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Dynamic Analysis of Energy Consumption and Environmental Impact on GDP in Sub-Saharan Africa

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Abstract
This study aims to explore the interrelationship between energy consumption, CO2 emissions, and GDP for Sub-Saharan African countries from 2000 to 2019. To effectively address this complex issue, a dynamic simultaneous-equation model is employed. The empirical findings reveal several key interdependencies. Firstly, there is a bidirectional causal relationship between energy consumption and economic growth, indicating that not only does increased energy consumption drive economic growth, but economic growth also leads to higher energy consumption. Moreover, the results demonstrate a bidirectional relationship between energy consumption and electricity consumption. This suggests that energy consumption influences electricity usage, and vice versa, reflecting the integral role of electricity in the overall energy framework of these countries. However, the study also finds that an increase in pollutant variables negatively impacts electricity consumption. This negative relationship indicates that higher levels of pollution may hinder the efficiency or availability of electricity, possibly due to regulatory measures or the adverse effects of pollution on power generation infrastructure. Additionally, the analysis confirms that economic growth and CO2 emissions are interlinked in a bidirectional manner. As economic activities expand, CO2 emissions rise due to increased industrial activity, transportation, and energy consumption. Conversely, higher levels of CO2 emissions can affect economic growth, potentially through the impacts of environmental degradation and regulatory constraints aimed at controlling emissions. The findings underscore the intricate balance between fostering economic growth and managing environmental impacts in Sub-Saharan Africa. The bidirectional relationship between energy consumption and economic growth suggests that policies promoting energy efficiency and sustainable energy sources could support economic development without exacerbating environmental issues. Similarly, the link between economic growth and CO2 emissions highlights the need for integrating environmental considerations into economic planning and development strategies. To mitigate the negative impacts of pollutants on electricity consumption and overall energy efficiency, Sub-Saharan countries could benefit from investing in cleaner energy technologies and infrastructure improvements. This could include expanding renewable energy sources, such as solar and wind power, which are abundant in the region. Additionally, enhancing the regulatory framework to promote energy efficiency and reduce emissions can help balance economic growth with environmental sustainability.
Keywords: Energy Consumption, CO2 Emissions, Economic Growth
JEL Codes: Q43, Q56, O55

1. INTRODUCTION

Sub-Saharan Africa accounts for 13% of the world population, yet its economic growth has historically lagged behind other developing regions. However, since 2000, Sub-Saharan Africa has experienced rapid economic growth, which has driven a 45% increase in energy demand. The region is endowed with a diverse array of energy resources, albeit unevenly distributed across the continent. Notably, nearly 30% of global oil discoveries over the past decade have occurred in Sub-Saharan Africa. In addition to oil, the region possesses significant gas reserves and vast untapped renewable energy potential, including hydropower and solar energy. Despite the diversity of its energy resources, Sub-Saharan Africa primarily relies on biomass energy. Biomass accounts for over 30% of the continent's energy consumption and more than 80% in many Sub-Saharan countries. Biomass remains the main energy source for the majority of African households, yet it generates substantial CO2 emissions. This reliance on biomass energy has significant implications for the CO2-energy-economic growth nexus in the region. We focus on this nexus in 35 Sub-Saharan African countries to explore the dynamics between CO2 emissions, energy consumption, and economic growth. Our interest in these countries is twofold: firstly, Sub-Saharan Africa has substantial renewable and non-renewable energy resources that remain largely untapped. Secondly, most recent studies on this topic have centered on other developing regions such as Latin America, Asia, and the Middle East, leaving a research gap in understanding these dynamics in Sub-Saharan Africa. Our study aims to shed light on how the utilization of energy resources influences economic growth and CO2 emissions in Sub-Saharan Africa. Given the region's potential for both renewable and non-renewable energy development, understanding this relationship is crucial for formulating policies that can foster sustainable economic growth while mitigating environmental impacts. This research is particularly timely as Sub-Saharan Africa continues to develop its energy infrastructure and seeks to balance economic development with environmental sustainability.

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2. LITERATURE REVIEW

Several studies have examined the intricate relationships between CO2 emissions, energy consumption, GDP, and other factors like financial development and external trade. For instance, Halicioglu (2009) explored this relationship in Turkey and found a bidirectional causality between CO2 emissions and GDP, suggesting that economic growth and environmental degradation influence each other. However, Halicioglu noted no significant relationship between energy consumption and GDP, indicating that energy consumption might not directly drive economic growth in Turkey's context. Omri et al. (2015) investigated the dynamics in MENA (Middle East and North Africa) countries and discovered bidirectional causality between GDP and CO2 emissions, as well as between electricity consumption and GDP. This implies a mutual influence where economic growth and electricity consumption spur each other. Additionally, they found unidirectional causality from electricity consumption to CO2 emissions, highlighting that increased electricity use directly contributes to higher CO2 emissions in the MENA region. In a similar vein, Ozturk and Acaravci (2013) analyzed the long-run and causal effects of carbon emissions in Turkey. Their findings reinforce the significant interdependencies between economic growth, energy consumption, and CO2 emissions.

Saidi and Hammami (2016) extended this analysis to a panel of 58 countries, confirming that economic growth and energy consumption significantly impact CO2 emissions. Their study underscores the global nature of these relationships across diverse economic contexts. Al-Mulali and Sab (2012) focused on Sub-Saharan African countries and identified bidirectional causal relationships between energy consumption, CO2 emissions, economic growth, and financial development. Their study suggests that in Sub-Saharan Africa, energy consumption and economic growth are interlinked with environmental degradation, and financial development also plays a crucial role in this nexus. This indicates that as these economies grow and their financial sectors develop, energy consumption and CO2 emissions tend to increase, highlighting the challenges of balancing economic growth with environmental sustainability. Sadorsky (2010) and Zhang (2011) further enriched the discourse on energy consumption by examining the roles of financial development and alloy anodes, respectively. Sadorsky (2010) emphasized the impact of financial development on energy consumption, suggesting that financial markets can significantly influence energy use patterns. Zhang (2011) explored the effects of alloy anodes on energy consumption, indicating that technological innovations in materials can also alter energy consumption dynamics.

The relationship between economic growth and energy consumption has been extensively studied, yet there remains a lack of consensus in the findings. This inconsistency is often attributed to variations in methodological approaches and data sources. Diverse results have been reported regarding the existence and direction of causality between these variables, leading to significant implications for energy policy in both the short and long term. The nature of the causality between energy consumption and growth rate is crucial for shaping effective energy policies. Ozturk and Acaravci (2010) underscored this complexity in their investigation of CO2 emissions, energy consumption, and economic growth in Turkey. Kraft and Kraft (1978), through their Granger causality analysis using annual data from 1947 to 1974, concluded that economic growth Granger-causes energy consumption in the United States. This finding aligns with the works of Warr and Ayres (2010) and Payne (2009), who reported unidirectional causality from electricity consumption to economic growth in the USA. On the other hand, Cheng and Lai (1997) discovered unidirectional causality from GDP to energy consumption between 1954 and 1993. Such studies underscore the variability in causal relationships across different time periods and regions.

Contradictory findings are prevalent in this research area. For instance, Mehrara (2007) found that economic growth Granger-causes energy consumption in oil-exporting countries. In contrast, Glasure (2002) observed bidirectional causality between energy consumption and GDP in Korea. Fallahi (2011) identified bidirectional causal relationships between energy consumption and economic growth in the USA, a conclusion also supported by Yoo (2006), who analyzed both short-term and long-term causal effects between these variables. Other studies, including those by Wolde-Rufael (2005, 2004, 2010), Masih and Masih (1996), and Odhiambo (2010), have documented unidirectional causality from energy consumption to economic growth in various countries and regions. These findings indicate that in some contexts, energy consumption directly drives economic growth. These diverse results highlight the complexity of the energy-economic growth nexus and suggest that the relationship may vary significantly depending on regional characteristics, methodological approaches, and time periods analyzed. As a result, energy policies must be tailored to the specific economic and energy contexts of individual countries to effectively address their unique challenges and opportunities. The diversity in the direction of causation between energy consumption and economic growth across different geographical areas can be attributed to several factors such as the availability of local energy resources, the political and economic history of the region, and the specific energy policies that have been implemented. For example, Apergis and Payne (2009) examined the Commonwealth of Independent States (CIS) and found that the causal link between energy and economic growth may evolve over time. In the short term, the relationship may be unidirectional, whereas in the long term, it could become bidirectional. This temporal evolution indicates that the dynamics between energy consumption and economic growth are not static and can change as countries develop and their energy policies and infrastructures evolve. Overall, the complex nature of the relationship between economic growth and energy consumption underscores the importance of considering diverse factors and employing varied methodologies in empirical studies. Such an approach is crucial for deriving meaningful insights that can inform the formulation and implementation of effective energy policies.

Numerous studies have investigated this relationship across different regions, yielding a variety of findings. For instance, Chu (2012) conducted a study on 49 countries and identified four hypotheses regarding the relationship between energy consumption and economic growth: the growth hypothesis in 5 countries, the neutrality hypothesis in 24 countries, the conservation hypothesis in 13 countries, and the feedback hypothesis in 7 countries. These varying hypotheses illustrate the diverse ways in which energy consumption and economic growth can interact depending on the specific context of each country. Similarly, Wolde-Rufael (2006) focused on 19 African countries and found diverse patterns of causality. The study revealed unidirectional causality from energy consumption to economic growth in 7 countries, supporting the growth hypothesis. In 3 countries, the conservation hypothesis was supported, indicating that economic growth leads to increased energy consumption. The feedback hypothesis, which suggests bidirectional causality, was observed in 2 countries. Meanwhile, the neutrality hypothesis, which posits no causal relationship between energy consumption and economic growth, was found in 5 countries. These varied findings highlight the complexity and context-specific nature of the energy consumption-economic growth relationship. They suggest that policy-makers should carefully consider the unique circumstances of their own countries when designing and implementing energy policies. Understanding the specific causal dynamics in each country can help tailor policies that effectively promote both economic growth and sustainable energy consumption. Further investigation by Wolde-Rufael (2005) expanded on the understanding of the relationship between energy consumption and economic growth in African countries. This study examined 20 African countries and identified diverse patterns of causality. For 6 countries, there was a positive and significant impact of GDP on electricity consumption, indicating that economic growth led to increased electricity usage. Conversely, for two countries, there was a negative and significant impact of GDP on energy consumption, suggesting that economic growth was associated with decreased energy usage. Additionally, the study found a neutrality hypothesis for 9 countries, indicating no significant causal relationship between GDP and energy consumption. Furthermore, a conservation hypothesis was observed for two countries, implying that economic growth led to a decrease in energy consumption. Finally, there was one instance of the growth hypothesis, where economic growth positively impacted energy consumption in one country. In contrast, Lee and Chang (2008) conducted a study on 16 Asian countries and found no significant relationship between energy consumption and economic growth in the short run. This finding suggests that in the short term, changes in energy consumption may not have a discernible impact on economic growth in these countries. Studies focusing on specific African countries, such as those conducted by Jumbe (2004), Odhiambo (2009), and Belloumi (2009), have employed various econometric techniques to analyze the relationship between electricity consumption and economic growth. These studies have provided valuable insights into the nuanced dynamics between energy consumption and economic growth in different African contexts. For example, Jumbe's study supported the feedback hypothesis between electricity consumption and economic growth in Malawi, while Odhiambo's study found evidence of the feedback hypothesis in South Africa. Similarly, Belloumi's study identified the feedback hypothesis between electricity consumption and economic growth in Tunisia.

The complexity of this relationship becomes evident when considering findings from studies across different geographical regions and time periods. For instance, Mehrara (2007) found that economic growth Granger-causes energy consumption in oil-exporting countries, while Glasure (2002) reported bidirectional causality between energy and GDP in Korea. Similarly, studies focusing on specific countries or regions have yielded diverse results. For example, Wolde-Rufael (2005, 2004, 2010) and Masih and Masih (1996) found evidence of unidirectional causality from energy consumption to economic growth in various countries and regions. Conversely, studies by Fallahi (2011) and Yoo (2006) identified bidirectional causal relationships between energy consumption and economic growth in the USA. Moreover, studies examining different energy sources or specific sectors have further enriched the understanding of this relationship. For example, Sadorsky (2010) and Zhang (2011) investigated the impact of financial development and alloy anodes on energy consumption, respectively, providing insights into additional factors influencing energy dynamics.

The wide array of findings across different studies and regions underscores the complexity of the relationship between energy consumption and economic growth. Studies have revealed diverse causal relationships, ranging from unidirectional causality from energy consumption to economic growth to bidirectional causality and even varying causal directions depending on the country or region under investigation.

For instance, research conducted in various panel countries by Wolde-Rufael (2005, 2010) found evidence of unidirectional causality from energy consumption to economic growth. Conversely, in specific nations like India, energy was identified as a driving factor for economic growth (Masih and Masih, 1996). However, studies focusing on individual countries yielded contradictory results. For example, Odhiambo (2010) found one-way Granger causality from economic growth to energy consumption in Congo, while Mehrara (2007) identified causality running from economic growth to energy consumption in oil-exporting countries. In addition, studies conducted in the G-7 countries revealed varying forms of causality. For instance, GDP was found to cause energy consumption in Germany, while energy was identified as a driver of GDP in France and the United States. Moreover, bidirectional causality was observed in Italy, Canada, Japan, and the UK (Soytas and Sari, 2006). However, other research suggested that energy causes GDP in the G-7 countries over a different period (Vakiani et al., 2008). Furthermore, the possibility of evolving causality over time was demonstrated in Commonwealth countries, where unidirectional causality was observed in the short term, but bidirectional causality emerged in the long term (Apergis and Payne, 2009). Additional studies have also provided evidence of varying causal relationships between energy consumption and economic growth (Fallahi, 2011; Yoo, 2006).

The Environmental Kuznets Curve (EKC) hypothesis has been a focal point in research aimed at understanding the intricate relationship between economic growth and environmental degradation. Initially proposed by Kuznets in 1955, the EKC posits an inverted U-shaped relationship, suggesting that environmental pollution initially worsens with economic growth but eventually improves as economies reach a certain level of development. However, subsequent studies have yielded mixed results regarding the validity of this hypothesis. While some studies have provided evidence supporting the EKC in various economies (Selden and Song, 1994; Galeotti et al., 2009), others have found contrasting results, including a monotone positive relationship between economic growth and pollution (Holtz-Eakin and Selden, 1995) or even an "N" shaped relationship (Friedl and Getzner, 2003). Additionally, neutral relationships between economic growth and pollution have also been observed in certain studies (Agras and Chapman, 1999; Richmond and Kaufmann, 2006). Further exploration into the EKC hypothesis has revealed varying causality directions between economic growth and environmental pollution. Some studies have identified unidirectional causality from GDP to CO2 emissions (Jaunky, 2011; Fodha and Zaghdoud, 2010), while others have suggested a causal relationship running from CO2 emissions to GDP (Menyah and Wolde-Rufael, 2010). Moreover, bidirectional causality between CO2 emissions and economic growth has been reported in additional studies (Omri et al., 2014). These findings underscore the complexity and regional variations inherent in the relationship between economic growth, energy consumption, and environmental pollution. It is evident that a one-size-fits-all approach to energy policy may not be sufficient, highlighting the importance of tailored strategies that account for specific contextual factors. Further research is essential to gain a comprehensive understanding of these dynamics and to inform the development of effective energy policies that promote sustainable growth while mitigating environmental degradation. A third line of research has emerged, integrating the analysis of economic growth, energy consumption, and pollution, aiming to provide a more comprehensive understanding of their interplay. This integrative approach has been the focus of recent studies conducted by researchers such as Soytas, Sari, and Ewing (2007), Akbostancı, Türüt-Aşık, and Tunç (2009), Jalil and Mahmud (2009), Ozturk and Acaravci (2010), Payne (2010), and Alam et al. (2012). For instance, one study delved into the causal relationships between energy consumption, economic growth, and CO2 emissions across three ASEAN countries—Malaysia, Indonesia, and Singapore—spanning the period from 1975 to 2011. The results revealed country-specific variations: in Malaysia, there were unidirectional causalities from CO2 emissions to energy consumption and from energy consumption to economic growth. Conversely, in Indonesia, economic growth Granger-caused CO2 emissions, and energy consumption Granger-caused growth. Interestingly, no causal relationships were identified among the three variables in Singapore (Soytas, Sari, and Ewing, 2007).

Another study explored the causal link between energy consumption, CO2 emissions, and income in India from 1971 to 2006. The findings indicated a long-term bidirectional relationship between energy consumption and CO2 emissions. However, the study observed a neutral relationship between income and both energy consumption and CO2 emissions (Alam et al., 2011). In the Middle East and North Africa (MENA) region, research conducted over the period 1980-2008 revealed that CO2 emissions and oil consumption exhibited a long-term relationship with economic growth. Nevertheless, the estimates suggested a short-term bidirectional relationship between CO2 emissions, oil consumption, and economic growth (Al-mulali, 2012). Further research conducted on six Sub-Saharan countries between 1971 and 2009, employing the Autoregressive Distributed Lag (ARDL) model, revealed unidirectional Granger causality from GDP and energy consumption to CO2 emissions, with no evidence of bidirectional causality among the variables (Kivyiro and Arminen, 2014). These studies shed light on the intricate interplay between economic growth, energy consumption, and pollution, underscoring the necessity of simultaneously considering all three variables to formulate effective policies and strategies. The findings emphasize the variability in causal relationships across different regions and time periods, highlighting the importance of adopting a nuanced approach to understanding and addressing the nexus between these critical factors.

3. ECONOMETRIC MODEL

The objective of our study is to examine the interrelationship between economic growth, energy consumption, and CO2 emissions using the Cobb-Douglas production function. This extended production function provides a useful framework to explore the three-way linkages among these variables. In addition to energy consumption and CO2 emissions, we include labor force and capital as additional factors of production, similar to the approaches used by Ang (2008), Pao, Yu, and Yang (2011), and Menyah and Wolde-Rufael (2010), among others. These studies demonstrate that empirical economic growth also depends on energy consumption, which is closely related to CO2 emissions. The Cobb-Douglas production function, extended to include energy consumption and CO2 emissions, allows for a comprehensive analysis of how these factors interact and influence economic output. This approach acknowledges that energy consumption is not only a crucial input for production but also a significant source of CO2 emissions, thereby linking economic activities directly to environmental outcomes. By incorporating labor and capital into the model, we aim to capture the complete spectrum of production inputs and their impact on both economic growth and environmental degradation.

According to the literature review, most studies claim that economic growth leads to changes in CO_2 emissions, it has also mentioned that energy consumption is a main cause of carbon emissions. It is therefore worth to examine the interrelationship between GDP, energy consumption and CO_2 emissions by considering them simultaneous them simultaneously in a modeling framework.

$$\mathrm{LnY_{it}} = \alpha_0 + \alpha_{1i}\mathrm{lnEL_{it}} + \alpha_{2i}\mathrm{lnCO2_{it}} + \alpha_{3i}\mathrm{lnL_{it}} + \alpha_{4i}\mathrm{lnK_{it}}\ \mu_{it} \qquad (1)$$

$$\mathrm{LnEL_{it}} = \alpha_0 + \alpha_{1i}\mathrm{lnY_{it}} + \alpha_{2i}\mathrm{lnCO2_{it}} + \alpha_{3i}\mathrm{lnOILP_{it}} + \alpha_{4i}\mathrm{lnCPI_{it}}\ \mu_{it} \qquad (2)$$

$$\mathrm{lnCO2_{it}} = \alpha_0 + \alpha_{1i}\mathrm{lnEL_{it}} + \alpha_{2i}\mathrm{LnY_{it}} + \alpha_{3i}\mathrm{lnINDVA_{it}} + \alpha_{4i}\mathrm{lnURB_{it}}\ \mu_{it} \qquad (3)$$

Equation (1) suggests that variables such as energy consumption, CO2 emissions, labor force, and capital can collectively determine economic growth. The relationship between energy consumption and economic development has been extensively studied, with findings indicating a strong linkage between a country's income and its energy consumption. Stern (2000) highlighted the role of energy consumption as a driver of economic development in the USA, a relationship supported by Masih and Masih (1996) and Wolde-Rufael (2005). Furthermore, CO2 emissions also play a significant role in influencing economic growth. Research by Dinda and Coondoo (2006) and Saboori, Sulaiman, and Mohd (2012) has demonstrated that environmental degradation, often represented by CO2 emissions, can have adverse effects on economic growth. A decline in environmental quality can constrain economic activities, underscoring the importance of environmental considerations in the pursuit of sustainable economic development. This highlights the delicate balance between harnessing energy resources for economic growth and mitigating the environmental impacts associated with it. Equation (2) presents the interaction between CO2 emissions, GDP, and electricity consumption, aiming to shed light on how electricity consumption responds to these variables. Previous studies have yielded varied findings regarding this relationship, reflecting diverse dynamics across different regions and contexts. For instance, Belloumi (2009) and Kivyiro and Arminen (2014) observed distinct patterns in Tunisia and Sub-Saharan Africa, respectively, while Soytas and Sari (2009) and Lotfalipour, Falahi, and Ashena (2010) explored similar themes in the EU and Iran. To enhance the model's robustness, we incorporate oil prices (OIL-PRICE) and the consumer price index (CPI) as additional variables, drawing on insights from studies such as Chandra et al. (2010), Lean and Smyth (2010), Mahadevan and Asafu-Adjaye (2007), and Tang and Tan (2013). These investigations suggest that oil prices exert a positive influence on electricity consumption, whereas CPI exerts a negative impact. By integrating these variables into the analysis, we aim to provide a more comprehensive understanding of the intricate relationship between economic growth, energy consumption, and environmental considerations, while accounting for key economic indicators that shape energy demand. Equation (3) delves into the determinants of CO2 emissions, aiming to elucidate the factors that influence the level of emissions. Previous research has underscored the pivotal role of electricity consumption in mitigating CO2 emissions. Studies by Soytas, Sari, and Ewing (2007) and Soytas and Sari (2009) have demonstrated that higher electricity consumption correlates with reduced CO2 emissions. Conversely, an uptick in income typically corresponds to an increase in CO2 emissions, as evidenced by investigations conducted by Wang et al. (2011) and Ozturk and Acaravci (2010). This trend suggests that as economies expand and income levels escalate, the demand for energy surges, consequently driving up emissions.

Energy consumption indeed stands as a pivotal factor in driving up CO2 emissions, as underscored by research findings. Studies by Halicioglu (2009) and Apergis et al. (2010) have indicated a direct correlation between heightened energy consumption and increased CO2 emissions. This linkage highlights the critical role of energy consumption patterns in shaping environmental outcomes and underscores the imperative of transitioning towards cleaner energy sources and enhancing energy efficiency measures. Moreover, urbanization, quantified by the rate of urban population to the total population (URB), emerges as another influential factor impacting CO2 emissions. Research conducted by Al-mulali (2012) and Parikh and Shukla (1995) has illustrated that urbanization tends to elevate CO2 emissions owing to heightened energy usage in urban settings. The concentration of population and economic activities in urban areas amplifies the demand for energy, predominantly sourced from fossil fuels, thereby contributing to increased emissions. Addressing the environmental repercussions of urbanization necessitates concerted efforts towards sustainable urban planning, energy-efficient infrastructure, and promoting renewable energy sources to mitigate CO2 emissions.

Including industrial value-added (INDVA) as a variable enriches our analysis, given its significant impact on CO2 emissions. Research by Shahbaz et al. (2014) and Nejat et al. (2015) underscores that as industrial activities expand, they typically lead to higher CO2 emissions owing to the energy-intensive nature of manufacturing and production processes. This comprehensive approach to examining the determinants of CO2 emissions provides a nuanced understanding of how various economic and demographic factors interplay to influence environmental outcomes. To scrutinize the interrelationship between variables, our models were concurrently estimated using the generalized method of moments (GMM) estimator, as proposed by Arellano and Bond (1991). The GMM approach is widely adopted in models with panel data due to its capability to address endogeneity issues effectively. This method employs a set of instrumental variables to mitigate potential bias arising from the correlation between lagged dependent variables and error terms. By tackling these econometric challenges, the GMM estimator yields more reliable and consistent parameter estimates, enhancing the robustness of our empirical findings. Our analysis utilizes annual data spanning the period 2000-2012, encompassing GDP per capita (constant US$), CO2 emissions in metric tons, electricity consumption in kWh per capita, urbanization (the urban population as a share of the total population), industrial value-added measured in real per capita terms, and the consumer price index serving as the energy price index. Additionally, POL-PRICE is employed as the price of substitutable energy. Labor force data, measured in thousands of workers, and capital are also included. Data for these variables are sourced from the World Development Indicator (WDI). Focusing on Sub-Saharan African countries, we selected 35 nations based on data availability, ensuring comprehensive coverage for our analysis.

4. RESULTS AND DISCUSSIONS

In our analysis, we commence by conducting a unit root test, a fundamental step aimed at assessing the stationarity of variables to determine their inclusion in the empirical model. The unit root test, introduced by Dickey and Fuller (1979), evaluates the presence of a unit root autoregressive process, which is vital for analyzing long-term processes involving static series. Notably, this test has been extended to panel data by Levin, Lin, and Chu (2002), addressing the heterogeneity inherent in such datasets by incorporating specific constants. The adaptation of the unit root test to panel data is particularly relevant due to the diverse forms of heterogeneity present, assuming the existence of individual fixed effects to account for these variations. Additionally, the method advanced by Im, Pesaran, and Shin (2003) has emerged as a standard approach for testing unit roots in heterogeneous panels. This approach plays a crucial role in understanding the dynamic properties of the data and ensuring that the variables employed in the empirical model exhibit appropriate levels of integration. By rigorously evaluating stationarity, we can ascertain the suitability of variables for inclusion in our analysis, thereby enhancing the robustness and reliability of our empirical findings. We employ the Arellano and Bond (1991) Generalized Method of Moments (GMM) approach to assess the interactions between CO2 emissions, GDP, and energy consumption across all countries. This method effectively addresses potential endogeneity issues by utilizing a set of instrumental variables. Our analysis comprises three distinct specifications, each corresponding to a different equation aimed at capturing the nuanced relationships between the variables.

In the first specification, we delve into the determinants of economic growth, incorporating variables such as labor force and capital alongside energy consumption and CO2 emissions. This approach follows the extended Cobb-Douglas production function framework, providing valuable insights into how energy consumption and CO2 emissions contribute to economic output while considering the influence of other production factors. Moving to the second specification, we explore the interaction between CO2 emissions and GDP with electricity consumption. This equation aims to elucidate how electricity consumption behaves in the presence of CO2 emissions and GDP. We include factors such as oil prices and the Consumer Price Index (CPI), as suggested by previous studies (Soytas and Sari, 2009; Kivyiro and Arminen, 2014). Oil prices are expected to positively impact electricity consumption, whereas CPI is anticipated to have a negative effect. Finally, the third specification concentrates on the determinants of CO2 emissions. Here, we examine the significant role of electricity consumption in reducing CO2 emissions and how increases in income and energy consumption influence CO2 emissions. Additionally, we incorporate urbanization and industrial value-added as factors influencing CO2 emissions, aligning with findings from studies by Halicioglu (2009) and Shahbaz et al. (2014). This comprehensive approach allows us to gain a deeper understanding of the intricate dynamics shaping environmental outcomes and economic growth across diverse contexts. These specifications provide a structured framework for comprehending the intricate interplay between CO2 emissions, GDP, and energy consumption across diverse countries, leveraging the robustness of the GMM approach. Through this comprehensive analysis, we aim to contribute to the ongoing discourse surrounding the environmental Kuznets curve and the energy-growth nexus, offering valuable insights into the dynamic interactions that shape both economic prosperity and environmental sustainability.

Our empirical findings reveal several key insights. Firstly, economic growth exhibits a significant positive effect on CO2 emissions, with a coefficient of 0.458. This implies that CO2 emissions increase by 0.458% with a 1% rise in GDP, underscoring the pivotal role of economic expansion in driving environmental degradation. This trend is particularly pronounced in sub-Saharan countries, where reliance on fossil fuels as the primary energy source contributes to elevated pollution levels. These results align with similar findings by Halicioglu (2009) in Turkey and De Freitas and Kaneko (2011) in Brazil, highlighting the common trajectory wherein economic growth often accompanies environmental deterioration. Conversely, our analysis reveals a negative and significant relationship between electricity consumption and CO2 emissions. Specifically, a 1% increase in electricity consumption corresponds to a 0.139% decrease in CO2 emissions, suggesting that greater electricity usage can indeed contribute to environmental preservation. This inverse association underscores the potential of electricity consumption as a means to mitigate CO2 emissions, aligning with broader environmental objectives aimed at promoting sustainable energy practices. Regarding urbanization, our findings indicate a negative yet statistically insignificant impact on CO2 emissions, consistent with observations by Al-Mulali (2014). This suggests that urbanization alone may not exert a substantial influence on CO2 emissions, possibly owing to variations in urban planning strategies and environmental policies across different regions. Additionally, our analysis reveals a negative and significant effect of industrial value-added on CO2 emissions, implying that a 1% increase in industrial value-added corresponds to a minute 0.006% decrease in CO2 emissions. While this effect size is relatively small, it suggests that industrial activities may indeed contribute to emission reduction efforts, echoing findings by Shahbaz et al. (2014). However, it's worth noting that studies like those by Islam et al. (2003) and Bala and Yusuf (2003) have highlighted significant pollution increases associated with industrialization in specific contexts like Bangladesh, underscoring the importance of considering regional nuances in assessing the environmental impact of industrial growth.

Table 3: Outcomes of GMM

Variables	Model (1) CO_2 Coefficient/p-value	Model (2) EC Coefficient/p-value	Model (3) GDP Coefficient/p-value
CO_2	-	-10.7383 (0.000)***	2.7883 (0.000)***
INDVA	-0.0060 (0.011)**	-	-
GDP	0.4548 (0.000)***	3.4059 (0.000)***	-
EC	-0.1397 (0.000)***	-	0.2489 (0.000)***
URB	-0.00082 (0.988)	-	-
OILPRICE	-	-0.0051 (0.014)**	-
CPI	-	-0.00006 (0.968)	-
GFCG	-	-	0.1646 (0.010)**
LABOR	-	-	-0.1515 (0.032)**
Const	-0.4 (0.000)***	-0.1394 (0.280)	-0.3201(0.000)***
Hansen J-test	21.81 (0.351)	20.96 (0.339)	23.47 (0.266)
DWH test (p-value)	29.425 (0.000)***		16.533 (0.000)***
AR2 test	-1.07 (0.284)	-0.99 (0.323)	-1.68 (0.092)*

The empirical results shed light on the dynamic relationship between GDP, CO2 emissions, and electricity consumption, revealing noteworthy insights into energy consumption patterns and environmental impacts. Specifically, the positive and significant effect of economic growth on electricity consumption confirms the conservation hypothesis, which posits a unidirectional causal relationship from growth to energy consumption. This suggests that implementing stringent energy policies aimed at curbing consumption may not necessarily impede economic growth, offering a viable avenue for sustainable energy management. The coefficient of GDP, estimated at 3.406, signifies that a 1% increase in GDP per capita corresponds to a 3.406% rise in energy consumption. This underscores the close link between economic prosperity and energy demand, highlighting the imperative of balancing growth objectives with energy sustainability considerations. Moreover, the negative and significant effect of CO2 emissions on electricity consumption underscores the inverse relationship between energy consumption and environmental pollution. Specifically, a 1% increase in CO2 emissions results in a substantial 10.738% decrease in electricity consumption. This indicates that efforts to mitigate CO2 emissions could inadvertently lead to reduced energy consumption, suggesting the potential for co-benefits in pursuing environmental and energy policy objectives. The prevalent use of biomass for energy purposes in Sub-Saharan Africa, accounting for a significant portion of energy consumption, underscores the region's reliance on traditional and often polluting energy sources for daily necessities like cooking and heating. This highlights the urgent need for sustainable energy interventions to address both environmental and social welfare challenges in the region. Furthermore, the negative and insignificant effect of the Consumer Price Index (CPI) on energy consumption (-0.0051) suggests that energy price dynamics may not significantly influence consumption behavior. This could be attributed to various factors, including inadequate infrastructure and investment in renewable energy sectors, as well as high energy costs in remote or isolated areas with sparse populations. The lack of affordability and accessibility to energy services may deter consumption despite underlying demand, emphasizing the importance of addressing these barriers to foster inclusive and sustainable energy access.

The existing literature on the relationship between the Consumer Price Index (CPI) and energy consumption corroborates the findings observed in the empirical analysis, particularly in the context of selected African countries. Studies by Apergis and Payne (2010), Ozturk et al. (2010), Mahadevan and Asafu-Adjaye (2007), and Odhiambo (2010) have similarly highlighted the intricate interplay between energy prices, economic growth, and consumption behaviors in African settings. These studies underscore the complexity of the relationship between CPI and energy consumption, emphasizing that its influence is multifaceted and contingent on various socio-economic factors unique to each context. While CPI may exert some degree of influence on energy consumption patterns, its impact is nuanced and requires careful consideration of factors such as income levels, infrastructure development, and government policies.

The empirical evidence suggests that the relationship between CPI and energy consumption cannot be viewed in isolation but must be understood within the broader socio-economic context of each country or region. Factors such as income inequality, access to energy infrastructure, and the availability of alternative energy sources all shape the dynamics of energy consumption and its responsiveness to changes in price levels.

The empirical findings provide valuable insights into the intricate relationships between energy consumption, CO2 emissions, labor dynamics, and GDP. The positive effect of energy consumption on GDP, as evidenced by a 1% increase in energy consumption leading to a 0.249% increase in per capita GDP, supports the validity of the growth hypothesis. This suggests that energy plays a vital role in the production process, acting as a complementary factor alongside traditional inputs like capital and labor. The findings align with the notion that energy availability and efficiency are crucial drivers of economic growth. Moreover, the significant influence of CO2 emissions on GDP underscores the complex relationship between economic development and environmental considerations. The observed 2.788% increase in economic growth corresponding to a 1% increase in CO2 emissions suggests that economic activities often come with environmental costs. While economic growth is desirable for improving living standards, it is essential to address the environmental implications and strive for sustainable development practices. Conversely, the negative impact of labor on GDP highlights the challenges associated with human capital dynamics in economic development. Factors such as education levels, skill mismatches, and brain drain can hinder productivity and overall economic growth. The observed decrease of 0.151% in GDP with a 5% increase in labor underscores the need for targeted policies to enhance labor productivity and address structural inefficiencies in labor markets. Overall, these findings emphasize the complex and interdependent nature of economic development, where energy consumption, environmental considerations, and labor dynamics intersect. Policymakers and stakeholders must consider these relationships comprehensively when formulating development strategies to ensure sustainable and inclusive growth that balances economic prosperity with environmental preservation and human capital development.

5. CONCLUSIONS

The objective of this study is to explore the causal relationship between energy consumption per capita, GDP per capita, and CO2 emissions per capita in sub-Saharan countries. While previous research has investigated this relationship individually, this study aims to analyze the interactions among these variables using simultaneous equations. By employing annual data spanning from 2000 to 2019, we seek to provide a comprehensive understanding of how energy consumption, economic output, and carbon emissions influence each other in the context of sub-Saharan Africa. While numerous studies have examined the relationship between these variables within sub-Saharan countries, few have employed simultaneous equation models to capture the dynamic interplay among them. By incorporating simultaneous equations, this study seeks to overcome the limitations of single-equation models and provide a more robust analysis of the causal links between energy consumption, GDP, and CO2 emissions. The inclusion of control variables allows us to account for potential confounding factors that may influence the relationship between energy consumption, GDP, and CO2 emissions. By controlling for these variables, we can more accurately isolate the causal effects of energy consumption and economic output on carbon emissions, providing valuable insights for policymakers and stakeholders in the region. By examining these causal triangles, we can discern overarching trends. Firstly, the presence of neutral causal relationships is minimal. Instead, our analysis sheds light on one of the hypothetical relationships outlined in the literature, namely the feedback hypothesis, which posits a bidirectional relationship between GDP, CO2 emissions, and energy.

Contrary to the neo-classical assumption that energy is neutral for growth, our empirical findings strongly reject this notion. Specifically, our results reveal bidirectional causality between energy consumption and economic growth. A higher level of energy consumption corresponds to increased economic growth, and vice versa. This bidirectional relationship underscores the interconnectedness between energy consumption and economic prosperity. Moreover, the increase in economic growth amplifies the demand for energy, exerting pressure on environmental quality. Overall, our findings challenge conventional assumptions and highlight the dynamic interactions between energy consumption, economic growth, and environmental sustainability. By elucidating these complex relationships, our study provides valuable insights for policymakers and stakeholders seeking to promote sustainable development while addressing the challenges posed by energy consumption and environmental degradation. Our findings underscore a bidirectional causal relationship between energy consumption and CO2 emissions, as well as between economic growth and CO2 emissions. While economic growth contributes to environmental pollution, energy consumption can have both positive and negative impacts on the environment.

This complexity arises from the prevalent use of fossil fuels in sub-Saharan countries, where biomass remains a primary energy source. To address these challenges, sub-Saharan countries must enhance their energy potential, invest in infrastructure development, expand electrification networks, and prioritize the adoption of renewable energy sources for electricity generation. By transitioning towards renewable energy, these nations can mitigate the adverse environmental effects associated with energy consumption while fostering sustainable economic growth. However, implementing such policies requires a concerted effort and coordinated action across various sectors. It necessitates the formulation and implementation of integrated economic, energy, and environmental policies. Moreover, given the scale and scope of these challenges, regional cooperation and collaboration may be essential to achieve meaningful progress. Ultimately, the question of whether these public policies can be effectively implemented on a continental scale remains. While it presents significant challenges, concerted efforts, political will, and international cooperation can pave the way for sustainable development and environmental conservation across sub-Saharan Africa.

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