

DISAGGREGATED ANALYSIS OF THE EFFECTS OF ENERGY CONSUMPTION ON GREENHOUSE GAS EMISSIONS IN AFRICA



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ABSTRACT

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This study investigates the effect of energy consumption on greenhouse gas (GHG) emissions in 33 African countries from 1995–2017. It contributes to the literature by investigating the effect of disaggregated measures of energy consumption (coal, oil and other liquids, renewable energy, and electricity) on GHG emissions (CO₂, N₂O, CH₄, and total GHG emissions) in Africa and identifies the transmission channels through which energy consumption affects GHG emissions. The system GMM is used in the study as it accounts for possible endogeneity and the potential correlation between the error term and the country fixed effects. The results show that coal consumption significantly increases CO₂, CH₄, and total GHG emissions and reduces N₂O emissions. Oil consumption increases CO₂ and total GHG emissions but reduces N₂O and CH₄ emissions. Renewable energy consumption reduces CO₂ and CH₄ emissions but increases N₂O emissions. Finally, electricity consumption promotes CO₂, N₂O, CH₄ and total GHG emissions in Africa. Further analyses show that foreign trade and economic growth are the channels through which oil consumption increases GHG emissions. The adverse effect of electricity is through urbanization. Renewable consumption could decrease GHG emissions through sustainable urbanization and trade policies. The findings suggest that countries should gradually reduce coal consumption and encourage renewable energy consumption, which has the lowest impact on the environment.

Contribution/Originality: This study differs from the existing literature in that it disaggregates total GHG emissions into CO₂ emissions, nitrous oxide (N₂O) emissions, and methane (CH₄) emissions to avoid aggregation bias. It also differs from other studies by examining the channels through which energy consumption affects GHG emissions in Africa.

1. INTRODUCTION

Energy is essential for daily activities. All living organisms need energy to develop and humans need it for cooking, heating, air conditioning, lighting, travel and transportation, production, entertainment, etc. (Zahid, 2008). Although contributing to 4% of the world's energy consumption, energy demand in Africa is constantly growing. It increased by 63.5% between 2000 and 2020 compared to the world average of 42.1% (Statistics, 2022). More

specifically, Africa's primary energy consumption rose from 12.32 quadrillion Btu¹ in 2000 to 19.96 quadrillion Btu in 2016. The different sources are broken down as follows: Coal consumption increased from 2.238 quadrillion Btu in 1980 to 4.6887 quadrillion Btu in 2016, surpassing 3.9997 quadrillion Btu in 2000; natural gas increased from 0.8338 quadrillion Btu in 1980 to 2.2020 quadrillion Btu in 2000 and to 5.0522 quadrillion Btu in 2016; oil and other liquids increased from 3.0719 quadrillion Btu in 1980 to 5.1922 quadrillion Btu in 2000 and to 8.6451 quadrillion Btu in 2016; finally, the amount of energy produced by nuclear power, renewables, and other sources increased from 0.6381 quadrillion Btu in 1980 to 1.5770 quadrillion Btu in 2016, surpassing 0.9287 quadrillion Btu in 2000 (EIA, 2019).

Although energy consumption plays a vital role in sustaining economic growth, its environmental costs cannot be ignored. Accordingly, Khan, Khan, Zaman, and Naz (2014) argued that around 64.1% of the world's anthropogenic GHG emissions are generated from the production and consumption of energy. The adverse effects of the energy sector on the environment comes from transportation, industrial production, construction, heating, etc. Concern regarding the environmental impact of energy consumption is reinforced by the dependence on fossil fuels (coal, oil, natural gas, etc.), which contribute to 80% of global energy demand (World Bank, 2019). Although admitted as a solution to global warming, the contribution of renewable energy to the world energy system remains insufficient. Increasing its share in the energy mix would reduce GHG emissions and bring a range of positive impacts, including an increase in gross domestic product (GDP), an improvement in global welfare, and employment in the renewable energy sector (IRENA, 2016). Many studies have investigated the effect of energy consumption on environmental quality, primarily measured by CO₂ emissions (Ang, 2007; Ang, 2008; Lean & Smyth, 2010; Menyah & Wolde-Rufael, 2010; Ozturk & Acaravci, 2010; Soytaş, Sari, & Ewing, 2007; Zhang & Cheng, 2009). Even when the energy mix is separated into renewable and non-renewable sources, the findings on the environmental effects of energy consumption are mixed.

Previous studies have mostly investigated the effects of renewable and non-renewable energy consumption on CO₂ emissions. However, CO₂ emissions do not reflect the overall state of air pollution. Therefore, this study attempts to fill the gap in the empirical literature by investigating the effect of energy consumption on GHGs at a disaggregated level. More specifically, it investigates the effects of coal, oil and other liquids, renewable energy, and electricity consumption on overall GHG emissions. It also disaggregates total GHG emissions into carbon dioxide (CO₂) emissions, nitrous oxide (N₂O) emissions, and methane (CH₄) emissions to avoid aggregation bias, as reported by Nkengfack and Kaffo (2019). Lastly, this paper uses the system GMM framework to account for possible endogeneity arising from the reverse causality between the dependent and independent variables (Omri, 2020) and the potential correlation between the error term and the country fixed effects (Dhahri & Omri, 2020).

After the introduction, the outline of this study is as follows: Section 2 presents the literature review; Section 3 presents the data and methodology; Section 4 presents the main results and discussions; and Section 5 presents the conclusion and implications.

2. LITERATURE REVIEW

The role of energy consumption on pollutants and emissions has been investigated by many authors. This role is seen in the study of Zou and Zhang (2020) in China, who used the spatial Durbin model with oil as the energy variable. They concluded that energy consumption increases carbon dioxide emissions. In the same vein, Zakari, Adedoyin, and Bekun (2021) examined the effect of energy consumption on the environment for OECD (Organization for Economic Cooperation and Development) countries from 1985 to 2017. They concluded that

¹ On a small scale, a quadrillion represents a number to the power of 15 (10¹⁵). On a long scale, it represents a number to the power of 24 (10²⁴), or a million to the power of four (10⁶). Btu (British thermal unit) is an Anglo-Saxon unit of measurement. It is used to represent the amount of heat required to raise the temperature of one gram of water by one degree Celsius or the temperature of one pound of water by one degree Fahrenheit.

energy has a positive link with CO₂ emissions. The conclusions of Ibrahim and Cudjoe (2021) are the same. They studied the environmental impact of energy consumption in Nigeria from 1990 to 2018 and found that wood, gas and oil consumption increased CO₂ emissions. Moreover, Osuntuyi and Lean (2022) in their study on heterogeneous countries found that energy consumption is linked to environmental degradation. Also, Ahmad, Ozturk, and Majeed (2022) investigated the asymmetric impact of energy consumption on environmental pollution from 1970 to 2019 in Pakistan, India and Bangladesh. Their results show that traditional energy sources (oil, coal, gas, and electricity) stimulate carbon emissions. Similar results were found by Saboori, Zaibet, and Boughanmi (2022). Their study on Oman from 1984 to 2014 using the fully modified ordinary least squares (FMOLS) and dynamic ordinary least squares (DOLS) methods showed that energy is positively linked to the environment.

However, Hanif (2018), in his study on 24 economies in Sub-Saharan Africa from 1995 to 2015, concluded that the use of renewable energy sources improves air quality. Also, Chen and Lei (2018) found a negative impact of renewable energy on CO₂ emissions. Similar results were obtained by Wang and Dong (2019) in Sub-Saharan Africa from 1990 to 2014. Awodumi and Adewuyi (2020) conducted a study on oil-producing countries from 1980 to 2015 using the autoregressive distributed lag (ARDL) model. The results show that oil and gas used as non-renewable energies reduced carbon emissions in Nigeria. Moreover, Ehigiamusoe (2020) examined the effect of electricity consumption of diverse sources (hydro, oil, gas and coal) on CO₂ emissions in 25 African countries from 1980 to 2016. The results based on the DOLS, FMOLS and AMG (augmented mean group) show that energy consumption has a detrimental effect on carbon emissions.

This enables us to formulate the following hypotheses:

H1: A positive link exists between non-renewable energy consumption and environmental degradation.

H2: A negative link exists between renewable energy consumption and environmental degradation.

Despite significant progress in the literature on the nexus between energy and GHG emissions, studies have failed to empirically identify the mechanisms² through which energy consumption impedes or improves the environmental quality. From the literature, urbanization, trade openness, and economic growth were selected as potential transmission channels in this study.

The trend toward urbanization has historically been suggested as a prerequisite for development. Since the industrial revolution, it has been widely accepted that the logic behind industrial–urban links may be the precursor to growth and the subsequent economic well-being of society. The trend toward industrial–urban interconnections has proved futile, as the consequences of environmental degradation are found in many developed economies, and in recent days, environmental degradation has even prevailed in developing and transitioning economies. The consequences of environmental degradation include acid rain, haze/smog, carbon dioxide emissions, and greenhouse gas problems. The urbanization process has already reached over 50% across the world. Half of the world's population living in urban areas will consume more than 50% of global energy and produce more than 60% of the carbon dioxide emissions that contribute to global warming in the years to come (Behera & Dash, 2017). In addition, millions of people are leaving rural areas and are adding to the growing population of urban areas. This migration creates pressure on urban development and urban energy supply. Urbanization can promote economic growth and improve living standards, but it can also increase energy consumption (Al-Mulali & Sab, 2012) and, in turn, result in energy crises. Since the early 1990s, there has been a dramatic increase in energy demand spurred by industrial development and population growth, leading to a greater demand for global energy supply as the gap between domestic supply and demand widens (Wang, 2014).

Trade openness involves a process aimed at reducing barriers to economic exchanges between nations. It involves the internationalization of internal trade by allowing greater production opportunities to meet consumer demand beyond national borders. The link between trade and energy consumption confirms that trade openness has

² In this study, we assume that transmission channels are the variables through which changes in ICT affect environmental quality.

exacerbated energy consumption due to additional production needed to meet international demand (Shahbaz, Nasreen, & Afza, 2014). This implies that the export of finished products and raw materials requires substantial and easily usable energy, otherwise international trade would be adversely affected. Therefore, energy has become a key player in opening up trade. In addition, the negative side of the heavy dependence on fossil fuels in production is also recognized in the literature, for example, it creates a disadvantageous position by increasing the cost of production and ultimately setting a higher price for national products (Shahbaz, Logana, Zeshan, & Zaman, 2015). The replacement of fossil fuels with renewable energies has a positive effect on the production process with the reduction of production costs. Therefore, reliance on renewable energy, especially for exported products globally, indicates a positive link between trade openness and renewable energy consumption (Qamruzzaman & Jianguo, 2020).

Energy is an essential factor for the socio-economic development of any community, but it is also a fundamental factor of production (Reilly, 2015). It is used to meet certain basic needs in daily life. With the evolution of the world, the use of existing energy sources has made it possible to improve living environments. Also, the type of energy used and the quantity consumed are indicators of the level of socio-economic development due to the objectives of sustainable development, the lack of access to electricity and the low efficiency of energy from fuel (Kebede, Kagochi, & Jolly, 2010). Energy is thus recognized as essential for the development of mankind. Access to energy is important for the development and well-being of individuals (IEA, 2017). Ahmad et al. (2016) considers it as the oxygen that gives life to all economic activity. It is regarded as the lifeline of an economy, the most vital instrument of socio-economic development, and is recognized as one of the most important strategic products (Sahir & Qureshi, 2007). This underlines its importance in any process of production and economic growth.

This brings us to the third hypothesis:

H3: Energy consumption can affect greenhouse gas (GHG) emissions through urbanization, trade openness, and economic growth.

3. METHODOLOGY

3.1. Data

To study the effect of energy consumption on economic growth in Africa, secondary source quantitative panel data is used for 33 countries from 1995–2017 (see the Appendix for the list of countries). Data on energy consumption were taken from the Energy Information Administration (EIA, 2018). Data relating to CO₂ emissions per capita, N₂O emissions per capita, CH₄ emissions per capita, GHG emissions per capita, GDP per capita, trade openness, urbanization, population growth, financial development, and foreign direct investments were extracted from the World Bank database (World Development Indicators, 2018).

3.2. Model

To investigate the effect of energy consumption on GHG emissions, we rely on the stochastic regression of the population affluence and technology (STIRPAT) model established by Dietz and Rosa (1994). This model was established to account for the effect of anthropogenic activities on the environment. The baseline model is represented as follow:

$$I = aP^b A^c T^d e \quad (1)$$

Where I represents environmental pressure; P represents the population; A represents affluence; T represents technology; a represents the coefficient of the model; b , c and d represent the coefficients of each independent variable; and e represents the error term.

Equation 1 is then written in log form to reduce the size of the variables and minimize the risk of heteroskedasticity. The model is thus written as follows:

$$\ln I = a + b \ln P + c \ln A + d \ln T + \ln e \quad (2)$$

Here, b , c , and d represent the elasticities of population, affluence, and technology, respectively.

It is then extended to account for the effects of other determinants of GHG emissions, such as energy consumption. This extension is useful as it helps to minimize the bias of omitted variables. Equation 2 is thus rewritten as follows:

$$\ln emis_{2it} = \alpha_0 + \alpha_1 \ln X_{it} + \alpha_2 \ln Z_{it} + \xi_{it} \quad (3)$$

Where $emis$ represents the different GHG emissions; X is a vector of the variables of interest, including energy consumption variables; and Z is a vector of the control variables.

Based on the data at our disposal, we segment the basic equation into five equations that take into account the effects of coal, oil and other liquids, renewable energy, electricity consumption and the combined effect of all these variables. After each estimation, the dependent variable is replaced by the proxies of GHG emissions, which are CO₂, N₂O, CH₄ and total GHGs. The different equations used will therefore appear as follows:

$$\ln emis_{2it} = \alpha_0 + \alpha_1 \ln oil_{it} + \alpha_2 \ln urb_{it} + \alpha_3 \ln trad_{it} + \alpha_4 \ln gdp_{it} + \xi_{it} \quad (4)$$

$$\ln emis_{2it} = \alpha_0 + \alpha_1 \ln coal_{it} + \alpha_2 \ln urb_{it} + \alpha_3 \ln trad_{it} + \alpha_4 \ln gdp_{it} + \xi_{it} \quad (5)$$

$$\ln emis_{2it} = \alpha_0 + \alpha_1 \ln renew_{it} + \alpha_2 \ln urb_{it} + \alpha_3 \ln trad_{it} + \alpha_4 \ln gdp_{it} + \xi_{it} \quad (6)$$

$$\ln emis_{2it} = \alpha_0 + \alpha_1 \ln elect_{it} + \alpha_2 \ln urb_{it} + \alpha_3 \ln trad_{it} + \alpha_4 \ln gdp_{it} + \xi_{it} \quad (7)$$

$$\ln emis_{2it} = \alpha_0 + \alpha_1 \ln oil_{it} + \alpha_2 \ln coal_{it} + \alpha_3 \ln renew_{it} + \alpha_4 \ln elect_{it} + \alpha_5 \ln urb_{it} + \alpha_6 \ln trad_{it} + \alpha_7 \ln gdp_{it} + \xi_{it} \quad (8)$$

Where $emis$ is a proxy for the various GHG emissions used in this study, such as CO₂ per capita, N₂O per capita, CH₄ per capita, and total GHG emissions per capita; $coal$, oil , $renew$, and $elect$ are disaggregated measures of energy consumption; gdp is the per capita economic growth rate used to measure economic growth; urb is the rate of urbanization; $trad$ is the openness ratio used to represent foreign trade or trade openness.

Finally, to investigate the existence of an indirect effect of energy on GHG emissions, we estimate the effect of energy consumption on each channel. The model to be estimated is presented as follows:

$$\ln transmi_{sit} = \tau_0 + \tau_1 energy_{it} + \mu_{it} \quad (9)$$

Where $transmi_s$ is the transmission channel, measured as urbanization ($s = 1$), trade openness ($s = 2$), and economic growth ($s = 3$); $energy$ is the various sources of energy; τ_0 and τ_1 are the parameters; and μ is the error term. The indirect effect or transmission mechanism operates only if τ_1 is statistically significant.

3.3. Estimation Technique

This study uses the generalized method of moments (GMM) proposed by Arellano and Bover (1995) and Blundell and Bond (1998). This method is frequently used in the literature to solve econometric problems such as heteroskedasticity and endogeneity, which appear in the estimation of panel data (Arellano & Bond, 1991; Arellano & Bover, 1995), over-identification, and the validity of results. According to Baum, Schaffer, and Stillman (2003), heteroskedasticity is a pervasive problem in empirical studies and the most effective way to manipulate it is to use the GMM. Bazzi and Clemens (2013) state that in related literature, the GMM is used to measure the force of the instrument. According to Roodman (2009), the dynamic panel GMM can handle too many instrument problems and

therefore creates weak instrument bias. To solve this problem, we follow the basic rule of thumb, which states that the number of instruments should be less than the number of countries. Theoretically, the problem of endogeneity can arise due to simultaneity, reverse causality, measurement errors, or omitted variable bias (bias that arises due to country-specific effects); these are problems taken into account by the GMM. In addition, it has the advantage of taking into account or processing the endogeneity of all explanatory variables by using their lagged values (in terms of level and first difference) as instrumental variables. The consistency of this estimator depends on two elements: the validity of the assumption that the error term does not show a serial correlation (AR(2)), and the validity of the instruments (Hansen test).

4. RESULTS AND DISCUSSIONS

4.1. Baseline Results

In this section, we present and discuss the results of the baseline specifications. Table 1 presents the estimated effects of energy consumption on CO₂ emissions, Table 2 presents the estimated effects of energy consumption on N₂O emissions, Table 3 presents the estimated effects of energy consumption on CH₄ emissions, and Table 4 presents the estimated effects of energy consumption on total GHG emissions. First of all, it is important to stress that the number of countries (33) is greater than the number of years covered in the study (23). The rule of thumb, which states that the number of instruments must be less than the number of cross-sections, is respected here. In addition, the second order correlation test (AR(2)) does not reject the null hypothesis of no second order autocorrelation.

Table 1. Effect of disaggregated energy consumption on CO₂.

Variable	(5)	(6)	(7)	(8)	(9)
	lnCO ₂				
l.lnCO ₂	0.239*** (0.061)	0.394*** (0.015)	0.399*** (0.029)	0.361*** (0.021)	0.361*** (0.023)
Lnoil	0.008* (0.112)				0.064* (0.052)
Coal		0.177*** (0.012)			0.147*** (0.030)
Lnrenew			-0.151*** (0.018)		-0.078** (0.035)
Lnelect				0.007* (0.021)	0.056* (0.039)
Lnurb	-0.048 (0.045)	-0.067*** (0.021)	-0.059*** (0.013)	-0.082*** (0.022)	-0.077*** (0.025)
Lntrad	0.078 (0.097)	0.084*** (0.026)	0.088*** (0.019)	0.081** (0.035)	0.141** (0.063)
Lngdp	0.859*** (0.188)	0.731*** (0.031)	0.600*** (0.040)	0.746*** (0.050)	0.820*** (0.086)
Constant	-7.096*** (1.803)	-6.071*** (0.228)	-4.549*** (0.329)	-6.169*** (0.440)	-6.427*** (0.808)
Prob > F	0.000	0.000	0.000	0.000	0.000
Observations	723	723	723	723	723
Instruments	33	33	33	33	33
AR(2)	0.473	0.510	0.510	0.454	0.552

Note: Standard errors are in parentheses; *** p < 0.01, ** p < 0.05, * p < 0.1; CO₂ = carbon dioxide emissions; *renew* = renewable energy; *elect* = electricity consumption; *urb* = urbanization; *trad* = trade openness; *gdp* = gross domestic product.

Table 2. Effect of disaggregated energy consumption on N₂O.

Variable	(5)	(6)	(7)	(8)	(9)
	lnN ₂ O				
l.lnNO ₂	0.908*** (0.030)	0.922*** (0.013)	0.919*** (0.029)	0.955*** (0.023)	0.851*** (0.01)
Lnoil	-0.042* (0.023)				-0.131*** (0.024)
Coal		-0.055*** (0.006)			-0.062*** (0.010)
Lnrenew			0.051*** (0.005)		0.035*** (0.008)
Lnelect				0.000 (0.013)	0.079*** (0.012)
Lnurb	-0.044*** (0.007)	0.001 (0.011)	-0.011 (0.013)	0.017 (0.016)	-0.003 (0.017)
Lntrad	0.087*** (0.021)	0.105*** (0.016)	0.084*** (0.019)	0.077*** (0.026)	0.096*** (0.027)
Lngdp	0.147*** (0.030)	0.105*** (0.014)	0.117*** (0.019)	0.083*** (0.025)	0.191*** (0.030)
Constant	-1.552*** (0.367)	-1.239*** (0.158)	-1.431*** (0.213)	-0.959*** (0.249)	-2.486*** (0.297)
Prob > F	0.000	0.000	0.000	0.000	0.000
Observations	723	723	723	723	723
Instruments	33	33	33	33	33
AR(2)	0.473	0.510	0.510	0.454	0.552

Note: Standard errors are in parentheses; *** p < 0.01, * p < 0.1; N₂O = nitrous oxide; *renew* = renewable energy; *elect* = electricity consumption; *urb* = urbanization; *trad* = trade openness; *gdp* = gross domestic product.

Table 3. Effect of disaggregated energy consumption on CH₄.

Variable	(5)	(6)	(7)	(8)	(9)
	lnCH ₄	lnCH ₄	lnCH ₄	lnCH ₄	lnCH ₄
l.lnch ₄	0.647*** (0.022)	0.537*** (0.024)	0.662*** (0.017)	0.634*** (0.044)	0.664*** (0.047)
Lnoil	-0.074*** (0.024)				-0.086 (0.052)
Coal		0.068*** (0.010)			0.032 (0.0263)
Lnrenew			-0.020** (0.010)		-0.040** (0.019)
Lnelect				0.000 (0.016)	0.009 (0.036)
Lnurb	-0.033* (0.018)	-0.081*** (0.024)	-0.020*** (0.004)	-0.070** (0.027)	-0.095** (0.038)
Lntrad	0.113*** (0.016)	-0.038* (0.020)	0.050*** (0.014)	-0.013 (0.018)	0.141*** (0.036)
Lngdp	0.059 (0.054)	-0.114*** (0.010)	-0.033 (0.029)	-0.131*** (0.046)	0.063 (0.082)
Constant	-1.217*** (0.441)	0.875*** (0.110)	0.006 (0.230)	0.934** (0.345)	-1.172 (0.714)
Prob > F	0.000	0.000	0.000	0.000	0.000
Observations	723	723	723	723	723
Instruments	33	33	33	33	33
AR(2)	0.473	0.510	0.510	0.454	0.552

Note: Standard errors are in parentheses; *** p < 0.01, ** p < 0.05, * p < 0.1; CH₄ = methane; *renew* = renewable energy; *elect* = electricity consumption; *urb* = urbanization; *trad* = trade openness; *gdp* = gross domestic product.

Table 4. Effect of disaggregated energy consumption on total GHG.

Variable	(5)	(6)	(7)	(8)	(9)
	lnGHG	lnGHG	lnGHG	lnGHG	lnGHG
l.lnGHG	0.912*** (0.099)	0.926*** (0.004)	0.934*** (0.008)	0.929*** (0.017)	1.014*** (0.064)
Lnoil	0.005 (0.036)				0.071* (0.040)
Coal		0.018*** (0.002)			-0.010 (0.020)
Lnrenew			-0.001 (0.004)		0.008 (0.011)
Lnelect				0.021*** (0.005)	-0.025 (0.020)
Lnurb	-0.009 (0.045)	0.003 (0.004)	0.013*** (0.004)	0.016** (0.007)	0.006 (0.019)
Lntrad	0.044 (0.036)	0.031*** (0.005)	0.056*** (0.006)	-0.002 (0.016)	0.020 (0.035)
Lngdp	0.015 (0.083)	0.050*** (0.004)	0.058*** (0.008)	-0.017 (0.014)	-0.028 (0.051)
Constant	-0.196 (0.692)	-0.440*** (0.018)	-0.609*** (0.083)	0.133 (0.124)	0.326 (0.526)
Prob > F	0.000	0.000	0.000	0.000	0.000
Observations	723	723	723	723	723
Instruments	33	33	33	33	33
AR(2)	0.473	0.510	0.510	0.454	0.552

Note: Standard errors are in parentheses; *** p < 0.01, ** p < 0.05, * p < 0.1; GHG = greenhouse gas; *renew* = renewable energy; *elect* = electricity consumption; *urb* = urbanization; *trad* = trade openness; *gdp* = gross domestic product.

First of all, it should be noted that the CO₂, N₂O, CH₄, and GHG emissions for the delayed (previous) year have a positive effect on those for the current year. This could be explained by an increase in emissions over time in view of modernization.

The results show that the coefficient of oil consumption is positive and significant at 10% when related to CO₂ and to GHGs in general. This means that, *ceteris paribus*, increasing the consumption of oil and other liquids by 1% results in an increase in CO₂ emissions per capita of 0.445% and an increase in GHG emissions per capita of 0.071%. On the one hand, the results for CO₂ emissions are consistent with those of Alam and Paramati (2015) and Koengkan (2018). The positive influence may be due to the great dependence on oil as a source of energy in these countries (Pablo-Romero & De Jesús, 2016). On the other hand, the results for GHG emissions are consistent with those of Sarkodie and Strezov (2019) and Bölük and Mert (2014), who concluded that oil consumption induces GHG emissions. In contrast, lnoil has a negative and significant coefficient at 1% and 10% when associated with N₂O, and at 1% when associated with CH₄. This result could be attributed to the fact that oil as a fossil fuel is responsible for 82% of CO₂ emissions (Durand-Lasserve, 2014). Thus, by emitting mainly carbon dioxide, its relationship with other gases is miniscule and may be the origin of this negative relationship.

The coefficient of coal consumption is positive and significant at 1% considering its relationship with CO₂, CH₄ and GHGs. This is in line with the literature, notably the work of Muhammad Shahbaz, Tiwari, and Nasir (2013) and Wang and Dong (2019), who found that coal consumption deteriorates the environment of the countries studied. Coal is a natural resource rich in carbon, and it is the primary energy source used to generate electricity. Its use for this purpose is in coal-fired power stations, which have a heavy negative impact on the environment because when coal burns, it emits more carbon dioxide than other fossil fuels. However, the hottest point on the planet is in South Africa, which is home to the most polluting coal-fired power station in the world (Greenpeace, 2018). These results underline the importance of energy in GHG emissions. The International Energy Agency (IEA) attributes 65% of these emissions to energy production. It also agrees with Bölük and Mert (2014); Hamit-Hagggar (2012);

Sarkodie and Strezov (2019) and Yusuf, Abubakar, and Mamman (2020), who found a positive impact of energy consumption on GHG emissions. At the same time, the coefficient of coal consumption is negatively and significantly (1%) related to N_2O . This result means that coal consumption mitigates N_2O emissions. All factors remaining constant, a unit increase in coal consumption reduces per capita N_2O emissions by about 0.062 units. The high carbon content of coal could be responsible for this inverse relationship, which indicates that the emission of other gases during its consumption is minimal.

The coefficient of renewable energy consumption is negative and significant at 1% and 5% when related to CH_4 and CO_2 , respectively. This indicates that renewable energy consumption does not aggravate GHG emissions. This result is in line with that of Balsalobre-Lorente and Shahbaz (2016), who found that renewable energy helps to reduce per capita GHG emissions. It is also in agreement with Vasylieva, Lyulyov, Bilan, and Streimikiene (2019), who found that the use of renewable energy helps to reduce GHG emissions. Renewable energy is low in GHGs and is better for the environment. The results for CO_2 emissions are in line with those of Bekhet and Othman (2018); Dong, Sun, and Hochman (2017); Chen and Lei (2018); and Wang and Dong (2019), who found a negative sign of renewable energy consumption on CO_2 emissions. Renewable energy, or green energy, is almost non-polluting. When compared to N_2O , renewable energy has a positive and significant sign at 1%. This suggests that increasing the consumption of renewable materials by 1% leads to an increase in N_2O per capita emissions of 0.051% on its own and 0.035% when combined with the other energy variables, all other things being equal. This result is in line with those of Sarkodie and Strezov (2019) and Yusuf et al. (2020), who found that energy consumption increases GHG emissions. Also, Bölük and Mert (2014) found that renewable energy contributes to GHG emissions. However, the use of renewable energy is not without effects on the environment. While wind turbines and solar panels can produce electricity without emitting polluting gases, their production does emit polluting gases.

The coefficient of electricity consumption has a positive and significant sign when associated with all emission variables, indicating that electricity consumption has a deleterious effect on GHG emissions in African countries. This is in line with the findings of Lean and Smyth (2010) and Nkengfack and Kaffo (2019), who found a positive impact of electricity consumption on CO_2 emissions. It is also consistent with Sarkodie and Strezov (2019) and Yusuf et al. (2020), who found a positive impact of energy consumption on GHG emissions. This result indicates that the consumption of electricity contributes to the increase of pollutant emissions and thus to the deterioration of the environment. Electricity consumption itself does not have a direct positive influence on carbon emissions, but it has an indirect influence depending on how it is produced. When the latter is extracted from fossil fuels (coal, in particular), its rate of GHG emissions is higher (IEA, 2016).

The results show that the coefficients of urbanization have a negative sign when related to CO_2 , N_2O , and CH_4 . This agrees with the findings of Charfeddine and Khediri (2016); Hossain (2011) and Sharma (2011), which could be explained by the fact that, in Africa, the process of urbanization does not align with the increase of industries which are GHG-emitting in nature. Rather, it aligns with the increase in urban populations. However, individuals relocating to cities do not have the means to afford devices that contribute to the deterioration of the environment. However, urbanization has a positive and significant coefficient in some equations when related to GHGs. This means that an increase in the urban population rate by 1% results in an increase in per capita GHG emissions of 0.013%, and 0.016% when combined with the other variables. This is in line with the work of Mignamissi and Djeufack (2022), who found that urbanization promotes pollution in Africa. This result assumes that urbanization is the cause of the increase in GHGs. In order to meet the nutritional needs of the growing populations in cities, agriculture and animal husbandry will be intensified and industries will grow to provide employment for the increasing population. This will therefore lead to an increase in the various greenhouse gases in the atmosphere and therefore to a deterioration of the environment.

The coefficient of trade openness is positive and mostly significant. This is in line with the work of Kasman and Duman (2015), which reveals a positive effect of foreign trade on CO_2 emissions. Also, Khan, Khan, and Rehan

(2020) found that trade openness induces GHG emissions. By separating places of production and places of consumption, international trade contributes significantly to global GHG emissions, particularly during the transport of goods. It also changes the locations of emissions (imported emissions). This is how the carbon footprint of consumption in developing countries is greater than the emissions they produce, unlike developed countries. However, trade openness is negative and significant when related to CH₄. So, all other things remaining equal, a 1% increase in foreign trade decreases CH₄ emissions per capita by 0.038%.

The coefficient of GDP is positive and statistically significant at 1%. This implies that economic growth contributes to GHG emissions. This is in line with the results of Chen and Lei (2018) and Zhang and Zhang (2018). They are also in line with the work of Hamit-Hagggar (2012) and Vavrek and Chovancova (2016), who found a positive relationship between economic growth and GHG emissions. Economic growth therefore participates in the pollution and degradation of the environment due to increasing industrial production activities with a view to simplifying the existence of populations and meeting various human needs. However, it has a negative and significant coefficient in some equations when related to CH₄. All other things being equal, a 1% increase in per capita GDP reduces per capita CH₄ emissions by between 0.0329% and 0.114%.

4.2. The Role of the Potential Transmission Channels

The results for the regression of energy consumption on transmission channels are presented in Table 5. Table 6 presents the regression of transmission channels on CO₂ emissions.

Table 5. Effect of energy consumption on the transmission channels.

Variable	Eq1	Eq2	Eq4
	LnU	LnTR	LnGDP
L.InU	0.787*** (0.010)		
Lnoil	-0.072*** (0.013)	0.152*** (0.031)	0.104*** (0.010)
Coal	-0.064*** (0.006)	-0.054** (0.021)	-0.010*** (0.003)
Lnrenew	0.013*** (0.003)	0.048** (0.018)	0.021*** (0.004)
Lnelec	0.076*** (0.013)	-0.070*** (0.022)	-0.023*** (0.005)
L.InTR		0.788*** (0.026)	
L.InGDP			0.901*** (0.015)
Constant	-0.054 (0.065)	1.247*** (0.211)	0.975*** (0.146)
Prob > F	0.000	0.000	0.000
Observations	723	723	723
Instruments	21	21	30
AR(1)	0.000	0.001	0.000
AR(2)	0.362	0.925	0.549
Hansen	0.712	0.279	0.425

Note: Standard errors are in parentheses; *** p < 0.01; U = urbanization; TR = trade; GDP = gross domestic product; renew = renewable energy; elec = electricity.

Urbanization, renewable energy and electricity consumption have a positive effect on CO₂ emissions. This implies that the increase in renewable energy and electricity consumption simultaneously induces an increase in urbanization and an increase in CO₂ emissions.

Renewable energy and electricity consumption could positively influence CO₂ emissions through urbanization. Therefore, urbanization is a transmission channel between renewable energy and electricity consumption. Oil and

coal consumption have a negative effect on urbanization. This means that urbanization cannot be a transmission channel between oil, coal consumption and CO₂ emissions. There would therefore only be a direct relationship between these variables.

Oil and renewable energy consumption have a positive effect on trade openness. This implies that an increase in oil and renewable energy consumption leads into an increase in trade openness. Likewise, trade openness has a positive and significant impact on CO₂ emissions, i.e., an increase in trade openness implies an increase in CO₂ emissions. This means that trade openness is a transmission channel between oil consumption, renewable energy consumption and CO₂ emissions. Coal consumption and electricity consumption have a negative effect on trade openness, which, in turn, has a positive effect on CO₂ emissions. This contradictory sign implies that trade openness cannot be a transmission channel between coal and electricity consumption and CO₂ emissions.

Table 6. Transmission channels.

	Eq1	Eq2	Eq3	Eq4
Variable	lnCO2	lnCO2	lnCO2	lnCO2
L.lnCO2	0.974*** (0.022)	0.960*** (0.013)	0.990*** (0.020)	0.705*** (0.078)
LnU	0.045** (0.019)			
LnTR		0.081** (0.031)		
LnGDP				0.230*** (0.080)
Constant	-0.072** (0.028)	-0.356** (0.135)	0.049* (0.027)	-1.940*** (0.633)
Prob > F	0.000	0.000	0.000	0.000
Observations	723	723	723	723
Instruments	11	15	11	11
AR(1)	0.000	0.000	0.000	0.000
AR(2)	0.489	0.439	0.494	0.494
Hansen	0.460	0.352	0.536	0.536

Note: Standard errors are in parentheses; *** p < 0.01, ** p < 0.05, * p < 0.1; CO₂ = carbon dioxide emissions; U = urbanization; TR = trade; GDP = gross domestic product.

Both oil and renewable energy consumption have a positive effect on GDP. This implies that an increase in oil and renewable energy consumption increases GDP. Likewise, economic growth has a significant and positive impact on CO₂ emissions, so an increase in economic growth increases CO₂ emissions. Thus, oil and renewable energy consumption can positively influence CO₂ emissions through economic growth. This means that economic growth is a transmission channel between oil and renewable energy consumption and CO₂ emissions. Coal and electricity consumption has a negative effect on economic growth, which, in turn, has a positive effect on CO₂ emissions. This contradiction in sign implies that economic growth cannot be a transmission channel between coal and electricity consumption and CO₂ emissions.

5. CONCLUSION AND IMPLICATIONS

This paper studies the effect of energy consumption on GHG emissions in Africa from 1995–2017. The GMM-based results reveal that coal consumption significantly increases CO₂, CH₄ and GHG emissions in general but has the opposite effect on N₂O emissions. Oil consumption promotes CO₂ and GHG emissions in general but has the opposite effect on N₂O and CH₄ emissions. Renewable energy consumption does not lead to CO₂ and CH₄ emissions but contributes to N₂O emissions. Finally, electricity consumption promotes CO₂, N₂O, GHG and CH₄ emissions.

Regarding transmission channels, foreign trade and economic growth are transmission channels for oil consumption; coal consumption does not have transmission channels, so only a direct positive effect exists;

urbanization, foreign trade and economic growth are transmission channels for renewable energy consumption; and urbanization is a transmission channel for electricity consumption.

Based on the results, it is suggested that countries should implement policies to reduce coal consumption because it is by far the biggest polluter. Also, in view of the favorable results obtained with renewable energy, we suggest that governments promote its generation and use. Investment in the technological sector would be beneficial to discover more efficient methods to intensify the production of green energy, which will do less damage to the environment. Governments could also focus on growing vegetation and planting trees in urban areas where activities are intensifying due to the growing population. This would help fight the concentration of carbon emissions, knowing that approximately 1000 kg of CO₂ can be absorbed per tree. Also, knowing that individual transport contributes significantly to GHG emissions, policy makers should encourage the use of electric vehicles. Further studies could enlarge the sample to include other African countries, which could not be considered due to a lack of data for some of the variables used in this study.

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Appendix (List of Countries)

Algeria, Benin, Botswana, Burkina Faso, Burundi, Cameroon, Cape Verde, Congo Republic, Democratic Republic of the Congo, Ivory Coast, Egypt, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Madagascar, Malawi, Mali, Morocco, Mozambique, Namibia, Niger, Nigeria, Rwanda, Senegal, South Africa, Togo, Tunisia, Uganda, Zambia, Zimbabwe.

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