Economics and Business
ISSN 2256-0394 (online)
ISSN 2256-0386 (print)
2023, *37*, 189–205
https://doi.org/10.2478/eb-2023-0012
https://content.sciendo.com

THE IMPACT OF RENEWABLE ENERGY AND ECONOMIC GROWTH ON ENVIRONMENTAL POLLUTION: USING SECOND-GENERATION PANEL TECHNIQUES

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Received 04.11.2023; accepted 15.11.2023

Abstract. This study examines the impact of economic growth, renewable energy consumption, and environmental stringency on environmental pollution within the framework of testing the environmental Kuznets hypothesis for 34 African countries during the period from 1990 to 2020 using second-generation panel estimation techniques. To ensure the stability of the variables, the study applied smoothing of the slopes, CADF, and CIPS unit root tests, and the Westerlund co-integration test to confirm the existence of a long-term balanced relationship between the variables based on the results obtained from the CCEMG model estimates of jointly correlated effects. The study confirmed the environmental Kuznets curve hypothesis in African countries, with the results indicating a relationship between growth and pollution in the form of an inverted "N". Furthermore, it was found that the consumption of renewable energy reduced carbon dioxide emissions.

Keywords: *Environmental pollution, environmental Kuznets curve, panel data, renewable energy.*

JEL Classification: C01, O13, O44, Q20, Q50

INTRODUCTION

The increase in global warming and climate change results from rising energy consumption, leading to environmental variations worldwide. As part of the response to this challenge, the international community aims to reduce the global average temperature. To achieve this goal, the United Nations adopted the 2030 Sustainable Development Project (UN, 2022) and the Paris Climate Agreement in 2015 (De Coninck & Sagar, 2015).

Reaching high rates of economic growth is the primary concern of policymakers, often without giving due attention to environmental quality. Therefore, achieving unsustainable economic growth should be a fundamental concern for governments of both advanced and developing countries alike. Furthermore, one of the most critical efforts of countries in achieving sustainable development is increasing economic growth while also pursuing goals related to improving environmental quality and mitigating environmental harm. Despite the necessity of energy for economic development, it can also be a primary source of environmental deterioration. The relationship between energy and the environment has become a crucial matter for governments, and according to numerous studies, the negative environmental impacts stem from non-renewable energy, not renewable energy (Islam, et al, 2022; Mujtaba, 2022). Therefore, increasing the use of renewable energy instead of non-renewable energy has several potential advantages, including reducing emissions, diversifying energy sources, and reducing dependence on non-renewable energy sources (Apergis, 2010).

The extensive use of non-renewable energy to support economic growth is the sole reason for global weather deterioration (Rob Swart, 2003), which calls for deeper studies on the relationship between development and the environment. This is to help implement the optimal acts related to energy to face the environmental issues in the correct way. The relationship between pollution and economic growth is evaluated by examining Kuznets' theory and its potential refutation (Mohammed et al., 2024).

The Environmental Kuznets Curve (EKC) is a widely recognised economic hypothesis that has been the focus of numerous studies over the years. This hypothesis posits a non-linear relationship between economic growth and environmental degradation concerning pollution levels (Akbulut, 2022). According to the EKC theory, environmental pollution increases as a country's economy grows, primarily due to higher industrialisation, urbanization, and increased energy consumption associated with economic development. This initial stage of pollution growth is commonly referred to as the "inverted U" or "N-shaped" curve (Özcan, 2019).

Numerous empirical studies have investigated the EKC hypothesis to understand the dynamics of this relationship. Researchers have found a mix of results, indicating that the shape and the inflection point of the EKC curve can vary across countries and pollutants. Some studies have supported the EKC theory, showing evidence of a turning point where environmental degradation begins to decline after reaching a certain level of per capita income. For instance, Mekhzoumi et al. (2022) estimated static and dynamic models for 31 industrialized countries and found evidence supporting the EKC hypothesis. Similarly, Balsalobre and Álvarez-Herranz (2016) used a fixed effects model for 17 countries from the OECD and confirmed the reliability of the EKC hypothesis, implying that environmental pollution and economic growth were linked in an inverted N-letter shape.

However, not all studies have confirmed the EKC hypothesis. The authors (Sasana, 2019) rejected the EKC hypothesis in Indonesia using OLS regression because the economic globalization (GE) did not significantly affect CO_2 emissions. Nevertheless, several other studies have confirmed the EKC hypothesis and found a "U" shaped pattern. For instance, the research (Ajanaku, 2021) used a Generalized Method of Moments (GMM) the empirical results of Panel GMM confirmed the EKC hypothesis, with a flipped "U" shaped pattern. These studies suggest that the relationship between economic growth and environmental pollution is complex and varies depending on the country and the model used. This is due to the multiple factors that influence this relationship, including factors such as the economic structure, the level of development, environmental policies, energy usage patterns, and the technology employed. These factors vary significantly from one country to another.

Although many studies are available, it is essential to continue studying the relationship between economic growth and environmental pollution to assist policymakers in developing effective environmental policies that promote sustainable economic growth in the equation of energy, growth, and the environment. This paper contributes to the ongoing discourse about the global transition to more environmentally friendly energy solutions. The study is not limited to exploring the relationship between economic growth, the use of renewable energy, and environmental pollution, but also delves into its dynamic nature through the use of statistical tools and techniques to identify long-term trends and patterns in the time-series analysis. The analysis does not only reveal whether economic growth and the utilization of renewable energy impact environmental pollution, but also sheds light on the strength and direction of these effects.

The study aims to measure the impact of renewable energies, the individual share from the Gross Domestic Product (GDP), carbon damage fees, the individual share of the carbon dioxide emissions in the African countries. This will be accomplished by testing Environmental Kuznets Curve (EKC) theory. The study extended Kuznets' curve, which includes measuring pollution and economic growth as well as the GDP with its square and cubic value, adding the renewable energy consumption variable, population density, carbon damage fees through testing the prototype on a sample consisting of 34 African countries in the long term.

1. THE CONCEPTUAL FRAMEWORK OF ENVIRONMENTAL KUZNETS CURVE

The Environmental Kuznets Curve is based on the interaction between the economic growth and the environmental deterioration, specifically the negative effect of the economic growth on the environmental quality. As economies develop, the pursuit of economic growth exerts significant pressure on the environment, driven by increased demand for natural resources. This heightened demand for resources, both directly and indirectly, is channeled through production operations, which provides the necessary foundation for economic growth.

Consequently, a substantial volume of industrial waste is generated, resulting in adverse environmental consequences. This, in turn, exacerbates environmental degradation, particularly as the income levels rise. During this stage, industrial and agricultural sectors often dominate economic activity, and the increasing national wealth necessitates structural changes in the industrial landscape. These changes have a transformative effect on the economy, impacting the environment in mostly positive ways. During this phase, environmental considerations gain prominence, and industries adopt cleaner production techniques, leading to an improvement in energy quality.

This transition marks the beginning of the third stage, where economic growth starts to exert a positive technical impact on the environment. The service sector emerges, and the economy transits from capital-intensive industries to a more knowledge-based and resource-efficient model, for example, the use of energy storage systems such as solar batteries to store excess energy, as well as harnessing widely available solar energy resources to generate electricity at a lower cost. This will reduce resource wastage, making the process more efficient. Consequently, investments are made in research and development, resulting in the replacement of outdated, polluting technologies with modern, eco-friendly alternatives. This simultaneous improvement in both economic growth and environmental quality gives rise to the characteristic bell-shaped, inverted "U" curve observed in the EKC relationship (Shahbaz & Sinha, 2019).

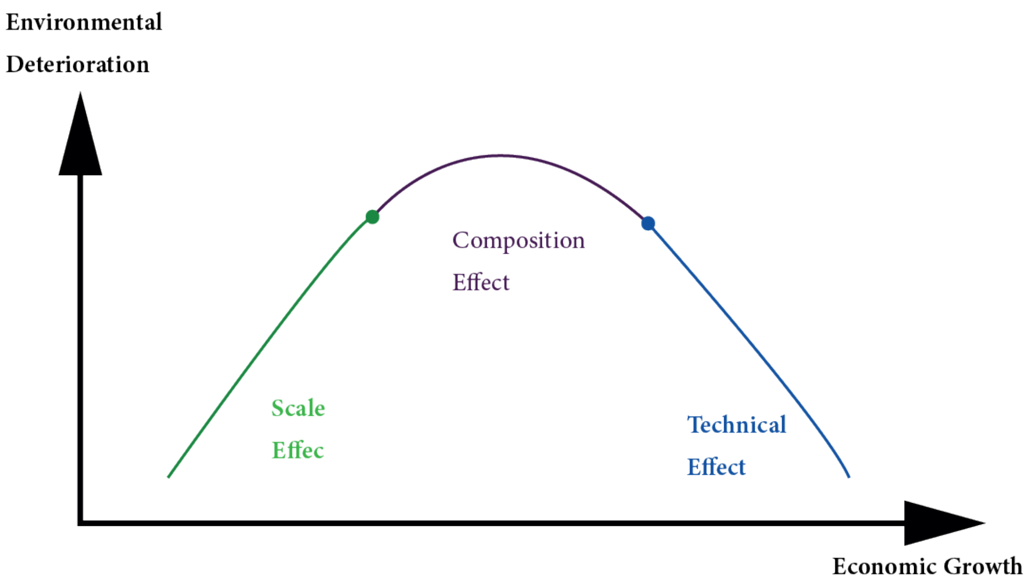


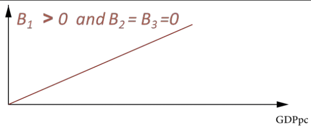
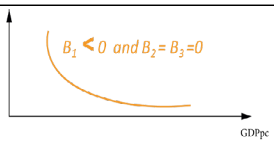
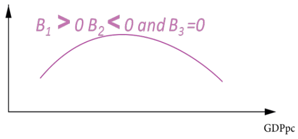
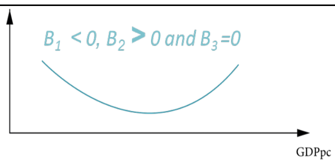
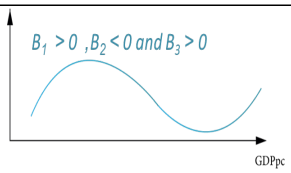
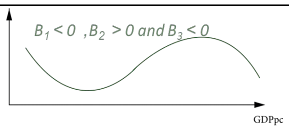
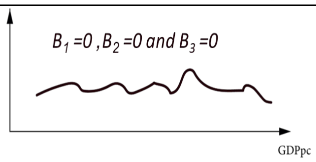
Fig. 1. EKC curve. Developed by the researchers based on AlKhars et al. (2022).

We apply the EKC theory to examine the relationship between economic growth and environmental deterioration. The individual contribution of environmental deterioration is represented on the vertical axis, while individual GDP is plotted on the horizontal axis.

The theory is tested by examining the values and significance of β_1, β_2, and β_3, which represent individual GDP, squared individual GDP, and cubic individual GDP, respectively.

The form of the relationship between economic growth and environmental deterioration is illustrated in Table 1.

Table 1. The Seven Forms of Relation between the Economic Growth and Environmental Deterioration

Model	Value of β1, value of β2, value of β3	The decision
	$\beta_1 > 0$ and $\beta_2 = \beta_3 = 0$	A linear increasing relation between the economic growth and pollution.
	$\beta_1 < 0$ and $\beta_2 = \beta_3 = 0$	A decreasing relation between the economic growth and pollution.
	$\beta_1 > 0,\ \beta_2 < 0$ and $\beta_3 = 0$	A flipped "U" shaped relation between economic growth and pollution.
	$\beta_1 < 0,\ \beta_2 > 0$ and $\beta_3 = 0$	A "U" shaped relation between economic growth and pollution.
	$\beta_1 > 0,\ \beta_2 < 0$ and $\beta_3 > 0$	An "N" shaped relation between economic growth and pollution.
	$\beta_1 < 0,\ \beta_2 > 0$ and $\beta_3 < 0$	A flipped "N" shaped relation between economic growth and pollution.
	$\beta_1 = 0,\ \beta_2 = 0$ and $\beta_3 = 0$	No relation between economic growth and pollution.

Source: Developed by researchers based on (Dinda, 2004), (Balsalobre-Lorente, 2016)

The entry point in the EKC can be determined based on the square and cubic models, with the maximum and minimum values corresponding to the following relationships (Uchiyama, 2016):

Cubic model: $$GDPpc_{TP} = \frac{-\beta_2 \pm \sqrt{\beta_2^2 - 3\beta_1\beta_3}}{3\beta_3};$$

Square model: $$GDPpc_{TP} = -\frac{\beta_1}{2\beta_2}.$$

2. ECONOMETRIC STUDY

2.1. Determining the Sample and Study Period

To investigate the impact of renewable energy usage and economic growth on pollution in Africa, taking into account Kuznets' environmental theory, the study encompassed 34 African countries. These countries were selected based on the availability of data collected over the years of study and their interest in renewable energy adoption and consumption. The period of study spans from 1990 to 2020, resulting in a sample size of 1054 observations. Data were collected annually in a linear fashion, with the variables sourced from the official website linked to the International Bank's database.

2.2. Identifying the Variables of the Model

To measure the impact of utilizing renewable energy and economic growth on environmental pollution in Africa while considering Kuznets' environmental theory, we have identified both the dependent and independent variables based on the economic theory and previous research. The variables are presented in Table 2.

Table 2. Variables and Data Source

Abbreviation	The variable	The source
CO2pc	CO_2 emissions* (individual average with cubic meter)	WDI (2022)
GDPpc	Individual GDP (USD 2015)	WDI (2022)
RNW	Renewable energy consumption (% of the final energy consumption)	WDI (2022)
CD	CO_2 damage† (% of GDP)	WDI (2022)

Source: Developed by the researchers

2.3. Describing the Standard Model

In order to assess the impact of utilizing the renewable energy and the economic growth on environmental pollution in Africa while considering the implications of Kuznets' environmental theory, we have formulated the following model:

$$CO2pc = f(GDPpc, GDPpc^2, GDPpc^3, RWN, CD,). \quad (1)$$

After applying the logarithm, we get:

* The average per capita carbon dioxide emissions (in metric tons) is a form of air environmental pollution and is currently the top concern for countries striving for a clean environment and prosperous economic growth.

†Carbon Dioxide Damage (% of GNI): (Adjusted Savings)The damage caused by carbon dioxide is estimated at $20 per ton of carbon (the unit of damage in 1995 US dollars) times the number of tons of carbon emitted.

$$\ln CO2pc_{it} = \beta_0 + \beta_1 \ln GDPpc_{it} + \beta_2 \ln GDPpc^2{}_{it} + \beta_3 \ln GDPpc^3{}_{it} + \beta_4 \ln RWN_{it} + \beta_5 \ln CD_{it} + \varepsilon_{it}, \quad (2)$$

where

$\ln(CO2pc_{it})$ – a logarithm of per capita carbon dioxide emissions;
$\ln(GDPpc_{it})$ – a logarithm of per capita gross domestic product;
$\ln(GDPpc^2{}_{it})$ – a logarithm of per capita gross domestic product squared;
$\ln(GDPpc^3{}_{it})$ – a logarithm of per capita gross domestic product cubed;
$\ln(RWN_{it})$ – a logarithm of renewable energy consumption;
$\ln(CD_{it})$ – a logarithm of carbon dioxide harm;
β_i – estimated parameters;
ε_{it} – a random error term.

Table 3. Descriptive Statistics for the Study Variables

	LnCO2pc	LnGDPpc	LnGDPpc²	LnGDPpc³	LnRNW	LnCD
Mean	−0.52308	3.020382	9.265823	28.87365	1.714794	0.009472
Std. Dev	0.60795	0.378484	2.351694	11.12625	0.490679	0.369265
Min	1.787474	2.309681	5.334628	12.32129	−1.22915	−1.9491
Max	0.93293	3.96698	15.73693	62.42808	1.992743	1.293374
Observation	$N = 34$, $T = 31$					

Source: Developed by the researchers from the STATA 17 output

3. ESTIMATION AND DIAGNOSTIC OF THE MODEL

3.1. Testing the Independence of the Cross-Sections

The interdependence among cross-sections is a common issue that often arises in the estimation of panel data. This implies the possibility of cross-sectional interrelation within panel data. Cross-sectional dependence can be a result of factors such as geographical factors, common omitted impacts, social influences, and interactions within the economic network (Chudik & Pesaran, 2013). In practice, first-generation unit root tests and cointegration tests typically rely on the assumption of cross-sectional independence. However, assuming cross-sectional independence has significant implications for the estimations and the conclusions drawn, as the covariance matrix grows with the number of cross-sections, rendering parameter estimates less reliable. In this context, we will utilize the following tests for assessing cross-sectional independence:

- Lagrange Multiplier (LM) Test (Breusch & Pagan, 1980)

$$LM = \sum_{i=0}^{N-1} \sum_{j=i+1}^{N} T_{ij} \hat{p}_{ij}^2 \sim \chi^2_{\frac{N(N-1)}{2}}, \quad (3)$$

where

LM – Lagrange Multiplier test statistics;

N – a number of cross-sections in the panel data;

T_{ij} – a number of time periods;

$\hat{p}_{ij}$ – the estimated pairwise correlation of the residuals between cross-section i and cross-section j.

- Scaled LM test (Pesaran M. , 2004)

$$LM_{BC} = \sqrt{\frac{1}{N(N-1)}} \sum_{i=0}^{N} \sum_{j=i+1}^{N} \left(T_{ij}\hat{p}_{ij}^2 - 1\right) \sim N(0,1), \quad (4)$$

where LM_{BC} – Bias-corrected scaled LM test statistic.

- The CD test is a first-generation test that shows the strong relation (Pesaran M. , 2004)

$$CD = \sqrt{\frac{2}{N(N-1)}} \sum_{i=0}^{N} \sum_{j=i+1}^{N} T_{ij}\hat{p}_{ij}^2 \sim N(0,1). \quad (5)$$

- Bias-adjusted LM test (Pesaran et al., 2008)

$$LM_{BC} = \sqrt{\frac{1}{N(N-1)}} \sum_{i=0}^{N-1} \sum_{j=i+1}^{N} \left(T_{ij}\hat{p}_{ij}^2 - 1\right) - \frac{N}{2(T-1)} \sim N(0,1). \quad (6)$$

Table 4. Results of the Cross-Sectional Independence Test for the Study Variables

Variables	Breusch-Pagan LM test		Scaled LM test		Pesaran (2004) CD test		Bias-corrected scaled LM test	
	CD	P-Value	Statistic	P-Value	Statistic	P-Value	CD	P-Value
ln(CO2pc)	6194.786	0.000	168.1915	0.000	33.715	0.000	167.62	0.000
ln(GDPpc)	8081.006	0.000	224.5028	0.000	40.007	0.000	223.93	0.000
ln($GDPpc^2$)	8089.932	0.000	224.7693	0.000	40.217	0.000	224.20	0.000
ln($GDPpc^3$)	8094.964	0.000	224.9195	0.000	40.413	0.000	224.35	0.000
ln(RNW)	6229.911	0.000	169.2401	0.000	49.112	0.000	168.67	0.000
ln(CD)	3508.016	0.000	87.98043	0.000	34.096	0.000	87.413	0.000

Source: Developed by the researchers, extracted from statistical outputs of Eviews 10 and Stata 17 software.

The results of the tests for cross-sectional independence confirm independence between cross-sections at a significance level of 1 % in all five applied tests. Given that the presence of cross-sectional dependence implies that any shocks in one country of the study sample can be easily transmitted to other countries, the commonly used first-generation panel model is considered unsuitable for this study.

3.2. Testing the Consistency of the Regressions

There is another important issue in panel data analysis, which is testing whether the regression coefficients are homoscedastic. In the heteroscedasticity test, the null hypothesis assumes that all coefficients are equal, while the alternative hypothesis suggests that at least one coefficient differs from the others. The Wald test is suitable for both small and large sample sizes (Mutaşcu, 2016), and similar to it, the Swamy test (Swamy, 1970) introduces a new heteroscedasticity test after relaxing the assumption of homoscedasticity. However, the Swamy test requires that N be relatively small compared to the time dimension T. Following that Pesaran & Yamagata (2008) developed a test for heteroscedasticity of regression coefficients in large panel data, the test statistics can be determined as follows:

The first step is to calculate the Swamy test:

$$\tilde{S} = \sum_{i=1}^{N}\left(\hat{\beta}_i - \tilde{\beta}_{WFE}\right)' \frac{x'_i M_T x_i}{\tilde{\sigma}_i^2}\left(\hat{\beta}_i - \tilde{\beta}_{WFE}\right), \quad (7)$$

where
$\tilde{S}$ – Swamy test statistic;
$\hat{\beta}_i$ – the estimated coefficient vector for the i^{th} cross-section;
$\tilde{\beta}_{WFE}$ – weighted fixed effects estimate of the regression coefficients;
x'_i – transposed matrix of regressors for the i^{th} cross-section;
M_T – a matrix that is used to remove fixed effects across time periods;
$\tilde{\sigma}_i^2$ – the estimated variance of the error term for the i^{th} cross-section.

Then, the standard deviation statistic was developed.

$$\tilde{\Delta} = \sqrt{N}\left(\frac{N^{-1}\tilde{S} - k}{\sqrt{2k}}\right), \quad (8)$$

where k – the number of regressors in the model.

The properties of the small sample for testing $\tilde{\Delta}$ under normally distributed errors can be improved using the modified bias-corrected version.

$$\tilde{\Delta}_{adj} = \sqrt{N}\left(\frac{N^{-1}\tilde{S} - E(\tilde{z}_{it})}{\sqrt{\mathrm{var}(\tilde{z}_{it})}}\right), \quad (9)$$

where

$E(\tilde{z}_{it})$ – mathematical expectation of the statistic $\tilde{z}_{it}$;

$\mathrm{var}(\tilde{z}_{it})$ – variance of statistic $\tilde{z}_{it}$.

However, the test cannot handle the case of non-homoscedastic and correlated errors. Therefore, this test has been enhanced by Blomquist & Westerlund (2013) to address this issue.

Table 5. Results of Testing the Consistency of Regressions in Different Study Models (*Source: Developed by the researchers based on the STATA 17 outputs*)

Tests	**Delta**	**P-Value**
$\tilde{\Delta}$	10.343	0.000
adj $\tilde{\Delta}$	12.190	0.000

Table 6 presents the results of the heteroscedasticity test. According to the test results, the null hypothesis, which suggests the presence of homoscedastic slopes for all models, was rejected at a significance level of 1 %. Therefore, panel data techniques that account for both cross-sectional dependence and heteroscedasticity should be used.

3.3. Panel Unit Root Test

First-generation panel unit root tests do not consider the independence of cross-sections, leading to biased results (Hussain et al., 2020; Destek, 2019). In this study, we will employ second-generation panel unit root tests, which are robust to cross-sectional dependence. Specifically, we will use panel unit root tests, such as CADF and CIPS (Pesaran M. H., 2007), known for their ability to provide reliable and consistent estimates in the presence of cross-sectional independence and/or heteroscedasticity. The test statistics are determined as follows:

$$CADF_i = t_i(N,T) = \frac{(y_i^T \bar{M} y_{i-1})^{-1}(y_{i-1}^T \bar{M} \vartriangle y_i)}{\sqrt{\sigma_i^2 (y_i^T \bar{M} y_{i-1})^{-1}}}. \tag{10}$$

The CIPS test is derived by calculating the average statistics of the CADF test for the entire panel, and the test statistics are determined as follows:

$$CIPS(N,T) = N^{-1} \sum_{i=1}^{n} t_i\,(N,T) = \sum_{i=1}^{N} CADF_i \big/ N\,. \tag{11}$$

Table 6. Results of Second-Generation Panel Unit Root Tests (CADF and CIPS)

Variables	CADF				CIPS			
	Levels		1ST Difference		Levels		1ST Difference	
	Constant & Trend	Constant	Constant & Trend	Constant	Constant & Trend	Constant	Constant & Trend	Constant
ln(CO2pc)	−2.008	−1.933	−4.134***	−3.909***	−2.249	−2.115*	−5.296***	−5.136***
ln(GDPpc)	−1.875	−1.596	−3.773***	−3.265***	−1.855	−1.598	−4.739***	−4.303***
ln(GDPpc²)	−1.890	−1.608	−3.776***	−3.260***	−1.862	−1.606	−4.723***	−4.286***
ln(GDPpc³)	−1.902	−1.620	−3.768***	−3.256***	−1.862	−1.612	−4.699***	−4.264***
ln(RNW)	−1.997	−1.540	−3.510***	−3.314***	−1.887	−1.500	−5.020***	−4.826***
ln(CD)	−2.947***	−1.799	−4.423***	−4.309***	−2.705**	−1.808	−5.415***	−5.303***

(*) (**) (***) indicate significance levels of 1 %, 5 %, and 10 %, respectively.
Source: Developed by the researchers based on the STATA 17 outputs.

Table 7 presents the results of CADF and CIPS unit root tests, where the results indicate that all variables become stationary after first differencing, i.e., integrated of order I(1), at a significance level of 1 %.

3.4. Panel Cointegration Test

Since traditional panel unit root tests do not consider the independence of cross-sections, Westerlund (2007) developed a panel unit root test based on error correction that remains powerful even in the presence of cross-sectional dependence. This is generally referred to as the second-generation panel data test for cointegration. The basic idea of the test is to examine the absence of cointegration by determining whether error correction exists among individual panel elements or across the entire panel as follows:

$$\Delta Y_{i,t} = \delta'_i d_t + \in_i \left(Y_{i,t-1}\beta'_i X_{i,t-1}\right) + \sum_{j=1}^{p} \varphi_{i,j} Y_{i,j-1} + \sum_{j=0}^{p} \varphi_{i,j} Y_{i,j-1} + \mu_{i,t}, \quad (12)$$

where $\in_i$ is the coefficient representing the speed of correction towards equilibrium. Westerlund (2007) proposed four formulations, including group mean statistics and panel statistics, which are presented in the following equations:

$$G_t = \frac{1}{N}\sum_{i=i}^{N} \frac{\in_i}{Se(\hat{\in}_i)} \quad (13) \qquad G_a = \frac{1}{N}\sum_{i=i}^{N} \frac{T \in_i}{\in_i (1)} \quad (14)$$

$$P_t = \frac{\hat{\in}_i}{NSe(\hat{\in}_i)} \quad (15) \qquad P_a = T\,\hat{\in}_i \quad (16)$$

All statistics are calculated from least squares estimates, where G_t and G_a statistics are used to determine whether cointegration occurs in at least one cross-section, while P_t and P_a indicate whether common integration exists in the entire panel.

To calculate cointegration, Westerlund generalized the testing procedures by employing a bootstrap approach. The results in Table 7 obtained from Westerlund's tests indicate statistical significance at the 1 % level for most of the results, implying acceptance of the alternative hypothesis, which suggests the presence of cointegration. Therefore, there is evidence of a long-term relationship between the dependent variable and the explanatory variables in the study model.

Table 7. Westerlund's Test Results for the Second-Generation of Common Integration for All Models

Statistic	Value	Z-value	P-value	Robust P-value
G_t	−2.417	1.255	0.105	0.016
G_a	−9.747	1.501	0.933	0.005
P_t	21.438	8.565	0.000	0.003
P_a	−13.184	3.778	0.000	0.003

Source: Developed by the researchers based on the STATA17outputs.

4. ESTIMATION OF THE LONG-RUN MODEL

To overcome the issue of cross-sectional dependence, Pesaran (2006) proposed a new model called the Common Correlated Effects (CCE) model. This latter can be estimated even in the presence of unstable data series, as this model is capable of showing the unobserved common effects f_t by using the averages of the dependent variables and the averages of the independent variables. We can obtain the Common Correlated Effects model, which solves the problem of cross-sectional dependence and takes the following form:

$$Y_{i,t} = a_i + \beta_i X_{it} + \gamma_i \bar{Y}_{it} + \delta_{it} \bar{X}_{it} + C_i f_t + \varepsilon_{it}. \quad (17)$$

After testing the independence of the variables, it became apparent that there was a problem of cross-sectional dependence. The hypothesis of independence was rejected, as shown in the results of Table 8. This means that the estimated parameters that we obtained might not be consistent. Therefore, we estimated the long-run parameters using the Common Correlated Effects Mean Group (CCEMG) model developed by Kapetanios et al. (2011). According to Chudik & Pesaran (2009), the estimates of this model remain efficient even in the presence of cross-sectional dependence. They can also be used even when the variable series contain unit roots, instability in their levels, and even in the presence of heterogeneity in the parameters of the individual models.

Table 8. Long-Term Estimation Results Using the CCEMG Model

Regressors	Coefficient	T statistic	P-Value
LnGDPpc	−192.45	−2.38	0.017**
$LnGDPpc^2$	81.85	2.52	0.012**
$LnGDPpc^3$	−10.60	−2.63	0.008*
LnRNW	−1.60	−5.78	0.000*
LnCD	0.083	3.83	0.000*

(*) (**) indicate significance levels of 1 %, 5 %, respectively.
Source: Developed by the researchers based on the STATA17 outputs.

Through the results of estimating the model measuring the impact of renewable energy use and economic growth on environmental pollution in Africa, under the test of the environmental Kuznets curve hypothesis, we observe that all variables have statistical significance in the long run. The coefficient of the $LnGDPpc$ variable is negative and significant, the coefficient of the square of the $LnGDPpc$ variable is positive and significant, and the coefficient of the cubic $LnGDPpc$ variable is negative and significant. This suggests an inverted N-shaped relationship between growth and pollution, according to the environmental Kuznets curve hypothesis.

In the initial stages of economic growth, pollution increases due to growing economic activities. However, when the economy reaches a certain level, people become more focused on environmental quality and actively engage in environmental protection. This is achieved through the application of modern energy-efficient technologies, the utilization of renewable energy sources, and the incorporation of environmentally friendly standards, all of which help reduce carbon dioxide emissions. And further details can be provided through the following:

- Rebound Effect: At higher income levels, the benefits derived from initial ecological systems and clean technologies are offset by an increase in consumption and production, leading to a rise in pollution.
- Structural Changes in the Economy: As economies grow, they move from manufacturing-based structures to service-based structures, initially reducing pollution. However, further economic growth may result in increased energy demand, potentially leading to higher pollution if sustainable energy sources are not utilized.
- Technological Evolution: The initial decrease in pollution with economic growth is often a result of adopting cleaner technologies. However, beyond a certain point, technological progress may not keep pace with economic activities, causing an increase in pollution.
- Political and Regulatory Framework: Effective environmental policies bring about initial improvements. However, if economic growth takes precedence without updating and enforcing environmental systems, pollution may become a problem once again.

Similar results have been found in 31 industrialized countries (Mekhzoumi. L., 2022) and in BRICS countries (Haseeb. A., 2018).

As the coefficients obtained for the cubic model of EKC meet the conditions $\beta_1 < 0,\ \beta_2 > 0\ and\ \beta_3 < 0$, and as the relationship between growth and pollution also takes the form of an inverted "N", it allows calculating the turning points $GDPpc_{TP1}$ representing the first turning point and $GDPpc_{TP2}$ representing the second turning point.

$$GDPpc_{TP} = e^{\frac{-\beta_2 \pm \sqrt{\beta_2^2 - 3\beta_1\beta_3}}{3\beta_3}} = \begin{cases} GDPpc_{TP1} = 6.285 \\ GDPpc_{TP2} = 26.866 \end{cases}$$

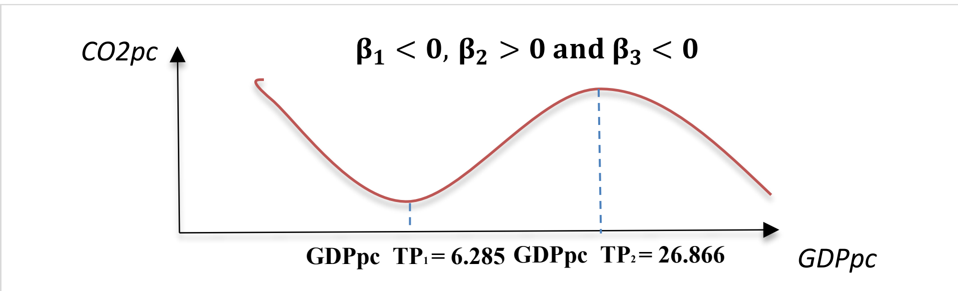


Fig. 2. Turning points of EKC

Source: Developed by the researchers based on EXCEL outputs.

The results reveal that the impact of renewable energy consumption on carbon dioxide emissions was negative and statistically significant. A 1 % increase in energy consumption leads to a 1.6 % decrease in carbon dioxide emissions, consistent with Kirikkaleli & Adebayo (2020). This finding confirms that there is no doubt that renewable energy has the advantage of being clean and sustainable. Renewable energy is an ideal alternative to fossil fuels, despite its relatively weak impact. Increasing support for clean energy use and clean production enhances environmental efficiency.

As for the cost coefficient of carbon dioxide emissions, it was positive and statistically significant, indicating a positive relationship between it and pollution on a global scale. This explains the lack of environmental standards implementation in various economic activities, and it should be supported by global and regional laws and regulations to protect the environment.

CONCLUSION

Balancing economic prosperity with environmental preservation is a key global priority in research and policymaking. Therefore, this paper has evaluated the impact of renewable energy consumption and economic growth on environmental pollution, utilising advanced second-generation panel data analysis techniques. The study has employed the cubic model of EKC to investigate the influence of GDP, its square and cubic forms, and renewable energy consumption on CO_2 emissions using panel data from 34 African countries spanning 1990–2020. Graphically, statistically, and economically confirming the cubic nature of the EKC, the research also emphasised the role of renewable energy consumption in mitigating environmental pollution. Furthermore, the study considered the cost implications of CO_2 emissions to underscore their environmental impact. Various tests were performed to ensure the robustness of the findings, including cross-sectional tests, stability checks using CADF and CIPS, and the Westerlund's integration test for long-term relationships between variables. The long-term parameters were estimated using the CCEMG model. The results reaffirm the presence of the Kuznets Curve in the African context, depicting an inverted "N" shaped relationship between economic growth and environmental pollution, implying that renewable energy adoption can reduce CO_2 emissions.

Therefore, the study recommends:

- African countries should work to enhance the role of renewable energy within their energy portfolios, a step endorsed by the study in line with the confirmation of the environmental Kuznets curve hypothesis. This hypothesis establishes a relationship between the consumption of renewable energy and the reduction of carbon dioxide emissions. In addition to this, there is a call for African countries to embrace trade openness, but with stringent environmental safeguards to ensure that economic integration does not come at the expense of environmental safety.
- The study also calls for the formulation and implementation of optimal environmental standards, advocating for a model where economic

development plans inherently intertwine with environmental considerations. This requires sustainable development practices that do not compromise environmental quality in the pursuit of economic growth. Therefore, African countries should be actively encouraged to participate in regional and global efforts that motivate environmental standards. This cooperative approach extends to investments in technology and infrastructure, especially in the renewable energy sectors that align seamlessly with the African environment.

- Encouraging strategic initiatives that emphasise the importance of public awareness and education. By increasing the general understanding of environmental issues and the pivotal role of renewable energy, there is potential to enhance public support for sustainable practices. The study findings indicate a precise "inverse N shape" for the environmental Kuznets curve in the African context, affirming the intricate relationship between economic growth and environmental pollution – a relationship that can be effectively addressed through the adoption of renewable energy and other sustainable practices.
- The need to establish coordination between legislative bodies, scientific institutions, and research centres to develop consistent and effective environmental legislation aimed at preserving and protecting the environment from pollution is crucial. Such legislation would encourage environmentally friendly investment projects and provide the necessary support for their implementation.

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