these energy sources, particularly in high-consumption economies.

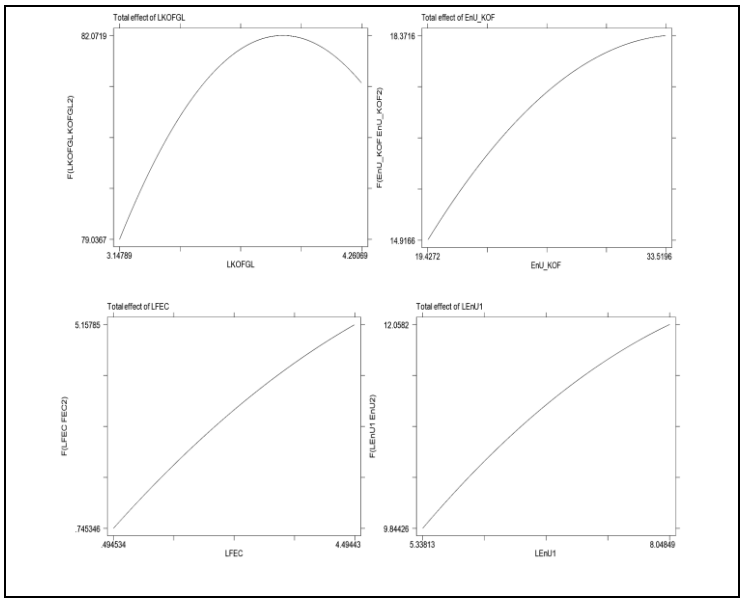
- *EnU_KOF (Interacting variable of EnU1 et KOFGL)*

The turning point of this interaction is significantly above the range, revealing complex dynamics between globalization and non-renewable energy consumption. The significant interaction suggests that globalization exacerbates the positive effect of non-renewable energy consumption on emissions. In fact, high economic openness combined with high consumption of non-renewable fossil fuels can further accelerate the growth of CO_2 emissions, particularly in industrialized or rapidly developing countries. This means that isolated policies targeting a single variable may be insufficient, requiring an integrated approach that takes into account synergies.

- *LFEC (Fossil Fuel Consumption)*

The turning point at 8.63 is above the observed range, indicating uncertainty about the actual threshold at which the effect of fossil fuel energy consumption on CO_2 emissions changes in nature. The high variability shows that the impact of this variable is complex and can evolve with contextual factors such as energy efficiency and the technologies used. Thus, the fossil fuel consumption can't hold EKC assumption because of the high variability and wide confidence interval, making it less reliable.

Figure 1: Curves of LKOFGL, LEnU1, EnU_KOF and LFEC



Source: Author's computations from PCSE technique, on stata 17.

This distribution suggests that environmental policies must absolutely take this variable into account by prioritizing the reduction of fossil fuel consumption. Emissions increase substantially when consumption exceeds this threshold, reflecting unsustainable energy dependence, with a significant impact on international climate goals.

Predictive turning points curves of LKOFGL, LEnU1, EnU_KOF and LFEC from PCSE technique are displayed in figure 1.

Only LKOFGL has a very low standard error and a narrow confidence interval, which reinforces the credibility of this estimate. These characteristics indicate robustness in the estimation of the turning point. The other variables (LEnU1, EnU_KOF, LFEC) have higher standard errors and wider confidence intervals, concluding that they are unstable and less reliable in the context of EKC hypothesis. To resume, the LKOFGL variable is the most reliable and complies with the EKC hypothesis, while the other variables show levels of uncertainty that require further attention.

4.3. Robustness Analysis and other Discussion

This subsection checks the robustness and discusses the specific subregions results of the SSA. The specific analysis of each subregion highlights the complexity of territorial dynamics. For robustness checks, and to observe the consistency of the findings, we deploy the Feasible Generalized Least Squares (FGLS) techniques. In econometric modelling, FGLS models are used to optimize estimation efficiency in regression models. This approach is relevant when errors are either heteroscedastic and/or autocorrelated. In the context of model parameter estimation, FGLS proposes a methodical approach that considers the variance-covariance structure of the errors, it can produce estimates with lower variance. This approach is particularly relevant for improving the accuracy of model coefficient estimates, compared to the PCSE model which is often used to obtain robust standard errors. FGLS allows for the control of specific effects and time trends. PCSE and FGLS are both the statistical tools that can be applied in various panel data analysis contexts.

4.3.1. Robustness Check by FGLS technique

The findings from the robustness checks (table 5) using FGLS techniques are consistent. As expected, non-renewable energy use has a significant impact on the environment in Sub-Saharan Africa, with a statistically significant long-run relationship of 1%. This indicates that a unit increase in non-renewable energy use contributes positively to carbon emissions by 2.56. This is consistent with the works of Nasreen and al. (2017), Hunjra and al. (2020), and Adeleye and al. (2021a), who found that being reliant on non-renewable energy sources for meeting energy demand induces poor environmental quality (Murshed, 2021; Murshed and al., 2022). Thus, SSA countries (at their early stage of development) are faced with hazardous substance that deteriorates human health. Futhermore, the squared term of non-renewable energy in relationship with CO_2 emissions is negative (-0.128), showing the inverted U-shaped EKC with a predicting turning point of about 10. Similarly, the combined effect of non-renewable energy consumption and globalization (EnU_KOF) is positive and statistically significant at the 1% level in Sub-Saharan Africa. This indicates that a unit increase leads to a rise in CO_2 emissions of 0.94.

However, the coefficient of the squared term is negative (-0.014) and significant at the 1% level, showing the inverted U shaped EKC with a predicting turning point of 33.59.

Table 5: FGLS estimation Results

Variables		Dependent variable: Environmental Quality (LCO2)				
		(1)	(2)	(3)	(4)	(5)
Long run	LREC	-0.888*** (0.070)	-1.321*** (0.046)	-1.963*** (0.041)	-0.682*** (0.066)	-1.310*** (0.052)
	LGDPpc	0.026*** (0.003)	0.022*** (0.002)	0.015*** (0.002)	0.011 (0.008)	0.026*** (0.002)
	POPga	0.159*** (0.054)	0.169*** (0.035)	0.193*** (0.042)	-0.011 (0.014)	0.268*** (0.072)
	LEnU1	1.105*** (0.054)	2.564*** (0.630)			
	EnU2		-0.128*** (0.048)			
	LKOFGL	1.641*** (0.181)		32.228*** (3.376)		
	KOFGL2			-4.168*** (0.445)		
	LFEC				1.158*** (0.095)	
	FEC2				-0.085*** (0.020)	
	EnU_KOF					0.939*** (0.072)
	EnU_KOF2					-0.014*** (0.001)
	Constant	-9.992*** (0.907)	-6.050*** (2.011)	-54.781*** (6.334)	-0.961*** (0.351)	-9.132*** (0.933)
Observations		692	692	692	692	692
Countries		21	21	21	21	21
Wald Test		1824.22***	5252.56***	3883***	1461.36***	4776.38***
Turning Point			9.995	3.865	6.814	33.595

Source: Author' computation on stata 17. Note: « L » is the natural logarithm, CO_2 is the carbon dioxide emissions indicating the Environmental quality, KOFGL is the globalization index, EnU1 is the non- renewable energy use, and FEC is the fossil fuel energy consumption, and EnU_KOF is the Interaction variable between non-renewable energy and the Globalization index.

With regard to the contribution of LKOFGL, a unit increase in globalization leads to an increase in carbon emissions of 32.23 at a statistically significant level of 1%. However, the relationship between the squared term of the globalization and CO_2 emissions is negative (-4.17) at a statistically significant level of 1%, validating the EKC theory with the predictive turning point of 3.865. This implies that Sub-Saharan Africa experiences environmental unsustainability due to globalization in the early stages of its development, which decreases once the threshold is reached. Thus, in the early stages, the result supports the pollution haven hypothesis, but thereafter the halo effect sets in. For the LFEC contribution, a unit increase of fossil fuel energy consumption leads to an increase in carbon emissions of 1.16 at a statistically significant level of 1%. However, the relationship between the squared term of the fossil fuel energy consumption and CO_2 emissions is negative (-0.085) at a statistically significant level of 1%, showing the inverted U-shaped EKC with a predicting turning point of 6.81.

The variables LEnU1, LKOFG and the interacting variable (EnU_KOF), as well as their squared terms, have almost the same magnitude and statistically significant effect on CO_2 emissions compared to the main estimates (from PCSE). The findings are also convincing when fossil fuel energy consumption is used as an alternative proxy indicator in the robustness check of the 'non-renewable energy' variable. The selected variables not only retain their signs, but their level of significance appears higher in some cases. This overall validates the previously established main findings in the SSA, and improves the accuracy of model coefficient estimates.

Furthermore, the non-significance of POPga in the model results (Tables 3 and 5), especially when FEC is included, suggests that its effect is partially captured by FEC. This reflects either a close relationship between the two variables or a confounding effect. Consequently, the inclusion of FEC in the model renders POPga insignificant[1].

4.3.2. Subregions specific analysis

Since panel analysis beclouds individual cross-sectional dynamics, Table 6 displays the SSA subregions (West Africa, Central Africa, East Africa, and Southern Africa) findings employing the FGLS technique. Findings from specifications (2), (3), and (5) are mixed. Discussions are restricted to non-renewable energy, globalization, and EnU_KOF (interacting variable).

The effects of the Globalization Index in all four subregions are positive and significant, suggesting that an increase induces a rise in CO_2 emissions by 22.6, 16.01, 27.44, and 15.80 in the West Africa, Central Africa, East Africa, and Southern Africa sub-regions, respectively. However, the coefficients of the squared terms are negative and significant, signifying a nonlinear relationship. Thus, the globalization EKCs hold in all subregions with the respective turning points at 4.04, 3.91, 3.98, and 3.68, which are within their ranges and relatively close to their limits, suggest that when the globalization index for subregions reaches the turning point, CO_2 emissions decline. LKOFGL complies with the EKC assumption in both subregions because their standard errors for the turning points are relatively weak, and their confidence intervals are also narrow.

The effects of non-renewable energy consumption are positive and significant, suggesting that an increase induces a rise in CO_2 emissions by 19.05 and 2.58 in the East and Southern African subregions, respectively. However, the coefficients of the squared terms are negative and significant, signifying a nonlinear relationship. Thus, the non-renewable energy consumption in the Southern Africa subregion can't hold the EKC assumption because of its high variability and wide confidence interval in the turning point computations results, making it less reliable. The non-renewable energy turning point, equal to 12.9, is above the observed range, indicating uncertainty about the actual threshold at which the effect of non-renewable energy consumption on CO_2 emissions changes in nature. The high variability shows that the impact of this variable is complex and can evolve with contextual factors such as energy efficiency and the technologies used. The non-renewable energy turning

[1] The correlation matrix (Appendix 4) reveals a strong correlation between FEC and CO2 (R=0.86), which overrides the direct effect of POPga on CO2 (R=-0.41) and its indirect effect via FEC (R=-0.41 between POPga and FEC). More broadly, disentangling the specific effects of GDP and POP in relation to FEC on CO2 remains challenging; this would warrant an in-depth analysis that falls outside the scope of this paper.

point in the East Africa subregion, equal to 7.31, is significantly above the observed range. The turning point value above 7.1 will start to see a decrease in the rate of increase of CO_2 emissions. The standard error relative to the coefficient value suggests that the estimate is relatively precise.

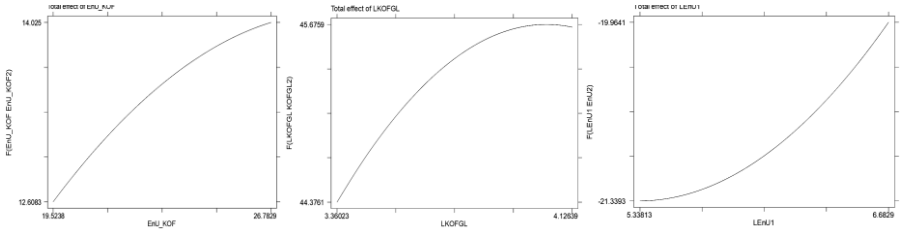
The effects of non-renewable energy consumption are negative and significant, suggesting that an increase induces a decrease in CO_2 emissions by 8.01 and 4.16, respectively, in the West and Central African subregions. This is counterintuitive, as one might expect that increased use of non-renewable energy would lead to higher CO_2 emissions. However, the coefficients of the squared terms are positive and significant, signifying a U-shaped relationship. The west subregion results suggest a complex relationship between non-renewable energy use and CO_2 emissions. The confidence interval for the turning point (equal to 5.33) suggests that there is a statistically significant range where the relationship changes, which is crucial for policymakers and researchers when considering the impacts of energy use on emissions. The non-renewable energy turning point for Central African subregions is equal to 6.66, which is within the range and relatively close to its limits, suggesting that when the non-renewable energy consumption reaches the turning point, CO_2 emissions increase. The non-renewable energy consumption complies with the U-shaped curve because the standard error for the turning point value is relatively weak, and the confidence intervals are also narrow.

The effects of the combined variable (EnU_KOF) are positive and significant, suggesting that an increase induces a rise in CO_2 emissions by 0.97, 0.36, 2.54, and 0.72 in the West, Central, East, and Southern Africa subregions, respectively. However, the coefficients of the squared terms are negative and significant, signifying a nonlinear relationship. The interaction variable turning points for the Central and Southern Africa subregions are 32.32 and 36.73, respectively, which are above the observed ranges, indicating uncertainty about the threshold at which the effect of EnU_KOF on CO_2 emissions changes in nature. The high variability shows that the impact of this variable is complex. Thus, the interaction variable (EnU_KOF) in the Central and Southern Africa subregions can't hold the EKC assumption because of the high variability and wide confidence interval, making it less reliable. For the East Africa subregion, the combined variable with the turning point at 26.33, which is within the range and relatively close to its limits, suggests that when it reaches the turning point, CO_2 emissions decline. EnU_KOF in the East African subregion complies with the EKC assumption because the standard error for the turning points is relatively weak, and the confidence interval is also narrow. With regard to the West Africa sub-region, the EnU_KOF turning point, equal to 28.95, is significantly above the observed range. The turning point value above 26.78 will start to see a decrease in the rate of increase of CO_2 emissions. The standard error relative to the turning point value suggests that the estimate is relatively precise. Above all, only LKOFGL (globalization index) complies with the EKC assumption in all SSA subregions, as it has the lowest standard error and a narrow confidence interval, indicating an accurate estimate. The results of non-renewable energy consumption and the interaction variable in SSA subregions, are mixed.

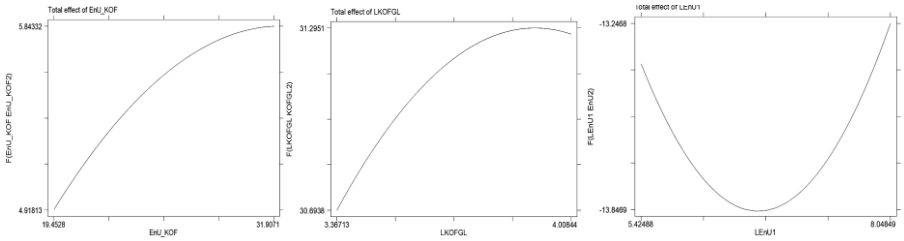
Predictive turning points Curves of LEnU1, LKOFGL, and EnU_KOF of SSA subregions from FGLS technique are displayed in Figure 2.

Figure 2: EnU_KOF, LKOFGL and LEnU1 turning points curves of the SSA subregions

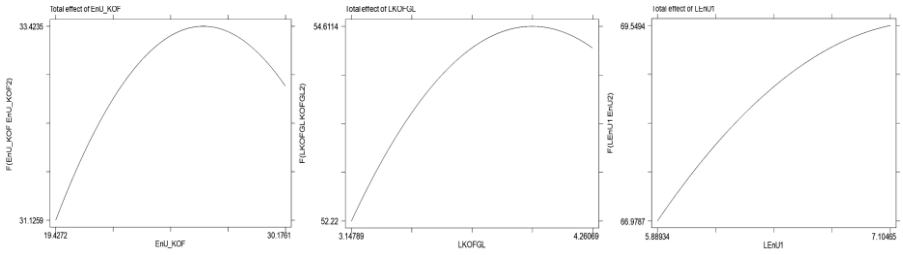
- West Africa subregion predicted turning points curves



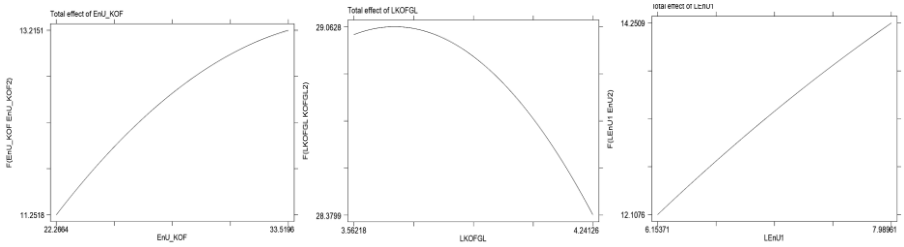
- Central Africa subregion predicted turning points curves



- East Africa subregion predicted turning points curves



- Southern Africa subregion predicted turning points curves



Source: Author's computations from FGLS technique on stata 17.

Table 6: FGLS estimation Findings for SSA sub-regions

Variables		Dependent variable: Environmental Quality (LCO2)											
		West Africa sub region			Central Africa Sub region			East Africa Sub region			Southern Africa Sub region		
		(2)	(3)	(5)	(2)	(3)	(5)	(2)	(3)	(5)	(2)	(3)	(5)
Long-run	LREC	-1.650*** (0.051)	-0.522*** (0.048)	-0.932*** (0.034)	-5.375*** (0.278)	-1.083*** (0.209)	-1.206*** (0.198)	-0.587*** (0.094)	-0.970*** (0.163)	-1.403*** (0.122)	-0.181*** (0.042)	-1.994*** (0.105))	-0.888** (0.149)
	LGDPpc	0.015*** (0.003)	0.011*** (0.0039	0.011*** (0.002)	0.152*** (0.019)	0.114*** (0.014)	0.121*** (0.013)	0.144** (0.060)	0.096* (0.056)	0.072** (0.032)	0.0005 (0.001)	0.023*** (0.005)	0.012*** (0.003)
	POPga	0.300** (0.118)	0.343*** (0.090)	0.005*** (0.097)	2.207*** (0.363)	-0.204 (0.291)	-0.292 (0.262)	0.001 (0.017)	0.327*** (0.075)	0.018 (0.060)	0.002 (0.037)	0.145 (0.112)	0.768*** (0.110)
	LEnU1	-8.007*** (0.966)			-4.161*** (1.551)			19.046*** (4.516)			2.583*** (0.523)		
	EnU2	0.751*** (0.081)			0.312*** (0.118)			-1.303*** (0.347)			-0.100*** (0.037)		
	LKOFGL		22.600*** (3.626)			16.013*** (5.595)			27.436*** (5.428)			15.805*** (4.592)	
	KOFGL2		-2.795*** (0.467)			-2.048*** (0748)			-3.445*** (0.743)			-2.149*** (0.591)	
	EnU_KOF			0.974*** (0.102)			0.361*** (0.144)			2.538*** (0.253)			0.725*** (0.107)
	EnU_KOF2			-0.016*** (0.002)			-0.005*** (0.002)			-0.048*** (0.005)			-0.0098*** (0.0019)
Observations		198	198	198	165	165	165	230	230	230	99	99	99
Constant		26.767***	-44.208***	-10.808***	37.199***	-27.785***	-1.656	-70.303***	-49.043***	-26.662***	-11.679***	-21.080***	-8.868***
Wald test		1255***	650.86***	1727***	1003***	114.42***	314***	326.44***	682.72***	2117***	30876***	1619.02***	1991***
Countries		6	6	6	5	5	5	7	7	7	3	3	3
Computations of the Predictive Turning Point													
Turning Point		5.329	4.042	28.952	6.656	3.908	32.317	7.308	3.980	26.330	12.900	3.677	36.730
Range		[5.338, 6.68]	[3.360 , 4.126]	[19.523, 26.783]	[5.42, 8.048]	[3.367, 4.008]	[19.452, 31.907]	[5.889, 7.104]	[3.147, 4.26]	[19.427, 30.176]	[6.153, 7.989]	[3.562 , 4.241]	[22.266, 33.519]
Std Error		0.073	0.0312	0.984	0.276	0.087	3.119	0.229	0.080	0.429	2.249	0.0679	2.282
C.I (95%)		[5.185, 5.474]	[3.980, 4.103]	[27.093, 30.811]	[6.114, 7.199]	[3.73 , 4.080]	[26.203, 38.432]	[6.859, 7.757]	[3.823, 4.138]	[25.489, 27.17]	[8.491, 17.309]	[3.544, 3.810]	[32.256, 41.204]
Countries		6	6	6	5	5	5	7	7	7	3	3	3

Source: Author' computation on stata 17. Note : C.I is the confidence interval.

4.3.3. Further Discussion

For the mixed results obtained from the subregions specific analysis, we formulate for example, the following lessons.

- Globalization index and carbon dioxide emissions: Existence of an inverted U shaped significant relationship in all SSA sub-regions.

This finding validates the EKC hypothesis on carbon dioxide emissions, and corroborates the results of Liu and al. (2020) work, reporting an inverted U-shaped relationship between carbon emissions and globalization carried out for the G7 countries.

- Non-renewable energy consumption and carbon dioxide emissions: existence of a U shaped significant relationship in Central and West african sub-regions.

This finding validates the work of Ozcan (2013) and Stern and Zha (2016), reporting a U-shaped curve for CO_2 emissions in 12 Middle Eastern countries and 50 Chinese cities respectively, and supports Passet's (1979) ecological approach to « normative management under constraint », which would contribute to the completion and modification of Western societies' relationship with nature. According to this approach, economic development is conditioned by the ecological efficiency of technical progress applied to economic activities (Njomgang, 2005). There would therefore be a pollution threshold above which the deterioration of environmental quality begins. This approach is explained by the nuanced long-run result, during the upward U-shaped relationship between non-renewable energy consumption and carbon dioxide emissions, given that the down-up U shaped relationship is only temporary because, above a certain pollution threshold, carbon dioxide sequestration by the environment (example: oceans, forests and Congo basin) will no longer be able to attenuate the effects. This threshold is considered to be the quantitative levels of extraction from nature and of release into the environment.

The U-shaped curve accurately depicts the nonlinear trajectory of CO_2 emissions in relation to energy and industrial developments in the subregions concerned. Initially, these subregions have limited access to energy, which restricts their use and emissions. This phase is characterised by low energy consumption, generally met by traditional and limited resources, thereby hindering economic and industrial expansion. The gradual adoption of renewable energies is beginning to gain momentum, helping to diversify the energy mix. However, this transition phase is characterised by a dual movement: on the one hand, the introduction of renewable energies increases energy efficiency and reduces the rise in emissions. On the other hand, industrial development often remains heavily dependent on fossil fuels (coal, oil, and gas) which are indispensable.

- Globalization in interaction with Non-renewable energy consumption, and carbon dioxide emissions: existence of an inverted U shaped significant relationship in East africa sub-region.

Globalization index, even when associated with non-renewable energy consumption in East subregion, holds an inverted U shaped relationship with carbon

dioxide emissions. Thus, finding validates the work of Yuping and al. (2021) which reports evidence of globalization reducing carbon emissions, and globalization and renewable energy consumption jointly contribute to lower carbon emissions in Argentina.

Globalization has a wide range of effects on the environmental performance of Sub-Saharan African economies, and these effects vary from one region to another (West, Central, East and Southern) through various mechanisms that lead to positive or negative outcomes. Sub-Saharan African economies, rich in natural resources (minerals, oil, timber, etc.), can benefit from access to international markets. However, this can also lead to overexploitation of resources and environmental degradation, particularly through unsustainable mining and deforestation.

Globalization can facilitate the transfer of green technologies and sustainable practices, such as renewable energy. This can help Sub-Saharan African countries improve their energy efficiency and reduce their carbon footprint. It is also conceivable that environmentally harmful technologies could be transferred, particularly if local rules and regulations are weak in controlling their use.

Globalization is often accompanied by rapid urbanisation and increased consumption, which can exacerbate pressure on natural resources and lead to increased waste and pollution. It can lead to the harmonisation of environmental standards. If Sub-Saharan African countries adopt stricter standards to attract investment or gain access to markets, this can have a positive impact on the environment. However, there is also a risk that some countries may lower their environmental standards to attract foreign investment, which can have negative consequences for local ecosystems.

Globalization facilitates the participation of Sub-Saharan African countries in international environmental agreements, which may encourage them to adopt more sustainable policies and implement environmental protection projects. International cooperation can also provide funding for environmental initiatives, such as combating climate change or conserving biodiversity.

CONCLUSION AND POLICY IMPLICATIONS

This study has examined the effects of globalization and non-renewable energy consumption on carbon dioxide emissions within the framework of the Kuznets hypothesis in Subsaharan Africa. The focus of the research is on 21 countries using panel data from 1990 to 2022. To achieve the five subsidiary objectives, a blend of two estimation techniques is employed: the Panel-Corrected Standard Errors (PCSE) and the Feasible Generalized Least Squares (FGLS) for the robustness checks and the Sub-Saharan Africa subregions comparison analysis. The interest variables are: carbon emissions measured in metric tons per capita, non-renewable energy consumption measured as kg of oil equivalent per capita, and the globalization index. The findings reveal that only the EKC hypothesis applied to globalization with a turning point equal to 3.9 is validated in Sub-Saharan Africa. The EKC hypotheses applied to non-renewable energy and the interactive variable (non-renewable energy and globalization) are not evident, as their turning points (9.89 and 34.33, respectively) in nonlinear relationships show high variability and a wide confidence interval, making them less reliable. For the West, Central, East, and Southern Africa sub-regions in Sub-Saharan Africa, only the globalization index confirms the EKC

hypothesis with the turning points at 4.04, 3.91, 3.98, and 3.68, respectively. For the other variables, the findings are mixed. For example, in the East Africa subregion, the EnU_KOF verifies significantly the EKC hypothesis, while in the Central Africa subregion, non-renewable energy has a significant U-shaped relationship. Clarifications as to why the other hypotheses are not validated are provided. Policy implications are discussed in what follows.

Globalization and non-renewable energy consumption have significant policy implications for environmental outcomes in Sub-Saharan African economies. Policy makers need to consider a range of strategies to mitigate the negative impacts while harnessing potential benefits. SSA Governments should:

- Establish and enforce stringent environmental regulations to mitigate the adverse effects of non-renewable energy extraction and use. This includes setting emission standards, pollution controls, and land use regulations.
- Implement effective monitoring and compliance mechanisms to ensure adherence to environmental standards, particularly for foreign direct investments in the energy sector.
- Negotiate trade agreements that incorporate environmental protection measures and promote sustainable practices. This can help prevent the "race to the bottom" in environmental standards.
- Consider implementing tariffs on non-renewable energy imports or providing preferential treatment for renewable energy technologies to encourage sustainable practices.
- Promote CSR (Corporate Social Responsibility) initiatives among companies, particularly multinationals, to adopt environmentally friendly practices. This can be achieved through incentives for companies that demonstrate sustainable operations.
- Foster partnerships between governments and the private sector to develop and implement sustainable energy projects and infrastructure.
- Create policies that incentivize investment in renewable energy sources, such as solar, wind, and hydroelectric power. This could include tax breaks, subsidies, and grants for renewable energy projects.
- Encourage diversification of the energy mix to reduce reliance on non-renewable sources. This can enhance energy security and lower environmental impacts.
- Develop policies that facilitate the transfer of clean and efficient technologies from developed countries to SSA countries. This includes partnerships with international organizations and private sector engagement.
- Invest in training and capacity-building programs to equip local communities and industries with the skills needed to adopt and maintain clean technologies.
- Engage in international collaborations to share knowledge, resources, and best practices in managing the environmental impacts of non-renewable energy and promoting sustainable development.
- Commit to international environmental agreements and frameworks that aim to mitigate climate change and promote sustainable development.
- Develop policies that enhance resilience to climate change impacts, particularly in sectors dependent on non-renewable energy. This includes adapting infrastructure and promoting sustainable agricultural practices.

- Leverage international climate finance mechanisms to support transitions to renewable energy and climate adaptation efforts, ensuring that SSA economies are adequately funded.
- Launch public awareness campaigns to educate communities about the environmental impacts of non-renewable energy use and the benefits of transitioning to renewable sources.
- Engage local communities in decision-making processes regarding energy projects to ensure that their needs and concerns are addressed, promoting greater acceptance and participation in sustainable practices.

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APPENDIX

Appendix 1

List of 21 countries included in the SSA sample

Angola, Benin, Botswana, Cameroon, Congo Dem, Congo Rep, Côte d'Ivoire, Ethiopia, Gabon, Ghana, Kenya, Mauritius, Mozambique, Namibia, Nigeria, Senegal, South Africa, Togo, Tanzania, Zambia, and Zimbabwe.

List of the SSA's four regions and countries

West Africa	East Africa	Central Africa	Southern Africa
Benin (BEN) Côte d'Ivoire (CIV) Ghana (GHA) Nigeria (NGA) Senegal (SEN) Togo (TGO)	Ethiopia (ETH) Kenya (KEN) Mauritius (MUS) Mozambique (MOZ) Tanzania (TZA) Zambia (ZMB) Zimbabwe (ZWE)	Angola (AGO) Cameroon (CMR) Congo Dem (COD) Congo Rep (COG) Gabon (GAB)	Botswana (BWA) Namibia (NAM) South Africa (ZAF)

Appendix 2: Variables and data sources

Variable	Description	Source
	Dependent variable	
LCO2	**CO_2** (carbon dioxide) emissions. CO_2 is a greenhouse gas that contributes to global warming. In this study, it is a dependent variable measured in metric tons per capita.	WDI (2024)
	Independent variables	
LKOFGL	**KOFGL** is the aggregation of the three dimensions of globalization (KOF) as reflected in the KOF globalization index (scale of 1 to 100). This index encompasses economic globalization, social globalization, and political globalization. The three dimensions of globalization shape the way in which businesses and governments interact on a global scale. Globalization is a multifaceted concept that encompasses much more than openness to trade and capital flows. It also includes citizens of different countries communicating with each other and exchanging ideas and information, or governments working together to tackle political problems of global reach. For this study, KOFGL is the globalization index.	*KOF Swiss Economic Institute* (2024)
LEnU1	**EnU1** (Non-renewable energy consumption) refers to the use of energy sources that do not regenerate on a human timescale and are generally derived from fossil or nuclear resources. The main types of non-renewable energy include: (*i*). Fossil fuels: - Oil: Used for transport, heating and electricity generation. - Coal: Mainly used for electricity generation and in certain industries. - Natural gas: Used for heating, electricity generation and as a raw material in the chemical industry. (*ii*). Nuclear energy: - Uses uranium or plutonium as fuel to generate electricity through nuclear fission. For this study, the non-renewable energy main proxy is the Energy Use (EnU1) measured as kg of oil equivalent per capita.	WDI (2024)
LGDPpc	**Gross Domestic Product per capita.** It measures the income earned on that production. The GDP per capita (constant US$ of 2015) of a country is calculated by dividing the country's GDP by its total population.	WDI (2024)
POPga	**The annual population growth rate** is the exponential growth rate of the population in the middle of year t-1 to t, expressed as a percentage. The population is based on the facto definition of population, which includes all residents regardless of their legal status or citizenship.	WDI (2024)
LREC	**Renewable energy consumption** (REC) refers to the use of energy sources that regenerate naturally and are considered sustainable, such as solar, wind, hydro, geothermal and biomass energy. REC promotes the reduction of emissions and other pollutants, and reduces dependence on fossil fuels.	WDI (2024)
LFEC	**Fossil fuels energy consumption**: - Oil: Used for transport, heating and electricity generation. - Coal: Mainly used for electricity generation and in certain industries. - Natural gas: Used for heating, electricity generation and as a raw material in the chemical industry. FEC is employed as another proxy of the non-renewable energy for the robustness check purpose.	WDI (2024)
EnU_KOF	**Interacting variable between energy use and Globalization index** is the variable that allows us to estimate the combined effect of non-renewable energy consumption and globalization index, on environmental quality. $EnU_KOF = LEnU1 * LKOFGL.$	*(Interacting variable)*

Source: author. Data are from the WDI (2024) and the KOF Swiss Economic Institute.
Note: « L » is the natural logarithm.

Appendix 3: Descriptive Statistics

Variable	Mean	Std. Dev.	Minimum	Maximum	Observations
LCO2	-0.672	1.314	-3.521	2.148	693
LKOFGL	3.839	0.191	3.147	4.265	693
LEnU1	6.356	0.590	5.338	8.048	693
EnU_KOF	24.452	3.049	19.427	33.519	693
LFEC	3.153	0.895	0.494	4.502	693
LREC	4.083	0.566	2.013	4.588	693
LGDPpc	19.107	7.536	5.811	26.963	693
POPga	0.817	0.613	-6.078	1.389	693

Appendix 4: Correlation Matrix

	LCO2	LKOFGL	LGDPpc	POPga	LEnU1	LFEC	LREC
LCO2	1.0000						
LKOFGL	0.5867	1.0000					
LGDPpc	0.1013	0.3452	1.0000				
POPga	-0.4143	-0.4592	-0.2116	1.0000			
LEnU1	0.7269	0.4318	0.2897	-0.3652	1.0000		
LFEC	0.8609	0.6097	0.0448	-0.4151	0.4204	1.0000	
LREC	-0.7149	-0.5857	-0.1170	0.6080	-0.5254	-0.7615	1.0000

Mondialisation, consommation d'énergie non renouvelable et émissions de dioxyde de carbone en Afrique subsaharienne

Résumé **-** Cette étude examine les effets de la mondialisation et de la consommation des énergies non-renouvelables sur les émissions de dioxyde de carbone dans le cadre de l'hypothèse de la courbe environnementale de Kuznets (EKC) en Afrique subsaharienne (ASS). La recherche se concentre sur 21 pays à partir de données de panel couvrant la période 1990-2022. Deux techniques d'estimation sont utilisées : le « Panel-Corrected Standard Errors » (PCSE) et le « Feasible Generalized Least Squares » (FGLS) pour les contrôles de robustesse et l'analyse comparative des sous-régions de l'ASS. Les variables d'intérêt sont les émissions de carbone (mesurées en tonnes métriques par habitant), la consommation d'énergie non-renouvelable (mesurée en kg d'équivalent pétrole par habitant) et l'indice multidimensionnel de mondialisation du KOF Swiss Economic Institute. Les résultats révèlent que seule l'hypothèse EKC appliquée à la mondialisation avec un point d'inflexion égal à 3,9 est validée en ASS. Les hypothèses EKC appliquées aux énergies non-renouvelables et à la variable interactive (énergies non-renouvelables et mondialisation) ne sont pas vraiment confirmées, car leurs points d'inflexion dans les relations non linéaires présentent une grande variabilité et un large intervalle de confiance. Seul l'indice de mondialisation confirme l'hypothèse EKC pour les sous-régions de l'Afrique occidentale, centrale, orientale et australe en ASS.

Mots Clés

Mondialisation
Énergies non-renouvelables
Émissions de carbone
Afrique subsaharienne
Méthode PCSE
Estimation FGLS