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Effects of Energy Efficiency and Renewable Energy Consumption on CO_2 Emissions in Sub-Saharan Africa: An Examination of Transmission Channels

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ABSTRACT

The aim of this research is to analyze, via transmission channels, the effects of energy efficiency and renewable energy consumption on carbon dioxide (CO_2) emissions in sub-Saharan Africa (SSA) over the period 2002-2020. For that, defactored instrumental variables method was used on a sample of 25 sub-Saharan African countries. The results show that energy efficiency, renewable energy consumption and interaction of these variables with transmission variables significantly reduce CO_2 emissions in SSA. Governments in this region should invest more in clean and energy-efficient technologies in order to move towards achieving Sustainable Development Goal 7 (SDG 7).

Keywords: Sub-Saharan Africa, Renewable Energy Consumption, Energy Efficiency, Defactored Instrumental Variables, CO_2
JEL Classifications: C01, D02, L91, H41, Q41

1. INTRODUCTION

Global warming is one of the most important environmental issues of the 21st century. Considered to be the main external effect of climate change, it is a global public good and a real challenge for the world's economies (Nordhaus, 2019). This problem is largely caused by greenhouse gas emissions into the atmosphere from the burning of fossil fuels (Zhang et al., 2011). This problem could jeopardize the achievement of the Paris objectives, which are to keep the global temperature increase below 2°C and to explore the actions needed to further limit the temperature increase to 1.5°C. To achieve the Paris objectives, GHG emissions will have to fall rapidly to prevent humanity from transgressing planetary limits and having a negative impact on the environment (Steffen et al., 2015). According to UNEP's report on progress towards the SDGs, GHG emissions forecast for 2030 still need to fall by 28% if we are to meet the 2°C trajectory set out in the Paris agreements, and by 42% if we are to meet the 1.5°C trajectory (UNEP, 2023). However, the opposite currently seems to be true: CO_2 emissions rose from 778.46 million metric tons in 2014 to 799.78 million metric tons in 2018, representing an annual growth rate of 1% (US-EIA, 2021).

Despite poor access to electricity, SSA remains one of the regions most affected by the external effects of climate change (Nathaniel and Iheonu, 2019). Based on the climate change vulnerability index, Sarkodie (2018) concludes that seven of the ten countries most vulnerable to climate change are in SSA. Analyses show that it seems theoretically impossible to ensure access to energy for all while avoiding the harmful effects of climate change (Riahi et al., 2022). However, according to Gielen et al. (2019) Renewable energies combined with increased energy efficiency could not only help to meet almost two-thirds of energy demand, but also contribute to achieving almost 94% of the GHG reductions required by 2050. The remaining 6% has already been achieved by other methods of reducing energy-related CO_2 emissions, such as fossil fuel substitution, nuclear power and carbon capture and storage (IEA, 2017).

Theoretically, the Environmental Kuznets Curve (EKC) hypothesis developed by Grossman and Krueger (1991) shows that renewable energies could smooth out the inflection point thanks to a technical effect on polluting emissions. Assuming environmental convergence, renewable energies could accelerate the process of environmental convergence and an eventual reduction in polluting emissions. Brock and Taylor (2010), through their green Solow model, support the existence of environmental convergence in the presence of a mechanism for reducing polluting emissions in economies. As a result, the deployment of renewable energies could also play an important role in the process of environmental convergence, in line with the predictions of (Brock and Taylor, 2010).

Empirically, the relationship between renewable energy consumption and CO_2 emissions has been of great interest to the research community. While most authors find that renewable energy consumption has a negative impact on CO_2 (Bilgili et al., 2016; Diallo, 2024a; Liu et al., 2020; Liu et al., 2023), However, some do manage to show that it has a positive impact on CO_2 emissions (Apergis et al., 2010; Baek, 2016; Jebli and Youssef, 2017).

In addition to renewable energies, energy efficiency is another factor that can affect the quality of the environment. Theory on this subject proves, through Jevons' paradox, that technological progress does not always lead to a reduction in energy demand - on the contrary, it leads to an increase in energy demand, causing a loss of energy efficiency gains. Empirically, authors such as Deka et al. (2023); González et al. (2019) and Destek et al. (2016) conclude that energy efficiency improves the quality of the environment by reducing energy demand through technological progress.

According to US-EIA (2021) Over the period 2014-2018, renewable energy consumption rose from 1.12 quadruple British thermal units (BTUs) in 2014 to 1.26 BTUs in 2018, an average annual growth rate of 4.38%. Over the same period, CO_2 emissions rose from 778.46 million metric tons in 2014 to 799.78 million metric tons in 2018, an annual growth rate of 1%.

In terms of energy efficiency, the amount of energy used per unit of wealth created improved from 4.96 megajoules (MJ) in 2015 to 4.63 MJ in 2020, an average annual improvement rate of 1.4%. This rate is still below the 2.6% required to achieve target 7.3 of MDG 7, which aims to double the global energy efficiency rate by 2030. To fill this gap, this rate would have to grow by an average of 3.4% per year until 2030. Energy is at the heart of the problem, so it must be at the heart of the solution. This raises the question: What are the effects and transmission channels of renewable energy consumption and energy efficiency on CO_2 emissions in sub-Saharan Africa?

The studies presented arrive at controversial results regarding the effect of energy efficiency on CO_2 emissions and the effect of renewable energy consumption on CO_2 emissions in SSA. However, existing studies have ignored the channels through which energy efficiency and renewable energy consumption could reduce CO_2 emissions. Other recent studies have limited themselves to analyzing the transition to green energy (Diallo, 2024b) and energy poverty and women's well-being (Compaoré et al., 2024) and have not focused on the effect of energy efficiency on environmental quality or on the transmission channels. The aim of this article is to analyze the effects of energy efficiency and renewable energy consumption on CO_2 emissions by highlighting the transmission channels.

The remainder of this article is organized into four sections. Section 2 highlights the theoretical and empirical literature review, section 3 presents the methodology used, section 4 presents and discusses the results, and the conclusion and policy implications are addressed in section 5.

2. LITERATURE REVIEW

2.1. Theoretical Foundations

This research is fundamentally based on three theories: the environmental Kuznets curve; the green Solow model; and the rebound effect or Jevons' paradox.

2.1.1. Environmental kuznets curve (EKC) theory

This theory has its origins in the work of Kuznets (1955), who found an inverted U-shaped relationship between inequality in the distribution of income and income growth. The hypothesis is that during the early stages of a country's economic development, there are few polluting emissions because production is low. However, this pollution will increase with industrialization, which exerts an ostentatious pressure on the environment. Finally, in the last phase, once a certain level of income has been reached, agents begin to realize the value of a healthy environment, and the combination of changes in individual preferences and the involvement of the executive in the issues. Following this logic, energy consumption initially increases up to a certain threshold before starting to fall. For developing countries, environmental protection takes second place to economic growth. During this phase, it seems almost impossible to reduce energy consumption or even to switch to cleaner, less polluting energy sources. However, once a country has reached a level of economic development, it can afford to focus on improving the quality of the environment through responsible energy consumption and even the use of renewable energies to reduce environmental damage.

2.1.2. Environmental convergence theory: The green solow model

Brock and Taylor (2010) explain the environmental Kuznets curve using Solow's model. They represent a fair specification based on the modern Solow model of growth-induced technical progress and a clean environment. The Green Solow Model explores the implications of sustainability-oriented technological innovation. Technological progress aimed at reducing the environmental impact of economic activities can lead to more balanced growth and greater convergence. Countries adopting environmentally friendly technologies can experience faster economic growth, while limiting negative externalities on the biosphere. This model is an environmental convergence model, which states that in the long term, countries with high CO_2 emissions will converge towards those with low emissions, thereby reducing global CO_2 emissions (Brock and Taylor, 2010).

2.1.3. The rebound effect or Jevons' paradox

Current technological development is based on the principle that technological advances make it possible to reduce the environmental impact of certain economic activities by using more efficient processes that reduce the quantity of waste and pollutants in the environment. This method is known as eco-efficiency. However, this principle has been called into question by a large number of researchers. This questioning is based on the rebound effect. The rebound effect is the phenomenon whereby a technology that leads to greater efficiency in the use of a resource generates a reduction in the cost of a product and therefore an increase in demand. The case that interests researchers who doubt eco-efficiency is where the increase in demand is greater than the gain in efficiency, which leads to a higher net consumption of the resources involved than before. This extreme case of the rebound effect is known as Jevons' paradox and was first put forward by William Stanley Jevons in 1866.

2.2. Empirical Review

2.2.1. Renewable energy consumption and CO_2 emissions

Several studies have looked at the relationship between renewable energy consumption and CO_2 emissions, using different estimation methods. The results are mixed, however. Research has focused on developed and emerging countries. We have Ulucak et al. (2024) who conducted their study on the impact of renewable energies on the control of consumption-related carbon emissions. Applying panel fixed effects on BRICS countries from 1990 to 2017, they conclude that renewable energy mitigates CO_2 emissions. Mirziyoyeva and Salahodjaev (2023) studied the relationship between renewable energy, GDP and CO_2 emissions in 50 highly globalized countries. Using a two-stage GMM system, they conclude that renewable energies reduce CO_2 emissions. Dagar et al. (2022) also arrived at the same result using panel data for 38 OECD countries over the period 1995-2019 using the generalized method of moments (GMM).

Other studies were then carried out in developing countries. Akram et al. (2020) used fixed-effect quantile regression methods and ordinary least squares estimation to analyse the relationship between renewable energy consumption and environmental quality over the period 1990-2014 in a sample of 66 developing countries. As a result, they find that renewable energy reduces CO_2 emissions with a substantial effect at the 10^{th} quantile. Hasnisah et al. (2019) used panel data from 1980 to 2014 with panel cointegration, fully modified ordinary least squares and dynamic OLS estimators on 13 developing countries in Asia. Their study concludes that renewable energies, which are environmentally friendly, do not contribute significantly to reducing polluting emissions, particularly CO_2. Using the PVAR technique, Charfeddine and Kahia (2019) highlighted the impact of renewable energy consumption on CO_2 emissions in the MENA region. Their results show the potential to improve environmental quality by further promoting the renewable energy sector as there is a negative and statistically significant relationship between these two variables. Liu et al. (2023) reach the same conclusion using the Dubin spatial model for a sample of 30 Chinese provinces covering the period 2002-2019.

Finally, studies specific to sub-Saharan Africa attempt to prove the positive relationship between renewable energy consumption and environmental quality. For example, Asongu et al. (2019) study the conditional relationship between renewable energy and environmental quality for 40 SSA countries over the period 2002-2017. Using a quantile regression technique, they conclude that renewable energy positively affects environmental quality. Salahuddin et al. (2020a,b) sought to analyze the connection between renewable energy consumption and environmental quality in 34 sub-Saharan African countries over the period 1984-2016. Using the MG, AMG, CCEMG and Common Correlated Effect Pooled (CCEP) estimators, they found that renewable energy consumption makes a significant contribution to improving environmental quality. Riti et al. (2022) apply the Panel Autoregression Distributed Lag (PARDL) technique to panel data from selected Sub-Saharan African economies spanning from 1990 to 2018. Their research exposes the fact that renewable energy significantly reduces CO_2 emissions. Adams and Acheampong (2019) used the GMM instrumental variable to analyze the effect of renewable energy consumption on environmental quality in 46 sub-Saharan African countries between 1980 and 2015. They also found a positive effect of renewable energy consumption on environmental quality. Wang and Dong (2019) analyzed the effect of renewable energy consumption on environmental quality in 14 sub-Saharan African countries over the period 1990-2014. The results of the AMG estimates show that renewable energy consumption positively affects environmental quality in SSA. Using a two-stage defactored instrumental variable estimation technique, Diallo (2024a) examines the effects of renewable energy consumption on environmental quality for 34 SSA countries over the period 1996-2018. The results of his analysis show that renewable energy consumption improves environmental quality. Maji et al. (2022) arrived at the same result using the GMM estimator of the two-stage system for 45 SSA countries between 2008 and 2020.

While the majority of authors find a positive relationship between renewable energy consumption, others find that renewable energy negatively affects environmental quality. In this sense, Jebli and Youssef (2017) studied the effect of renewable energy consumption on CO_2 emissions for 5 North African countries over the period 1980-2011. The results of the estimates using the DOLS and FMOLS methods indicate a positive effect of renewable energy consumption on CO_2 emissions. Al-Mulali et al. (2016) examined the effect of renewable energy consumption on environmental quality in 58 developed and developing countries over the period 1980-2009. The results of the GMM (General Method of Moment) estimates show that renewable energy consumption negatively affects environmental quality. Farhani and Shahbaz (2014) examine the connection between renewable energy and CO_2 emissions in 10 MENA countries over the period 1980 to 2009 and find that the consumption of both renewable and non-renewable electricity increases carbon dioxide emissions. To do this, they use estimation techniques such as fully modified ordinary least squares (FMOLS) and dynamic ordinary least squares (DOLS).

2.2.2. Energy eficiency and CO_2 emissions

Studies have been carried out to try to understand the effect of energy efficiency on CO_2 emissions. Bargaoui et al. (2014) also proved that energy efficiency reduces CO_2 emissions for all samples with different impacts from one group to another. Özbuğday and Erbas (2015) applied MG (mean group) and CGM (Common Correlated Effects Mean Group) to examine the effect of renewable energy and energy efficiency, share of manufacturing sector, population, income on CO_2 emissions. Using a panel of 36 countries, 21 advanced and 15 emerging, over the period 1971-2009, they show that efficiency is the main driver of CO_2 emission reductions. Bargaoui and Nouri (2017) used a dynamic panel to examine CO_2 emissions from "Driving forces" vehicles for 114 countries. Using fuel efficiency as one of the explanatory variables from 1980 to 2010, they show that fuel efficiency contributes to the reduction in CO_2 emissions with a significant elasticity coefficient. They therefore recommend that decision-makers invest more in research and development in order to improve the development of energy-saving technologies, especially for developing countries. González et al. (2019) applied a dynamic panel over the period 1990-2015 for 13 European countries and their result shows that the reduction in CO_2 emissions from cars is linked to technological progress and changes in energy efficiency. Deka et al. (2023) worked on the effects of energy efficiency and tourism development on the environment in SSA. To do this they use a set of 48 SSA countries over the period 1990-2020. Using the CS-ARDL, they conclude that energy efficiency improves environmental quality by reducing carbon emissions. Akpanke et al. (2023) conducted their analysis on seven emerging and fifteen developing countries from 1990 to 2019. Using the ARDL AMG and CCEMG estimation techniques, they arrived at the same result as the previous authors.

However, the reducing effect of energy efficiency is not always obvious because of the rebound effect (Birol and Keppler, 2000; Brookes, 1990; Herring, 1999; Jevons, 1866; Khazzoom, 1980; Saunders, 2000; Schipper and Grubb, 2000).

2.2.3. Transmission channels

In this section, we look at the mechanisms by which energy efficiency and renewable energy consumption affect carbon emissions.

The first channel we are looking at is Information and Communication Technologies (ICTs). The literature shows that its effect on carbon emissions remains mixed. The literature on the effect of energy efficiency and renewable energy consumption is abundant, and most of it concludes that these two variables have a negative effect on CO_2 emissions, suggesting that ICTs could reduce CO_2 emissions if they improve energy efficiency and reduce the cost of renewable energy (Avom et al., 2020). However, ICTs could indirectly increase CO_2 emissions insofar as improving energy efficiency, rather than reducing energy consumption, increases it. This phenomenon is known as the rebound effect. Li and Wang (2022) find an inverted U-shaped relationship between ICTs and carbon emissions, i.e. the development of ICTs is accompanied by an increase in carbon emissions and once a certain level of integration is reached, they reduce CO_2 emissions. To find this result they used a non-linear analysis with the combination of the DURBIN spatial model (SDM) and the panel threshold model (PTM). Park et al. (2018) looked at the effect of ICT, financial development, growth and trade openness on CO_2 emissions. In their approach, the pooled mean group (PMG) estimator is used for 23 EU countries over the period 2001-2014. They conclude that, in the long term, internet use has a negative impact on CO_2 emissions. Asongu et al. (2018) examine the impact of ICT on CO_2 emissions in 44 SSA countries using the generalized method of moment (GMM). The results suggest that ICT has a positive influence on CO_2 emissions, however increased use of ICT decreases CO_2 emissions. Ren et al. (2021) analyse the relationship between digitization and energy in 30 Chinese provinces using a GMM and conclude that digitization measured by internet use favors a decrease in energy consumption intensity, thereby negatively affecting energy-related CO_2 emissions.

The second channel is institutional quality. Sarkodie and Adams (2018) examine the effect of renewable energies and nuclear energy on environmental pollution, taking into account the role of institutional quality. Using the ARDL model for the period 1971-2017 for South Africa, they conclude that institutional quality reduces CO_2 emissions. The energy efficiency performance of a sample of 71 developed and developing countries between 1990 and 2014 was analyzed by Sun et al. (2019). They adopted a stochastic frontier analysis to estimate the energy efficiency of different green technologies and argued that the country's paradigm shift towards green technologies requires resilient governance. Bhattacharya et al. (2017) studied the role of renewable energy consumption and institutional quality on growth and CO_2 emissions across regions and income groups. They used annual data from 85 developed and developing economies around the world between 1991 and 2012. Their results suggest that renewable energy deployment and institutions play an important role in promoting economic growth and reducing CO_2 emissions. Godil et al. (2021) study the role of financial development, R&D spending, globalization and institutional quality on energy consumption in India from 1995 to 2018. They use a Quantile Autoregressive Distributed Lag (QARDL) approach and conclude that increasing the quality of institutions reduces energy consumption, thereby lowering CO_2 emissions. Meanwhile, Sarkodie et al. (2020) analyze an interactive effect of income level, governance and renewable energy for 47 SSA countries. This effect worsens GHG levels, indicating that if the effect of scale, composition and technology work together, they worsen climate change; only renewable energies are proving effective in these countries in reducing GHGs.

3. METHODOLOGY AND DATA SOURCE

3.1. Methodology

3.1.1. Methodology for constructing the institutional quality index

This paper uses multiple component analysis (MCA) to aggregate Kaufman's six governance indicators (voice and accountability, political stability and absence of violence/terrorism, government effectiveness, regulatory quality, rule of law, and anti-corruption) into one that constitutes institutional quality. This is a synthetic index of institutional quality measurement that was constructed using this approach. Yerbanga's (2018) paper had already used this multiple component approach to construct the synthetic index for measuring the quality of institutions and the wealth measurement index. Similarly, multiple component analysis was used by Vyas and Kumaranayake (2006).

3.1.2. Econometric specification

To analyze the effect and transmission channels of energy efficiency and renewable energy consumption on CO_2 emissions in SSA, we use the IPAT (Impact of Population, Wealth and Technology) model developed in the work of Ehrlich and Holdren (1972). The model is written as follows:

$$I = P \times A \times T \quad (1)$$

Where I denotes environmental impact; P is population; A is wealth; and T is technology.

The model will be refined by (Dietz and Rosa, 1997) which is presented as follows:

$$I_{it} = \alpha P_{it}^{\beta} A_{it}^{\gamma} T_{it}^{\delta} \varepsilon_{it} \quad (2)$$

Where P, A, T represent population, wealth and technology respectively and α, the constant; β, γ, δ are the parameters associated with population, wealth and technology respectively.

York et al. (2003) reformulate the second equation in logarithmic form to better perform regressions on the effects of each explanatory variable. From this transformation comes the STIRPAT model (stochastic impacts by regression on population, affluence and technology). The empirical specification of our model follows that of Schneider (2020) and is as follows:

$$lnCO_{2it} = \alpha_0 + \alpha_1\, lnCO_{2i,t-1} + \alpha_2\, lnCER_{it} + \alpha_3\, lnEFF_{it} + \alpha_4\, lnGDP_{it} + \alpha_5\, lnENRH_{it} + \alpha_6\, FDI_{it} + \alpha_7\, URB_{it} + \alpha_8\, IQ_{it} + \alpha_9\, Internet_{it} + \alpha_{10}\, mobile\_phone_{it} + e_{it} \quad (3)$$

$$lnCO_{2it} = \alpha_0 + \alpha_1\, lnCO2_{i,t-1} + \alpha_2\, lnEFF_{it} + \alpha_3\, lnGDP_{it} + \alpha_4\, lnENRH_{it} + \alpha_5\, FDI_{it} + \alpha_6\, URB_{it} + \alpha_7\, IQ_{it} + \alpha_8\, (lnEFF_{it}{*}IQ_{it}) + e_{it} \quad (4)$$

$$lnCO_{2it} = \alpha_0 + \alpha_1\, lnCO_{2i,t-1} + \alpha_2\, lnEFF_{it} + \alpha_3\, lnGDP_{it} + \alpha_4\, lnENRH_{it} + \alpha_5\, FDI_{it} + \alpha_6\, URB_{it} + \alpha_7\, Internet_{it} + \alpha_8\, (lnEFF\_it{*}Internet_{it}) + e_{it} \quad (5)$$

$$lnCO2_{it} = \alpha_0 + \alpha_1\, lnCO2_{i,t-1} + \alpha_2\, lnEFF_{it} + \alpha_3\, lnGDP_{it} + \alpha_4\, lnENRH_{it} + \alpha_5\, FDI_{it} + \alpha_6\, URB_{it} + \alpha_7\, mobile\_phone_{it} + \alpha_8\, (lnEFF_{it}{*}mobile\_phone_{it}) + e_{it} \quad (6)$$

$$lnCO_{2it} = \alpha_0 + \alpha_1\, lnCO_{2i,t-1} + \alpha_2\, lnCER_{it} + \alpha_3\, lnGDP_{it} + \alpha_4\, lnENRH_{it} + \alpha_5\, FDI_{it} + \alpha_6\, URB_{it} + \alpha_7\, IQ_{it} + \alpha_8\, (lnCER_{it}{*}IQ_{it}) + e_{it} \quad (7)$$

$$lnCO_{2it} = \alpha_0 + \alpha_1\, lnCO_{2i,t-1} + \alpha_2\, lnCER_{it} + \alpha_3\, lnGDP_{it} + \alpha_4\, lnENRH_{it} + \alpha_5\, FDI_{it} + \alpha_6\, URB_{it} + \alpha_7\, Internet_{it} + \alpha_8\, (lnCER_{it}{*}Internet_{it}) + e_{it} \quad (8)$$

$$lnCO_{2it} = \alpha_0 + \alpha_1\, lnCO_{2i,t-1} + \alpha_2\, lnCER_{it} + \alpha_3\, lnGDP_{it} + \alpha_4\, lnENRH_{it} + \alpha_5\, FDI_{it} + \alpha_6\, URB_{it} + \alpha_7\, mobile\_phone_{it} + \alpha_8\, (lnCER_{it}{*}mobile\_phone_{it}) + e_{it} \quad (9)$$

Where α_0 is constant; $lnCO_2$ denotes the logarithm of total GHG emissions in CO_2 equivalent; lnGDP is the logarithm of GDP/capita; lnCER is the logarithm of renewable energy consumption; lnEFF is the logarithm of the energy efficiency variable; lnENRH is the logarithm of fossil fuel consumption per capita; IDE stands for foreign direct investment and URB stands for urbanization rate, IQ represents institutional quality, mobile phone represents telephone subscriptions and the internet variable refers to individual use of the latter. e_{it} Refers to the model error term, which represents omitted variables affecting CO_2 emissions but which were not captured by this model. I denotes the country; t is the annual period and the coefficients $\alpha_1, \alpha_2, \alpha_3, \alpha_4, \alpha_5, \alpha_6, \alpha_7, \alpha_8, \alpha_9, \alpha_{10}$ are the elasticities of our different variables.

3.1.3. Estimation method

Our empirical model shows the need to use dynamic panel data methods because the lagged dependent variable is part of our explanatory variables. As a result, traditional estimation methods lead to biased results. Indeed, the introduction of the lagged dependent variable creates a dynamic panel bias known as nickel bias, more precisely it creates a correlation with the error term (Nickell, 1981). The generalized method of moments (GMM) helps to alleviate this problem by eliminating individual effects and using the lags of the dependent and independent variables (Arellano and Bond, 1991; Blundell and Bond, 1998). According to Roodman (2006), GMM provides robust results in dynamic panel however in the presence of problems such as cross-sectional dependence, unobserved common factors and non-stationarity of variables could produce biased results (Sharma et al., 2021). According to Hansen (1982), the GMM model is based only on the stationarity process. According to Sarkodie et al. (2021), we can overcome these problems by resorting to the defactored instrumental variables method developed by Norkutė et al. (2021). They propose two types of estimators namely the two-stage defactored instrumental variables (2SIV) estimator for homogeneous panel models and the mean group defactored instrumental variables (MGIV) estimator for heterogeneous panel models. This estimator is based on the autoregressive staggered lag model. The equation looks like this:

$$Y_{i,t} = \rho Y_{i,t-1} + \varnothing Z_{i,t} + \xi_{i,t}\ Avec\ \xi_{i,t} = \lambda' Y_i + fY_t + \varepsilon_{i,t} \quad (10)$$

Where Z_{it} is a vector of explanatory variables and ξ_{it} is the idiosyncratic error term and $\lambda' Y_i + fY_t + \varepsilon_{i,t}$ are respectively the unobserved common factors, the factor scores and the idiosyncratic error term. Norkutė et al. (2021) propose a two-step IV estimator for models with homogeneous slope coefficients. The first step is obtained using instruments based on the defactored covariates; in the second step, the entire model is defactored based on the factors extracted from the residuals of the first step estimation. Subsequently, an instrumental variable (IV) regression is set up using the same instruments as in the first step. As it is an instrumental variable estimator, it is not subject to nickel bias. The choice between 2SVI and MGIV is made using the Hausman test which assumes as a null hypothesis the effectiveness of the MGIV method on the 2SIV estimator.

3.2. Data Sources and Descriptive Statistics

3.2.1. Data sources

It uses secondary data from 2002 to 2020 for 25 sub-Saharan African countries from the world development indicators, US-EIA and world governance indicators. CO_2 is our endogenous variable. It is measured by the logarithm of global CO_2 equivalent GHG emissions. Energy efficiency is one of our variables of interest. It is measured by the logarithm of energy intensity in accordance with the study by Deka et al. (2023). Our second variable of interest is renewable energy consumption measured by the share of renewable energy in overall energy consumption following the work of Mert and Bölük (2016). In terms of transmission channels, we first use ICT measured by individual internet use as a percentage of the population and by telephone subscriptions (Avom et al., 2020). The second channel is institutional quality calculated by principal component analysis (Asongu et al., 2018). For the control variables we have: first the income level is captured by the logarithm of the gross domestic product (GDP) per capita expressed in constant price (purchasing power parity, 2017 US dollars). Next, non-renewable energy consumption (NRE) refers to the use of coal, petroleum, rock oil and natural gas as energy sources (Diallo, 2024a). In terms of FDI, this variable represents net FDI inflows into SSA expressed as a percentage of gross domestic product for each year. Finally, the urbanization rate refers to the urban population as a percentage of the total population (Lee and Zhao, 2023).

3.2.2. Variable dictionaries and descriptive statistics

Table 1 presents all the variables used in this analysis.

The Table 2 shows the descriptive statistics of the variables used for the analysis.

3.2. Preliminary Tests and Estimation Strategy

A number of preliminary tests are being undertaken to empirically assess the effect of energy efficiency and renewable energy consumption on CO_2 emissions across transmission channels. Table 3 below presents the results of the inter-individual dependence test. There is dependence for all variables except the logarithm of energy efficiency and the institutional quality index.

In addition to the dependence test, we perform a unit root test for our variables. For variables where independence is confirmed, we perform a first-generation unit root test and for the others, second-generation unit root tests. The results are presented in Table 4 below showing that our variables are integrated at level (Leff, IQ, FDI, Lenrh, mobile phone and LCO_2), at first difference (Lcer, internet and Lgdp) and at second order (Urb).

4. RESULTS AND DISCUSSION

In order to test the effect of energy efficiency and renewable energy consumption on CO_2 emissions in SSA, we estimated our model via 2SIV and MGIV. Subsequently, we perform a second estimation by crossing our variables of interest with our channels. The results are reported in Table 5.

The results of the Hansen over-identification test confirm the validity of the instruments used in the model. The probability associated with this test therefore makes it possible to reject the null hypothesis of correlation between the variables and the random disturbances at the 10% threshold. Next, the Hausman test highlights the fact that the results obtained with the 2SIV estimator are more efficient than those obtained with the MGIV estimator. Since the probability of this test is less than 1%, we reject the null hypothesis in favor of the alternative hypothesis. This shows that the 2SIV estimator should be preferred to the MGIV.

The coefficient associated with the lagged endogenous variable (0.284) is positive and significant at the 1% level. This means that past CO_2 emissions have a positive influence on current emissions. This result contradicts the theoretical predictions of Brock and Taylor (2010), which show a divergence in the level of per capita income in sub-Saharan African countries. However, this result corroborates those of (Diallo, 2024a) and (Adams and Acheampong, 2019). Renewable energy consumption has a negative and significant coefficient (−0.265) at the 1% threshold; in other words, a 1% increase in renewable energy consumption leads to a 0.265% decrease in CO_2 emissions, all other things being equal. More precisely, this implies that renewable energy consumption reduces CO_2 emissions in Sub-Saharan Africa. This result is in line with our expectations insofar as it verifies our hypothesis. Theoretically, this result follows the logic of the CEK, which stipulates that renewable

Table 1: Dictionary of variables

Variables	Full variable names	Terms or method of calculation	Expected sign
LCO_2	Carbon dioxide	Total greenhouse gas (GHG) emissions in kt CO_2 equivalent	
Lcer	Logarithm of renewable energy consumption	Renewable energy consumption is the share of renewable energy in final energy consumption.	−
Leff	Logarithm of energy efficiency	Energy intensity which can be used to measure energy efficiency	−
Lgdp	Logarithm of gross domestic product per capita	GDP per capita based on purchasing power parity	+
Lenrh	Logarithm of non-renewable energy consumption	Fossil fuel consumption includes coal, oil and natural gas products	+
Urb	Urbanization rate	Urban population growth as an annual percentage	±
FDI	Foreign direct investment	Foreign Direct Investment, net inflows as a percentage of GDP	±
IQ	Institutional quality	Authors' calculation using ACM	−
Internet	Internet	Individual internet usage as a percentage of the population	±
Mobile phone	Mobile phone	Telephone subscriptions	±

Table 2: Descriptive Statistics

Variable	Obs	Mean	Standard Deviation	Min	Max
$lgCO_2$	475	9.662	1.331	6.293	12.714
lcer	475	4.089	0.519	2.191	4.565
lgdp	475	8.067	0.837	6.563	10.072
leff	475	0.781	0.542	−0.488	2.479
lenrh	475	15.729	1.096	13.117	18.167
IQ	474	0.161	0.079	0.102	0.388
Internet	475	12.872	15.669	0.072	72.748
Mobile phone	475	56.801	41.699	0.07	150.882
Urb	475	39.086	17.535	8.682	90.092
FDI	475	3.697	4.576	−11.192	38.943

Table 3: CD Pesaran interindividual dependence test (2004)

Variables	P-value	Decision
$LgCO_2$	0.000***	Dependence
Lcer	0.000***	Dependence
Leff	0.398	Independence
Lgdp	0.000***	Dependence
Lenrh	0.000***	Dependence
Urb	0.000***	Dependence
FDI	0.000***	Dependence
IQ	0.233	Independance
Internet	0.000***	Dependance
Mobile phone	0.000***	Dependance

Table 4: Unit root test

Variables	Level	First difference	Decision
Méthodes	Cross Sectionally	Augmented Dickey Fuller test	
Lgco2	0.002**	-	I (0)
Lcer	0.105	0.000***	I (1)
Lgdp	0.954	0.000***	I (1)
Lenrh	0.001***		I (0)
Urb	1.000	0.000**	I (2)
FDI	0.000***		I (0)
Internet	0.662	0.018**	I (1)
Mobile phone	0.006**		I (0)
	Im Pesaran Shin (IPS)		
Leff	0.0116**	-	I (0)
IQ	0.0000***	-	I (0)

energies would make it possible to flatten the top of the curve by acting negatively on polluting emissions through technical, compositional and scale effects. This result is also in line with Green Solow's prediction that the existence of a depollution sector in an economy considerably reduces polluting emissions, leading to environmental convergence between SSA countries. Empirically, this result is consistent with those of (Diallo, 2024a; Khan et al., 2021; Maji et al., 2022; Vural, 2020) who found in their results that renewable energy consumption improves environmental quality in SSA. High consumption of renewable energies will therefore lead to a reduction in the traditional energy production process in favor of energies that emit less polluting emissions.

Energy efficiency significantly reduces CO_2 emissions in SSA, which is justified by the fact that this variable has a negative

Table 5: Results of direct effect

Variables	(1)	(2)
	MGIV	2SIV
	Lg CO_2	Lg CO_2
L.lgCO_2	−0.218**	0.284***
	(0.105)	(0.061)
Lgdp	−0.097	−0.359
	(0.575)	(0.361)
Lcer	−0.156	−0.265***
	(0.339)	(0.075)
Leff	−0.266	−0.550*
	(0.482)	(0.320)
Lenrh	0.205	0.577*
	(0.629)	(0.318)
Urb	0.183	0.074***
	(0.140)	(0.026)
FDI	0.003	−0.004***
	(0.004)	(0.001)
IQ	0.407	−0.289**
	(0.509)	(0.133)
Mobile phone	0.002	0.000
	(0.002)	(0.000)
Internet	−0.003	−0.001*
	(0.003)	(0.001)
Constant	5.362	−0.600
	(6.988)	(2.674)
Observations	397	397
Numbers of country	25	25
Diagnostic test		Statistic (P-value)
Hansen test statistic		14.3635 (0.4230)
Hausman test statistic		38.08 (0.0000)

Standard deviations in brackets ***P<0.01, **P<0.05, *P<0.1

coefficient (−0.550) and is significant at 10%. This result is intuitive in that it shows that when energy efficiency increases by 1%, CO_2 emissions fall by 0.550%, all other things being equal. This means that a technological innovation in the energy sector will have the effect of reducing energy consumption, which in turn will reduce energy-related CO_2 emissions. This result consolidates our research hypothesis and is in line with those of several other studies conducted (Bargaoui and Nouri, 2017; Deka et al., 2023). Theoretically, this result is in line with the Kuznets environmental curve hypothesis more precisely in the descending phase where any increase in income leads to an improvement in environmental quality. Indeed, once a certain level of development is reached, we adopt clean technologies in the production process, thereby reducing energy consumption and, by the same token, CO_2 emissions.

The results of the interaction effects show that the consumption of renewable energy positively affects CO_2 emissions via institutional quality and ICT. In fact, energy consumption, by acting positively on the two channels, increases CO_2 emissions by 3.717% and 0.014% for institutional and internet quality respectively. This result could be explained on the one hand by the fact that sub-Saharan Africa suffers from chronic political instability, which weakens its institutions and prevents the implementation of clean energy infrastructure. The lack of will on the part of decision-makers could also explain this. On the other hand, the Internet, with a further increase in the number of Internet users, is leading, all other things being equal, to greater consumption of electricity, which in turn is increasing CO_2

emissions. This result is in line with those of Avom et al. (2020), Dabbous (2018) and Sadorsky (2012).

Energy efficiency shows a negative and significant coefficient with the different channels, i.e. any improvement in energy efficiency of 1% translates into a reduction in CO_2 emissions of 1.503%, 0.0015% and 0.002% respectively via institutional quality, internet and mobile phone. This result could be explained by the fact that, with the development of the internet, we can reach a large section of the population with energy-saving practices. The use of ICTs, combined with good institutional quality, makes it possible to increase production efficiency and the efficiency of energy use, and also to reduce the cost of energy use, which will have the effect of reducing CO_2 emissions. This result follows that of Takase and Murota (2004) and Salahuddin et al. (2016).

According to the results in Table 6, fossil fuels have a positive and significant effect at 10%. In other words, any 1% increase in fossil fuel consumption translates into a 0.577% increase in CO_2 emissions. Fossil fuel consumption is deteriorating the quality of the environment in SSA countries. Indeed, in order to meet the high demand for energy and in a bid to catch up with developed countries, SSA economies are resorting to a disproportionate consumption of non-renewable energy (Hanif, 2018). This is in line with some previous findings (Salahuddin et al., 2020a,b; Hanif, 2018; Keho, 2016).

The urbanization rate has a positive and significant coefficient at 1%. This shows that any growth in urbanization of one (1) percentage point results in an increase in CO_2 emissions of 0.074%, all things being equal. This result is explained by the fact that Sub-Saharan Africa is experiencing the strongest growth in urbanization due to a stronger rural exodus (Un-Habitat, 2010); which will have the effect of increasing the demand for public goods and services, putting pressure on available resources. This rapid growth in urbanization will thus generate negative externalities such as CO_2 emissions. This result is consistent with those of Balogan (2021); Rafiq et al. (2016).

FDI has a significant and negative coefficient which states that foreign direct investment has a negative effect on CO_2 emissions

Table 6: Results with interaction effects

	(1)	(2)	(3)	(4)	(5)	(6)
VARIABLES	$LgCO_2$	$LgCO_2$	$LgCO_2$	$LgCO_2$	$LgCO_2$	$LgCO_2$
$L.lgCO_2$	0.201***	0.363***	0.197***	0.162***	0.239***	0.118**
	(0.047)	(0.046)	(0.063)	(0.054)	(0.055)	(0.052)
Lgdp	0.219***	0.208***	−0.077	0.253***	0.436***	0.227***
	(0.072)	(0.054)	(0.129)	(0.061)	(0.042)	(0.064)
Leff	0.079	−0.066*	−0.162*			
	(0.087)	(0.037)	(0.098)			
Lenrh	0.296***	0.351***	0.407***	0.046*	0.141***	0.131***
	(0.045)	(0.047)	(0.127)	(0.028)	(0.015)	(0.031)
Urb	0.057***	0.006	0.051***	0.048***	0.008	0.075***
	(0.010)	(0.009)	(0.014)	(0.014)	(0.011)	(0.011)
FDI	−0.004**	−0.001	0.001	−0.000	−0.004**	−0.008***
	(0.002)	(0.002)	(0.002)	(0.001)	(0.002)	(0.003)
IQ	1.083**			−16.421***		
	(0.454)			(3.308)		
LeffxIQ	−1.503***					
	(0.445)					
Internet		0.006			−0.060***	
		(0.005)			(0.017)	
Leffxinternet		−0.015***				
		(0.005)				
Mobile_phone			0.007***			0.009*
			(0.002)			(0.005)
Leffxmobile_phone			−0.002**			
			(0.001)			
Lcer				−0.844***	−0.326***	0.006
				(0.210)	(0.070)	(0.165)
LcerxIQ				3.717***		
				(0.801)		
Lcerxinternet					0.014***	
					(0.004)	
Lcerxmobile_phone						−0.001
						(0.001)
Constant	−0.939	−1.097*	−0.230	7.192***	2.784***	1.462
	(1.113)	(0.621)	(1.375)	(1.362)	(1.003)	(1.692)
Observations	397	397	397	397	397	397
Numbers of country	25	25	25	25	25	25
Diagnostic test					Statistics (p value)	
Hansen test statistic	13.7596 (0.6166)	19.3886 (0.2490)	12.1588 (0.7330)	12.6671 (0.6969)	16.7740 (0.4004)	12.0908 (0.7377)

Standard deviations in brackets ***P<0.01, **P<0.05, *P<0.1

at the 1% level. Otherwise, if FDI increases by 1%, CO_2 emissions decrease by 0.004% which is consistent with the Pollution Halo hypothesis. The significant negative relationship between FDI and CO_2 emissions shows that foreign direct investment can contribute to the adoption of cleaner industrial practices or the adoption of less polluting technologies. This can also be related to the environmental convergence hypothesis, raised by (Cole and Neumayer, 2006). Their research suggests that FDI can promote the adoption of stricter environmental standards in host countries, but also through immediate adjustments in environmental practices following foreign investment (Zhang et al., 2024).

Institutional quality has a negative and statistically significant effect at 5%. This means that any improvement in institutional quality results in a reduction in CO_2 emissions. Indeed, good quality institutions promote the implementation of environmental regulations and policies, thus leading to an improvement in environmental quality through the reduction of CO_2 emissions. This result is in line with those of (Diallo, 2024a; Haldar and Sethi, 2021; Yang et al., 2022).

As for the internet variable, it has a negative and significant coefficient at 10%. This result is intuitive insofar as an increase of one unit of internet results in a decrease in CO_2 emissions of 0.001%, all things being equal. Indeed, the internet will promote the transformation and modernization of companies to replace traditional resource-intensive products with technology-intensive products, thus improving energy efficiency, which will reduce CO_2 emissions. Empirically, this result corroborates those of Li et al. (2019).

In order to make objective economic policy recommendations, we further disaggregate institutional quality into its different components. The results presented in Table 7 show that only voice and accountability and the control of corruption can significantly reduce CO_2 emissions in sub-Saharan Africa.

4.1. Robustness Analysis

In order to test the robustness of our results, we use an alternative measure for our variables of interest. For energy efficiency (EFF) we take it as GDP per unit of energy consumed in line with studies

Table 7: Analysis with disaggregated institutional quality

Variables	(1)	(2)	(3)	(4)	(5)	(6)
	$LgCO_2$	$LgCO_2$	$LgCO_2$	$LgCO_2$	$LgCO_2$	$LgCO_2$
L.lgCO_2	0.443***	0.570***	0.421***	0.342***	0.417***	0.378***
	(0.120)	(0.061)	(0.060)	(0.078)	(0.061)	(0.075)
Lgdp	0.032	−0.287**	0.007	−0.936*	−0.000	−0.007
	(0.568)	(0.142)	(0.210)	(0.540)	(0.157)	(0.312)
Lcer	−0.256***	−0.154***	−0.065	−0.330***	−0.124*	−0.292***
	(0.080)	(0.052)	(0.071)	(0.080)	(0.074)	(0.088)
Leff	−0.339	−0.371**	−0.140	−1.027**	−0.152	−0.263
	(0.567)	(0.148)	(0.179)	(0.497)	(0.162)	(0.349)
Lenrh	0.358	0.365**	0.222	1.040**	0.210	0.249
	(0.569)	(0.144)	(0.162)	(0.484)	(0.146)	(0.364)
Urb	−0.016	0.043**	0.068***	0.053***	0.074***	0.056
	(0.053)	(0.017)	(0.013)	(0.019)	(0.016)	(0.040)
FDI	−0.001	−0.002	0.000	−0.003*	−0.000	−0.004**
	(0.002)	(0.002)	(0.001)	(0.002)	(0.001)	(0.002)
Mobile phone	−0.001	0.000	0.001**	−0.000	0.001***	0.000
	(0.001)	(0.000)	(0.000)	(0.001)	(0.000)	(0.001)
Internet	−0.000	−0.001**	−0.001**	−0.001	−0.000	−0.001
	(0.001)	(0.000)	(0.000)	(0.001)	(0.001)	(0.001)
Voice and responsibility	−0.136*					
	(0.081)					
Political stability		0.074***				
		(0.020)				
Effectiveness of public authorities			0.025			
			(0.037)			
Quality of regulation				−0.130		
				(0.107)		
Rule of law					−0.061	
					(0.041)	
Control of corruption						−0.157**
						(0.068)
Constant	1.445	0.016	−0.272	−2.378	−0.005	1.269
	(3.313)	(1.900)	(2.023)	(3.653)	(2.071)	(3.537)
Observations	397	397	397	397	397	397
Numbers of country	25	25	25	25	25	25
Diagnostic test						Statistics (p value)
Hansen test statistic	13.1361 (0.5158)	18.6541 (0.1786)	15.3844 (0.3524)	15.7040 (0.3318)	16.6132 (0.2774)	16.3022 (0.2953)

Standard deviations in brackets***P<0.01, **P<0.05, *P<0.1

Table 8: Robustness test

Variables	$LgCO_2$
L.lg CO_2	−0.033
	(0.206)
Lgdp	−0.856
	(0.737)
Lerh	−0.049*
	(0.028)
Leff	−1.394*
	(0.833)
Lenrh	1.006**
	(0.477)
Urb	−0.258
	(0.190)
FDI	0.019
	(0.014)
IQ	−3.389
	(3.148)
Internet	−0.019**
	(0.008)
Mobile phone	−0.003
	(0.002)
Constant	14.775
	(14.073)
Observations	250
Number of country	25
Diagnostics test	Statistic (p value)
Hansen test statistic	4.8019 (0.5695)

Standard deviations in brackets ***P<0.01, **P<0.05, *P<0.1

by Schneider (2020) and Shafiei and Salim (2014). Renewable energy consumption (REC) is taken as the logarithm of renewable energy consumption from renewable sources (hydro, biomass, solar, wind, tidal, waste and geothermal). Table 8 presents the robustness results.

These results show that energy efficiency and renewable energy consumption have a negative and significant effect on CO_2 emissions in SSA at the 10% threshold. This means that any increase in energy efficiency and renewable energy consumption reduces CO_2 emissions in SSA. This result is consistent with those of Schneider (2020) and Shafiei and Salim (2014). The similarity of the effects with the initial estimates leads to the conclusion that the results obtained are robust.

5. CONCLUSION AND POLICY IMPLICATIONS

The aim of this research was to analyze the effect of energy efficiency and renewable energy consumption on CO_2 emissions via transmission channels for 25 sub-Saharan African countries from 2002 to 2020. We apply the defactored instrumental variables estimation method to a dynamic panel. The results obtained with 2SIV show that the consumption of renewable energy reduces CO_2 emissions in SSA and that the promotion of energy efficiency leads to a significant reduction in CO_2 emissions. Also, interaction variables such as the energy efficiency product and the quality of institutions, the energy efficiency product and the degree of access to the internet and the energy efficiency product and access to mobile phones reduce CO_2 emissions in SSA.

The results found give rise to economic policy implications that decision-makers would be well advised to take into account. Firstly, it is necessary to promote the implementation of green technologies that reduce energy consumption and improve energy efficiency by facilitating access to the internet. Given that energy efficiency reduces CO_2 emissions when institutions are of better quality, our second recommendation is to improve institutional quality by fighting corruption. Fighting corruption and putting in place an effective regulatory framework will help mobilize investment in clean technologies and facilitate the energy transition through the implementation of sound environmental policies.

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