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The Impact of Renewable Energy Consumption and Economic Growth on Environmental Quality in Africa: A Threshold Regression Analysis

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Abstract: Nonrenewable energy makes up a sizeable portion of Africa's gross domestic product. The continent heavily relies on nonrenewable energy sources, such as gasoline, for industrial and commercial uses, which helps it expand and develop, especially in oil-producing nations. Incorporating nonrenewable energies when analyzing the relative effects of renewable energy consumption and economic growth on environmental quality is paramount. The transition to renewable energy has been identified as a contributing factor in clean energy and sustainable development, but the consumption of renewable energy in Africa is negligible. This study employed panel threshold regression and covered data from 1990 to 2019, and examined the non-linear relationship between renewable energy consumption, economic growth, and environmental quality. According to the study's findings, the consumption of renewable energy has a nonlinearly negative relationship with carbon emission proxied environmental quality. The relationship between environmental quality and economic growth was also shown to be nonlinearly positive, pointing to the dominance of nonrenewable resources in the African industry. The report recommends an effective policy for boosting the use of renewable energy sources in order to support clean energy and sustainable development.

Keywords: nonrenewable energy intensity; renewable energy consumption; economic growth; environmental quality; panel threshold regression

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1. Introduction

The issue of environmental sustainability remains a significant concern for economies worldwide [1]. In the 21st century, global climate change has become a critical problem, due to high levels of greenhouse gases (GHGs), dominated by carbon dioxide (CO_2). Human activities, such as burning fossil fuels and deforestation, are the primary sources of CO_2 emissions [2–6]. The utilization of traditional energy derived from fossil fuels, such as petroleum, natural gas, and coal, has been recognized as the primary contributor to (GHGs) emissions, resulting in global warming [7]. The Global Carbon Project [8] predict global warming to reach 1.5 °C between 2030 and 2052 if it continues to increase at the current rate [9]. This has adverse negative effects on climate, which manifests in increased desertification, rising sea levels, and the melting of the ice, among others [10]. Given its role as a prominent driver of global climate change, the significant volume of CO_2 emissions has exerted a profound impact on the maintenance of environmental sustainability [11]. In light of increasing concern about climate change and greenhouse gas emissions, researchers and practitioners have invested a lot of time and money in determining alternative energy sources for green and sustainable development [12].

Moreover, there is an increased awareness by organizations such as the Intergovernmental Panel on Climate Change (IPCC) and the United Nations Framework Convention on Climate Change (UNFCCC) to the use of renewable energy sources to reduce (GHG) and environmental pollution arising from (CO_2) [13]. Even though Africa produces less

CO_2 than other continents (3.7% of the world total in 2018), it is the most severely affected by global warming [14]; therefore, controlling the level of CO_2 emissions may be difficult, since it could ultimately slow economic growth, especially in oil-producing developing economies (where nonrenewable fuels are important drivers of economic expansion) by as much as 2–4% by 2040, and 10% by 2100 [11,14,15]. Therefore, to meet their industrial, urbanization, and transportation needs, developing nations need a lot of energy, which has an impact on the carbon level [16]. According to recent data on Africa's total primary energy supply, biomass makes up around half of it [17], while coal, natural gas, and oil make up 14%, 14%, and 22% of it, respectively. The environmental economics literature has extensively explored the impact of environmental degradation [18].

The dependence of economic activities and, by extension, development on energy, in the spirit of environmental sustainability, places renewable energy at the apex of sustainable and ecological development [19]. Renewable energies are self-renewing across timescales that are significant for economic decision-making [20]. Renewable energy's acceptability worldwide has grown, due to its excellent features in performing an environmentally friendly energy role [21,22]. It contributes to meeting the industry's energy needs and, simultaneously, achieving sustainable development goals [21]. Modern renewables also offer great potential in empowering local communities [23]. The African continent has a lot of potential for renewable energy. While biomass and hydropower possibilities are more numerous in the moist, forested central and southern regions, solar resources are abundant everywhere, and the great rift valley is where geothermal energy is concentrated, whereas, the north, east, and south have the best wind resources [17]. Africa's 2030 analysis identified modern renewable technology options across sectors, and across countries, collectively contributing to meet 22% of Africa's total final energy consumption (TFEC) by 2030 [23]. Accordingly, governments have committed to increase the share of renewable energy in aggregate energy production to 50 percent by 2063 [24]. Thus, renewable energy is preferable for the economic growth process because its by-product has a lesser adverse effect on the environment. The economic and environmental sustainability of renewable energy is increasingly attracting research attention [24].

The energy sector, especially nonrenewable, is a significant contributor to the nation's gross domestic product (GDP) for both developed and developing countries alike [25], and oil-dominating countries largely consume nonrenewable energies, such as fuel, for commercial and industrial purposes, which contribute immensely to their economic growth [26]. Africa is home to 13% of the world's natural gas and 7% of the world's oil resources [27]. Africa's energy consumption is mainly nonrenewable [22]. However, because these resources are depletable, investments in renewable energy resources have increased strikingly [28]; as such, the magnitude of change in renewable energy consumption heavily depends on nonrenewable energies. Hence, the transformation of nonrenewable energy regimes holds utmost importance in assessing the collective impact of renewable energy and economic growth on reducing carbon emissions in Africa. The selection of nonrenewable energy intensity as the threshold variable enables a comprehensive examination of the implications of renewable energy consumption and economic growth on environmental quality, particularly at specific threshold stages. Consequently, a pivotal inquiry arises: to what extent do renewable energy consumption and economic growth, determined by the threshold of nonrenewable energy intensity, contribute to enhancing environmental quality in Africa?

The contribution of this study is threefold. Firstly, the body of literature in this field, see [7,12,29–33], included and examined this relationship, covering regional and/or group of countries analysis, with little attention paid to covering the entirety of Africa. Secondly, carbon emissions were not taken into account when examining the relationship between economic and renewable energy, especially in the African context. Thirdly, to examine the relationship between renewable energy, GDP, and CO_2 emissions, this area of literature has used typical linear estimating methods, see [18,34]. The linear models directly accepted the presupposition that the variables display similar behaviors, regardless of the production structure of the country [35]. Contrarily, renewable energy and other variables used in the study can have a non-linear effect, depending on the use of energy, such as nonrenewable and other factors [26]. Similarly, the non-linearity could be because of discrete regime shifts or time-varying coefficients, or arising because the data generating process is inherently non-linear [28]. Similar to this, the majority of studies that calculate CO_2 emissions as a function of GDP and its powers have weak econometrical foundations, and have issues with heterogeneity, misspecification, collinearity, and multicollinearity. Additionally, an integrated series' quadratic or polynomial term is not integrated in any order with the underlying integrated series [36]. Therefore, this work examines this association in a panel of all the African countries divided into five regions, using a more suitable nonlinear model (panel threshold model).

The panel threshold model allows testing whether the relationship between study variables varies if a given country consumes nonrenewable energy above or below the threshold [37]. It takes cross-sectional dependence into account, distorting the assumption of cross-sectional independence [26]. Hence, the study aims to achieve the objective of examining the impact of renewable energy consumption and economic growth via the threshold of nonrenewable energy intensity on environmental quality in Africa.

The following sections constitute the remaining text: the literature review and theory, followed by the threshold effect mechanism of nonrenewable energy intensity and hypotheses development are presented in Section 2, data and model specification are presented in Section 3, the study's findings and analysis are presented in Section 4, and the conclusion is presented in Section 5.

2. Literature Review and Theory

The Sustainable Energy for All Initiative, sponsored by the World Bank, aims to provide universal access to energy, speed up energy efficiency gains, and significantly increase the amount of renewable energy in Africa's energy mix, particularly by 2030 [38]. It is crucial to research how renewable energy affects environmental sustainability, especially in Africa, where there is a need for stable economic growth, energy security, and environmental sustainability. Investigating the relationship between renewable energy, economic growth, and the environment has recently become a popular topic in the literature, due to the necessity to implement a greener economic growth process in order to accomplish the developmental goals of nations in the next decades [7]. Although increasing investments in renewable energy production are thought to be related to economic development and growth, it is unclear from the literature currently available whether greater economic growth enhances the usage of renewable energies, or whether the opposite is true. According to [13], which examines the impact of renewable energy consumption on sectoral environmental quality in Nigeria in the presence of government effectiveness, the study covers the period from 1989 to 2019 and uses regression analysis. The result produced a mixed result on the impact of renewable energy consumption on sectoral environmental quality; for example, the impact is favorable in the case of agriculture, manufacturing, construction, and oil, but unfavorable in the case of the transportation, residential, commercial, and public sectors. Cherni and Jouini (2017) [39] uses an Autoregressive Distributed Lag model to analyze the link between CO_2 emissions, renewable energy consumption, and economic growth in Tunisia. The findings show that, for the gross domestic product, CO_2 emissions and renewable energy consumption are steady over the long-run. The Granger causality tests, however, show that there is no correlation between CO_2 emissions and renewable energy consumption, but there is a bidirectional relationship between GDP and CO_2 emissions, as well as between renewable energy consumption and GDP. In some oil-producing nations, such as Angola, Algeria, Equatorial Guinea, Egypt, Gabon, Congo Republic, Libya, Nigeria, and Sudan, the impact of renewable energy on economic growth is minimal, according to [40], but this study's findings revealed that CO_2 emissions have a significant impact on growth for nations such as Algeria, Equatorial Guinea, and Egypt. The empirical literature in this field focuses on a single country, see [7,13,38–46], which often results in inconsistent results [47] and weakens the power of cointegration [48]. Likewise, panel analysis is essential to fully comprehend the potential of Africa's renewable energy and its stage of development.

In their study, Ref. [44] examines the relationship existing between renewable energy consumption, economic growth, and environmental sustainability, in a panel of sub-Saharan African countries (SSA). The study adopts a commonly used autoregressive distributive lag model approach to examine the cointegrating relations and granger causality techniques, pioneered by Dumitrescu and Hurlin, to examine the causal direction between the study variables. The findings support the idea that economic growth, renewable energy, greenhouse gas emissions, and gross fixed capital formation all exhibit strong long-run relationships. The findings on the economic pillar of sustainability show that real gross fixed capital formation and renewable energy have favorable and significant effects on SSA nations' long-term growth. Furthermore, the environmental pillar of sustainability results demonstrates that, while renewable energy has a negative and significant impact on GHG emissions, real GDP and real gross fixed capital formation have positive and large impacts on GHG emissions. The results of the causality study demonstrate that real GDP, renewable energy, and gross fixed capital formation all have long-term feedback effects; renewable energy has a one-way causal relationship with CO_2 emissions. Inal et al. (2022) [40] also used a second-generation panel data analysis to look at the relationship between growth, CO_2 emissions, and renewable energy in oil-producing Angola, Algeria, Equatorial Guinea, Egypt, Gabon, Congo Republic, Libya, Nigeria, and Sudan from 1990 to 2014. In order to account for the horizontal cross-sectional dependency, the study used a bootstrap panel Lagrange multiplier (LM) cointegration, the autoregressive moving average (AMG) estimator to examine cointegration coefficients, and the country-based Kónya panel causality test. The study's findings, which supported the neutrality hypothesis, revealed no appreciable impact of renewable energy on economic growth. The findings also show that CO_2 emissions have a sizable positive impact on growth in Algeria, Equatorial Guinea, and Egypt. Due to the nonlinear behavior, the Panel Smooth Transition Model is utilized to investigate the link and transition between the low and high regimes.

Other literary categories: The results of an investigation into how economic growth affects CO_2 emissions, using the dynamic panel threshold framework of 31 developing nations, show that, while economic growth has a marginally positive impact on CO_2 emissions under low growth conditions, it has a marginally negative impact under high growth conditions [49]. Also, [40], utilizing the bootstrap panel LM cointegration, which takes into consideration the horizontal cross-sectional dependency, the AMG estimator, and the country-based Kónya panel causality test, examine these associations. In 25 African countries between 1990 and 2017, ref. [50] looks at the issue of the decoupling between economic growth and carbon emissions. The impact of international trade on carbon emissions is also evaluated in the study. In the regional decoupling analysis, the study takes into account both consumption- and production-based carbon emissions methodologies, as well as the corresponding independent effects of exports and imports on the decoupling process. The threshold levels of GDP per capita are placed well within the range of data in all estimations, but above the sample average of $3770, indicating some evidence of relative decoupling for production-based emissions. In contrast, there is no solid proof of decoupling emissions linked to consumption. The population and primary energy intensity are shown to be the main contributors to carbon emissions. Additionally, exports and imports have negligible influence on emissions based on production, but considerable and countervailing effects on emissions based on consumption. To this end, this study contributes to the body of literature by analyzing the following hypothetical questions:

1. Does the use of renewable energy have a nonlinear relationship to the quality of the environment?
2. Is there a nonlinear relationship between environmental quality and economic growth?

The revised neoclassical theory of environmental sustainability is addressed in order to illustrate the theoretical basis for the connection between economic growth and environmental sustainability [38]. Neoclassical economists make the basic assumption that the economic system is closed and linear, while ignoring the relationship between the environment and the economic system. This assumption is harshly challenged by classical economists. The production process requires a resource-rich environment, which can also be employed to achieve market equilibrium: "The unlimited exploitation of natural resources is commonly accepted as the price to pay for fueling economic growth and providing employment" [51].

The relationship between the economy and the environment was formalized by the Material Balance Model (Dragulanescu and Dragulanescu 2013) [51]. According to the theory, the economic system is made up of two distinct economies: (1) the real economy, which is the portion of the economic system made up of economic activities and value creation, as well as the efficient allocation and distribution of scarce resources, and (2) the extended economy, which supports life on Earth, and is the portion of the economic system that acknowledges the interdependence between the economy and the environment [38]. In Figure 1, this is further described.

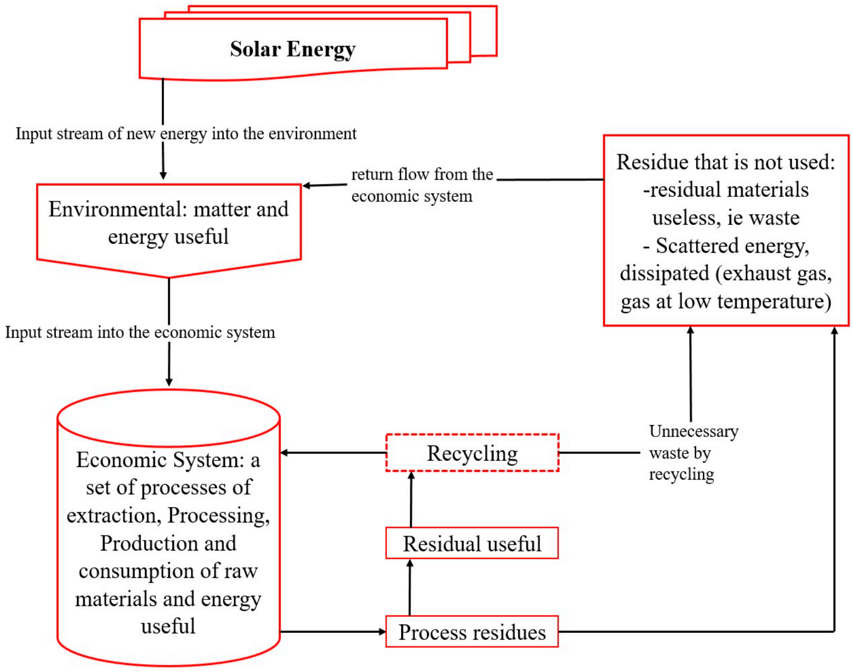

Figure 1. Material balance model. Source [51].

The economic system is open and circular in this model, and it is characterized by a series of environmental matter and energy extraction activities, followed by basic processing, manufacturing, and consumption. At the conclusion of each of these processes, the residues are no longer usable in the environment or in the receptor bodies. The first and second laws of thermodynamics, which underline the environmental restrictions that the system must take into account, shall regulate such accounting [51].

Threshold Effect Mechanism of Nonrenewable Energy Intensity and Hypotheses Development

This study measures the impact of renewable energy consumption and economic growth on environmental quality in all African countries, using a nonlinear panel threshold approach. The panel threshold regression model incorporates the threshold value into an empirical model as an unknown variable [52], and conducts a piece-wise function of the regression coefficients of the explanatory variables, so as to estimate the threshold value internally and estimate the parameters of different threshold intervals [53]. The following hypothetical analysis will justify the threshold effect mechanism, refs. [22,28]. Nonrenewable energy intensity is expressed in terms of nonrenewable consumption per unit of economic output [53]. Energy intensity reflects the countries' dependency on particular energy consumption (nonrenewable); the higher the intensity, the higher the economic growth dependency on nonrenewable energy consumption; thus, the economic cost structure of energy transformation and renewable energy development largely hinge on this dependency. The energy field explained the path dependency through the self-reinforcing mechanism of economies of scale and synergy effects, which increase the marginal return of nonrenewable energy, thereby promoting the economic development's dependence and inertia on nonrenewable energy industry structure, technology, and mechanism. This reliance thwarts the development of renewable energy technologies as economic changes toward renewable energy structures.

Following the 1973 global oil crisis, national energy efficiency measurement and monitoring became a crucial part of many countries' energy strategies, especially those that had a lack of energy. With the sharp rise in the price of oil, many nations realized they needed to improve energy efficiency and understand how effectively energy was being used in their economy. In order to achieve these goals, suitable energy efficiency indicators were created and used, allowing any efficiency changes to be quantitatively quantified. These variables were also utilized for international benchmarking and cross-country comparisons to explain variations in energy performance between nations [54]. Increasing energy efficiency in all economic sectors is a fundamental component of most nations' strategies for reaching their greenhouse gas reduction goals. Energy efficiency improvement has become yet another natural step for governments to take to minimize GHG emissions since the late 1980s, as a result of the growing worry about global warming caused by the burning of fossil fuels. According to the literature, energy efficiency is frequently assessed using thermodynamic indicators, physical-based indicators (such as the amount of energy used to produce one unit of physical output), and monetary-based indicators (energy requirements per dollar output) [54]. Energy efficiency improvement often entails consuming less energy, while producing the same quantity of beneficial services or output.

Energy policy planning and analysis frequently use monetary-based indicators, such as the "energy-to-GDP ratio", also known as the ratio of energy consumption to gross domestic product (EGR). The EGR is typically calculated as a country's GDP divided by its total primary energy consumption (TPEC). A country needs less energy to produce a unit of GDP over time if the ratio declines. This is a good development because it increases sustainability, economic competitiveness, and energy security.

Energy efficiency increases at the sector or end-use level are unknown, based only on EGR adjustments [55]. Energy efficiency may change without any impact from the EGR changes. For instance, research has revealed that when GDP rises, the EGR adopts an inverse U shape [54]. As energy-intensive sectors are introduced during the early stages of economic development, it rises to a peak, and then falls as the economy develops and the country moves its focus from energy-intensive industries to less energy-intensive ones, such as services. Energy efficiency is unrelated to a significant portion of this behavior, which can be explained by structural changes in manufacturing [55]. It is frequently believed that the EGR's numerator (TPEC) and denominator (GDP) correspond one-to-one. The TPEC is divided among the following sectors in energy accounting: industry, passenger, freight, services, residential, and the energy sector [22,28]. The unwavering commitment to renewables involves large expenditures in infrastructure and technologies. With more energy being produced from renewable sources, scale economies may be explored, which reduces fixed costs. Without subsidies, profitability is made possible by lower average costs. Therefore, a long-term commitment to renewables is expected after an investment in it has been made.

Three alternative approaches, the production approach, the expenditure approach, and the income approach, can be used to distribute the GDP by sector. In energy analyses, the production approach is most frequently utilized. The energy intensity is calculated as the sector's energy use as a percentage of the overall GDP or population [55].

Therefore, this study proposes the hypothesis that renewable energy consumption and economic growth have a nonlinear effect on environmental quality, via the direction or degree of change in nonrenewable energy intensity. When nonrenewable energy intensity reaches a certain level, the degree of expectation brought by the benefits of renewable energy consumption and economic growth, as well as the degree of dependency of environmental quality on nonrenewable energy intensity, is a positive direct relationship. In other words, the greater the path dependence and inertia of nonrenewable energy intensity, the greater the economic cost of reducing renewable energy and increasing renewable energy consumption during the energy transition. Once the anticipated benefits are not realized, it will hinder the development of renewable energy. Therefore, for countries with high nonrenewable energy intensity, the economic cost of increasing renewable energy consumption has become greater. Thus, the hypothesis is formulated as:

H1: *Renewable energy consumption has a negative nonlinear effect on environmental quality.*

H2: *Economic growth and environmental sustainability have a negative nonlinear relationship.*

3. Data and Model Specifications

3.1. Data

This study explores the effects of renewable energy consumption and economic growth on environmental quality, using nonrenewable energy intensity as a threshold variable. The data are sourced from the World Development Index. The threshold regression may not be suitable for all types of data. Its effectiveness depends on underlying assumptions and the nature of the relationships being investigated. Therefore, balanced panel data ranging from 1990 to 2019 was used. The range was narrowed to 2019 to include an adequate number of countries for regional representations. Country selection is based on data availability, as estimating threshold regression requires balanced data. The missing values are replaced by the median value of the series, given the series is skewed, and the countries with substantial missing values are dropped to balance the data. This is what makes the amount of countries to be 43. The selected African countries were divided into five regions: northern, western, eastern, southern, and central Africa, based on the IRENA 2014 report [17]. Table 1 provides a description of the study variables, abbreviations, and source remarks. As shown in [9], deforestation, solid waste, grazing, sulfur emissions, carbon emissions, erosion, water pollution, etc. are all elements that affect environmental quality. The choice of CO_2 emissions as proxy to environmental quality was based on insufficient data on the other proxies of environmental quality. Another reason is about 75% of the three categories of GHG emissions are CO_2 emissions, ref. [56]. The remaining 15% is made up of fluorinated gases, methane, and nitrous oxide [9]. Lastly, it is supported by empirical literature, see [1,2,38,57]. Economic growth is proxied by gross domestic product.

Table 1. Study variables and their descriptions.

Variables		Abr.	Explanation
Explained	Environmental quality	CO_2	The production of cement and the combustion of fossil fuels both produce carbon dioxide emissions
Threshold	Nonrenewable Energy intensity	EI	Ratio of fossil fuels to GDP at constant 2010 US$
Explanatory	Renewable Energy Consumption	RE	Consumption of renewable energy is the proportion of renewable energy in all final energy consumption
	Economic Growth	GDP	The total gross value added by all resident producers in the economy is calculated as GDP at purchaser's prices. Data are presented in constant 2015 prices and are stated in USD
Control	Industrial Structure	IS	Industrial value added as a share of GDP
	Trade Openness	TO	The GDP value divided by the total amount of items exported and imported
	Population Size	PS	A mid-year estimate based on the definition of population
	Urbanization	URB	The proportion of urban population in the total population

3.2. Model Specifications

The aim of this paper is to investigate the effect of renewable energy consumption and economic growth on environmental quality. Following the work of [38,57], in accordance with the underlying theories and earlier research, the study adopts and modifies the functional form as:

$$\ln co_{2i} = (\ln gdp_{i,t}, \ln re_{i,t}, \ln is_{i,t}, \ln to_{i,t}, \ln ps_{i,t}, \ln urb_{i,t}) \quad (1)$$

The definition of the variables is presented in Table 1. The model can further be specified as:

$$\ln co_{2i} = \alpha_1 \ln gdp_{i,t} + \beta_1 \ln re_{i,t} + \beta_2 is_{i,t} + \beta_3 \ln to_{i,t} + \beta_4 \ln ps_{i,t} + \beta_6 \ln urb_{i,t} + \varepsilon_i \quad (2)$$

$\ln co_2$ is the natural logarithm of carbon emissions as a dependent variable in the model, having its parameter as α_1. The variables $\ln gdp$ and $\ln re$ are the explanatory variables. The control variables in this model are $\ln is$ $\ln to$ $\ln ps$ and $\ln urb$. i represents the index of the country, t represents the year, β are the regression slopes, which distinguish regime's ε_{it} error term.

3.3. Econometric Techniques

3.3.1. Cross Sectional Dependency Specification

The statistical characteristics of panel unit root tests are likely to be significantly impacted by cross-sectional dependence. The power of panel unit root tests under the assumption of independent and identically distributed (i.i.d.) disturbances is examined by [58], who demonstrate that it is orders of magnitude higher than in a univariate situation. If the disturbances are not separate, however, then there are actually two problems. First, alternative distributions that take into account the presence of cross-sectional correlation must be derived, because the limiting distributions produced by [58] will no longer be valid. Second, even if the true distribution of the test statistic were accessible, we might assume that power is reduced as a result of the panel's overall decrease in independent information [59]. Because they were all designed under the stringent assumption of independence, the results from the first generation of panel unit root tests are inaccurate [24]. To determine whether the relevant variables exhibit cross-sectional dependence (CD), we perform the Pesaran (2004) [60,61] CD test. The cross-sectionally augmented Im-Pesaran-Shin (CIPS) panel unit root test takes into account the averages of lagged levels and differences for each unit to enable the cross-sectional dependence [24]. Following are the calculations for Pesaran CD test statistics:

$$CD = \sqrt{\frac{2T}{N(N-1)}} \left(\sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \hat{\rho}_{i,j} \right) \cdot N(0,1) \quad (3)$$

where $\hat{\rho}_{i,j}$ is the sample estimate of the pairwise correlation of the residuals.

First-generation panel unit root tests are used to formulate tests that assume cross-sectional independence, rather than taking into account cross-sectional dependency. Additionally, second-generation panel-unit root tests are used to describe tests that consider cross-sectional reliance (assumption of cross-sectional dependency) [62].

3.3.2. Unit Root Specifications

Given the close trade ties across nations within the global economic order, the impact of shocks on those nations, and the contagion effect, it is a more plausible assumption that cross-sectional dependence exists. The Pesaran CD test findings show that first-generation unit root tests are employed if there is no relationship between the cross-sections and the sections are independent of one another. However, second-generation unit root testing ought to be favored if there is a link between the cross-sections [62]. Pesaran (2003) [60] presented the CADF (Cross Sectionally-Augmented Dickey-Fuller Test) panel unit root test, which is a unit root test that considers cross-sectional dependence. This test, which can be applied in both the T > N and N > T instances, extends the conventional augmented Dickey-Fuller (ADF) regression with initial differences and lagged values of horizontal sections. For the entire panel, the CIPS test examines unit root attributes. The CADF test served as the basis for the CIPS test [62]. As a result, we apply the CIPS test to determine whether the relevant variables exhibit cross-sectional dependence [24]. The following is the estimation equation:

$$\mathrm{CIPS} = \mathrm{N}^{-1}\sum_{i=1}^{n}\mathrm{CADF}_t \tag{4}$$

The null of non-stationarity of the series is tested against alternative of stationarity of the series.

3.3.3. Threshold Model Design

In order to incorporate a specific threshold value as an unknown variable in the regression model, create a piecewise function, and empirically test and estimate the appropriate threshold value and the influence of the threshold, we use the panel threshold regression (PTR) model [63]. Based on the study's data, the single threshold model can be expressed as follows:

$$Y_{it} = \delta_i + \beta' x_{it} + \theta_1 g_{it} I(d_{it} \le r) + \theta_2 g_{it} I(r < d_{it}) + \omega_{it} \tag{5}$$

where y_{it} and g_{it} denote the explanatory variable (renewable energy consumption and economic growth), x_{it} is a collection of regulating factors that significantly affect carbon emissions, such as industrial structure, population, trade openness, and urbanization, β is the corresponding coefficient, r is the specific threshold value, d_{it} is the threshold variable (nonrenewable energy), and $I(.)$ is an indicator function. δ_i is an unpredictable factor, reflecting the individual effects of the country. ω_{it} represents a random interference term. The altered equation is stated as follows, with the average value for each group subtracted from each observation to remove any individual effects [63]. The transformed equation is given as:

$$Y^*{}_{it} = \beta' x^*{}_{it} + \theta_1 g^*_{it} I(d_{it} \le r) + \theta_2 g^*_{it} I(r < d_{it}) + \omega^*_{it} \tag{6}$$

The observations are stated as follows, after stacking:

$$Y^* = X^*(r)\theta + \omega^* \tag{7}$$

The above equation is estimated with ordinary least square to obtain the estimated value of θ, which is:

$$\theta(r) = \left(X^*(r)' X^*(r)\right)^{-1} X^*(r)' Y^* \tag{8}$$

The sum of the corresponding squared residuals is given as: $S_1(r) = \hat{e}^*(r)'\hat{e}^*(r)$, and the residual vector is given as: $\hat{e}^*(r) = Y^* - X^*(r)\theta(r)$. It is critical to ascertain the statistical significance of the threshold effect, the option of a threshold effect being present, and the null hypothesis of no threshold effect [64] and the alternative of presence of threshold effect.

$$F_1 = \frac{s_0 - s_1(\hat{r})}{(\hat{\sigma})^2} \tag{9}$$

Among them, under the null hypothesis, the threshold, r, cannot be identified. Moreover, the bootstrap approach achieves the first-order asymptotic distribution, so that the null of no threshold impact is rejected if F_1 is larger than the intended critical value, according to the asymptotic distribution of F_1, which is non-standard and rigorously dominates the chi-square distribution [64].

The second is whether the actual value and the estimated threshold are equal. The test's original hypothesis is that the threshold estimator equals the actual value [63], and the associated likelihood ratio (LR) statistic is provided as:

$$LR_1 = \frac{s_1(r) - s_1(r)}{\hat{\sigma}^2} \tag{10}$$

Because of the non-standard nature of its dispersion, when using $LR_1(r_0) \le -2\ln(1-\sqrt{1-\alpha})$, the null hypothesis cannot be rejected, where α is the significance level.

Testing for multiple-threshold model (double threshold):

$$Y^*{}_{it} = \delta_i + \beta^i x_{it} + \theta_1 g_{it} 1(d_{it} \le r) + \theta_2 g_{it} 1(r < d_{it} \le r_2) + \theta_3 g_{it} 1(r_2 < d_{it})\omega_{it} \tag{11}$$

Prior to using the estimate approach to find $\hat{r}_2$, we make the assumption that $\hat{r}_1$, in the single threshold model, is known. At last, we reach:

$$S_2^{\alpha}(r_2) = \begin{cases} S(\hat{r}_1, r_2) \text{ if } \hat{r}_1 < r_2 \\ S(r_2, \hat{r}_1) \text{ if } \hat{r}_1 > r_2 \end{cases} \tag{12}$$

$$\hat{r}_2^{\alpha} = \operatorname{argmin} S_2^{\alpha}(r_2)$$

$\hat{r}_2^{\alpha}$ donates progressive effective and r_2^{α} can be fixed for $\hat{r}_1$; then, r_2 can be updated to produce a reliable estimate.

The panel threshold model can effectively divide the threshold variables into low and high regimes and examine the differential influences. The double threshold effect of nonrenewable energy consumption of the renewable energy consumption-growth-environment nexus can be expressed as:

$$\begin{aligned} \ln co_{2it} = {} & \mu_0 + \mu_{11} \ln re_{it} I(\ln ei_{it} \le b_1) + \mu_{12} \ln re_{it} I(b_1 < \ln ei_{it} \le b_2) + \mu_{13} \ln re_{it} I(\ln ei_{it} > b_2) \\ & + \mu_2 \ln is + \mu_3 \ln to + \mu_4 \ln ps + \mu_5 \ln urb + \varepsilon_{it} \end{aligned} \tag{13}$$

$$\begin{aligned} \ln co_{2it} = {} & \omega_0 + \omega_{11} \ln gdp_{it} I(\ln ei_{it} \le c_1) + \omega_{12} \ln gdp_{it} I(c_1 < \ln ei_{it} \le c_2) + \omega_{13} \ln gdp_{it} I(\ln ei_{it} > c_2) \\ & + \omega_2 \ln is + \omega_3 \ln to + \omega_4 \ln ps + \omega_5 \ln urb + \varphi_{it} \end{aligned} \tag{14}$$

4. Results and Analysis

The study examines the nonlinear effect of renewable energy consumption and economic growth on environmental quality using the threshold of nonrenewable energy intensity, where carbon emission is used as a proxy for measuring environmental quality. A nonlinear-based threshold regression model was used. Table 2 explains the correlation matrix of the combined African countries. The explained variable (CO_2 emission) is found to be negatively correlated to renewable energy consumption and population structure, but positively correlated to gross domestic product. Nonrenewable energy consumption is positively correlated to carbon emissions and to gross domestic product. Tables A1–A5 of Appendix A explains regional descriptive and correlation.

Table 2. Descriptive statistics and correlation matrix.

	Mean	Std. Dev.	Min.	Max.	$lnCO_2$	lnre	lngdp	lnei	lnurb	lnps	lnto	lnis
$lnCO_2$	7.389	3.827	21.469	3.337	1.000							
lnre	2.273	1.173	5.956	0.975	−0.153	1.000						
lngdp	1.114	−2.813	2.113	0.495	0.188	−0.067	1.000					
lnei	13.129	5.000	26.943	4.649	−0.073	0.056	−0.169	1.000				
lnurb	7.389	3.827	21.469	3.327	−0.148	−0.029	−0.286	−0.228	1.0000			
lnps	2.273	1.173	5.956	0.975	0.422	0.086	0.375	0.019	−0.1921	1.0000		
lnto	1.114	−2.813	2.113	0.495	−0.036	−0.124	−0.035	−0.189	0.1151	−0.1967	1.0000	
lnis	13.129	5.000	26.947	4.609	0.195	−0.135	0.067	0.116	−0.1353	0.1306	0.0776	1.0000

4.1. Cross Sectional Dependency Test

Although cross-sectional independence in this relationship is assumed in the early unit root and cointegration literature, it is typical for macro-level data to deviate from this assumption, leading to low power and size distortions for the tests that rely on this assumption [65]. Table 3 presents the cross-sectional dependence test. Under the null hypothesis of cross-sectional independence, the null hypothesis is rejected at 10% level of significance for almost all the variables in combined and regional African countries. This finding suggests that economic growth and energy consumption are likely to follow similar transmission mechanisms throughout Africa [24]. High economic growth in one country is likely to have an impact on its neighbors. This demonstrates the substantial economic and energy dependence of some African nations on their neighbors.

Table 3. Cross-section dependency test.

	All		Central		Eastern		Northern		Southern		Western	
	Stat.	Prob.	Stat.	Prob.	Stat.	Prob.	Stat.	Prob.	Stat.	Prob.	Stat.	Prob.
$lnCO_2$	40.52 ***	0.000	32.10 ***	0.000	11.3 ***	0.000	8.53 ***	0.000	44.05 ***	0.000	10.83 ***	0.000
lnre	22.57 ***	0.000	30.05 ***	0.000	7.58 ***	0.000	4.71 ***	0.000	36.79 ***	0.000	3.300 ***	0.001
lngdp	48.71 ***	0.000	26.21 ***	0.000	11.4 ***	0.000	8.58 ***	0.000	38.09 ***	0.000	14.76 ***	0.000
lnei	13.82 ***	0.000	30.05 ***	0.000	7.05 ***	0.000	3.39 ***	0.001	44.15 ***	0.000	0.03	0.976
lnurb	35.03 ***	0.000	26.21 ***	0.000	2.46 ***	0.014	6.16 ***	0.000	14.91 ***	0.000	14.55 ***	0.000
lnps	51.08 ***	0.000	33.7 ***	0.000	12.2 ***	0.000	8.61 ***	0.000	44.15 ***	0.000	15.78 ***	0.000
lnto	48.65 ***	0.000	23.96 ***	0.000	11.5 **	0.000	8.31 ***	0.000	34.39 ***	0.000	14.91 ***	0.000
lnis	17.67 ***	0.000	2.32 **	0.020	6.88 ***	0.000	0.55 ***	0.583	−0.99	0.321	2.10 **	0.035

Notes: ** and *** represent the significance level of 5 and 10%, respectively.

4.2. Unit Root Test

The first generation of panel unit root tests, which are founded on the cross-sectional independence assumption, are inappropriate, given that the variables are cross-sectionally dependent [37], since they would suffer from size distortions and the ignorance of cross-section dependence [65]. Therefore, we utilize the (CIPS) unit root test, introduced by [60], to account for the presence of cross-sectional dependency in the variables [37]. The results of the CIPS unit root test are shown in Table 4 for combined African countries, and Tables A6–A10 of Appendix A for regional African countries. For all of the given samples, we are unable to reject the null hypothesis of unit root at levels. When we obtain the first-order differences of the variables used, however, the null hypothesis of non-stationarity can be rejected at the 10% significance level for most of the variables in combined and regional African countries. As a result, we conclude from the findings that the variables are stable in initial differences, but non-stationary in levels.

Table 4. Panel unit root test (CIPS) for combined African countries.

	Level					First Difference				
	Statistics	Prob.	1%	5%	10%	Statistics	Prob.	1%	5%	10%
$lnCO_2$	−1.46	0.586	−2.07	−1.90	−1.82	−5.43 ***	0.000	−2.07	−1.90	−1.82
lnre	−1.18	0.929	−2.07	−1.90	−1.82	−5.28 ***	0.000	−2.07	−1.90	−1.82
lngdp	−1.17	0.996	−2.07	−1.90	−1.82	−4.145 ***	0.000	−2.07	−1.90	−1.82
lnnre	0.52	1.000	−2.07	−1.90	−1.82	−1.99 **	0.000	−2.07	−1.90	−1.82
lnurb	−0.20	1.000	−2.07	−1.90	−1.82	−0.92	0.99	−2.07	−1.90	−1.82
lnps	−1.54	0.364	−2.07	−1.90	−1.82	−5.33 ***	0.000	−2.07	−1.90	−1.82
lnto	−1.61	0.343	−2.07	−1.90	−1.82	−6.52 ***	0.000	−2.07	−1.90	−1.82
lnis	−1.54	0.364	−2.07	−1.90	−1.82	−5.37 ***	0.000	−2.07	−1.90	−1.82

Note: ** and *** represent the significance level of 5% and 10% respectively. 10%, 5%, 1% are the critical values.

4.3. Estimation of the Panel Threshold

4.3.1. Test of Threshold Existence

The first step in implementing the threshold is figuring out how many thresholds there should be. To do this, the study employed Stata 15, which is based on the Hansen threshold panel model estimate, and tested the thresholds 300 times, using the bootstrap approach [26]. The initial phase of the study involves investigating the presence of a threshold, and the findings reveal that, when nonrenewable energy intensity is employed as the threshold variable, both renewable energy consumption and economic growth exhibit a singular threshold effect on carbon emissions. These outcomes are depicted in Table 5 and illustrated by the likelihood ratio function in Figures 2 and 3. In this context, Panel A pertains to the impact of renewable energy consumption on carbon emissions, utilizing nonrenewable energy intensity as the threshold variable, while Panel B represents the impact of economic growth on carbon emissions. The results highlight the presence of a significant double threshold in all the models, with respective values of 13.620 and 51.870 surpassing the critical values of [11.334, 13.264] and [18.081, 25.682, 40.625] at a significance level of 5% and 1%. The corresponding *p*-values are 0.047 and 0.003, respectively.

Table 5. Threshold existence test, and estimated threshold variables.

	Thr. No.	***p*-Value**	**F-Value**	**Critical Value**			**Th. Value**	**95% Conf. Int.**	
				10%	**5%**	**1%**		**Lower**	**Upper**
Panel A	Single	0.047	13.620 **	11.334	13.264	19.464	$R_1 = 5.911$	5.880	5.947
Panel B	Single	0.003	51.870 ***	18.081	25.682	40.625	$R_1 = 6.120$	6.114	6.120

Notes: ** and *** represent the significance level of 5% and 10%, respectively.

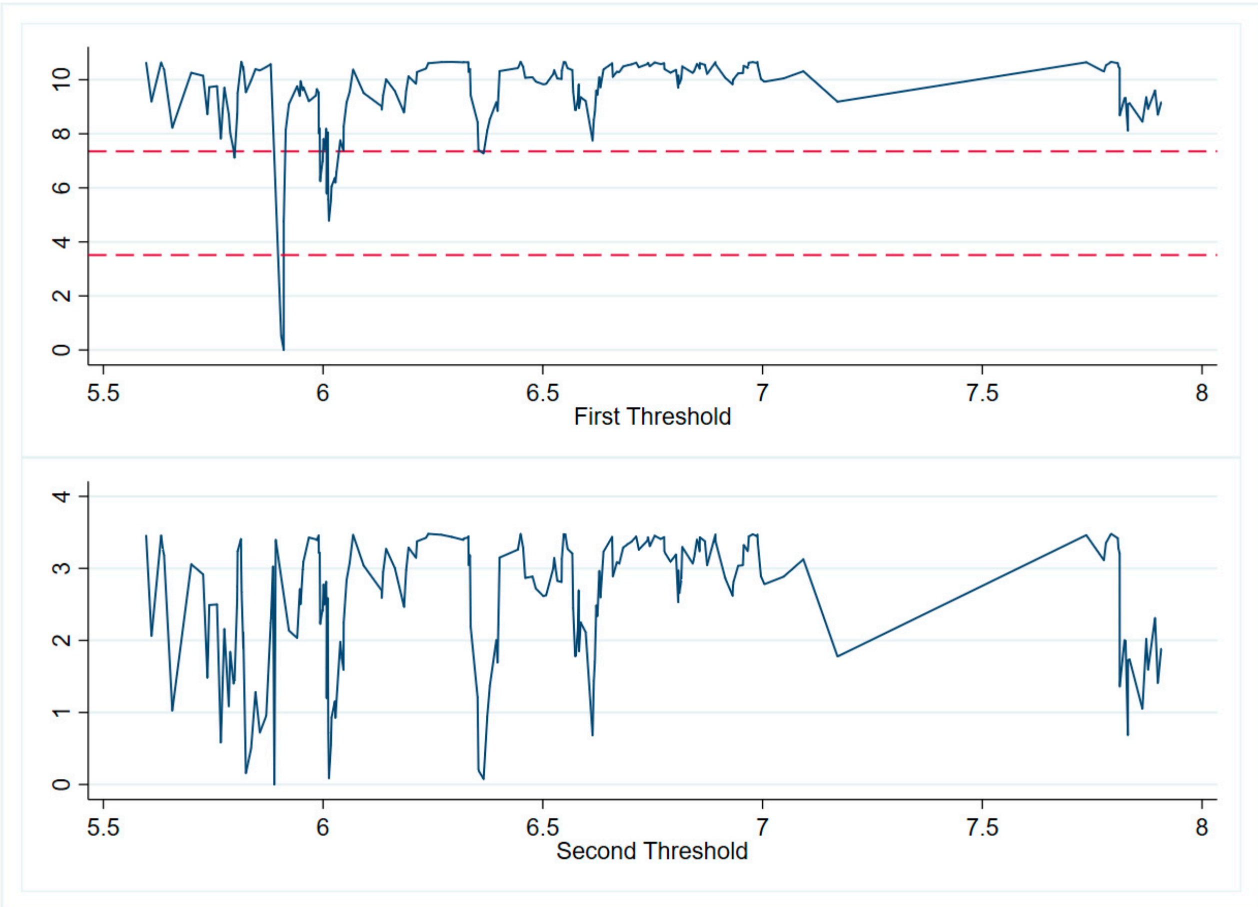

Figure 2. Likelihood ratio function graph panel A.

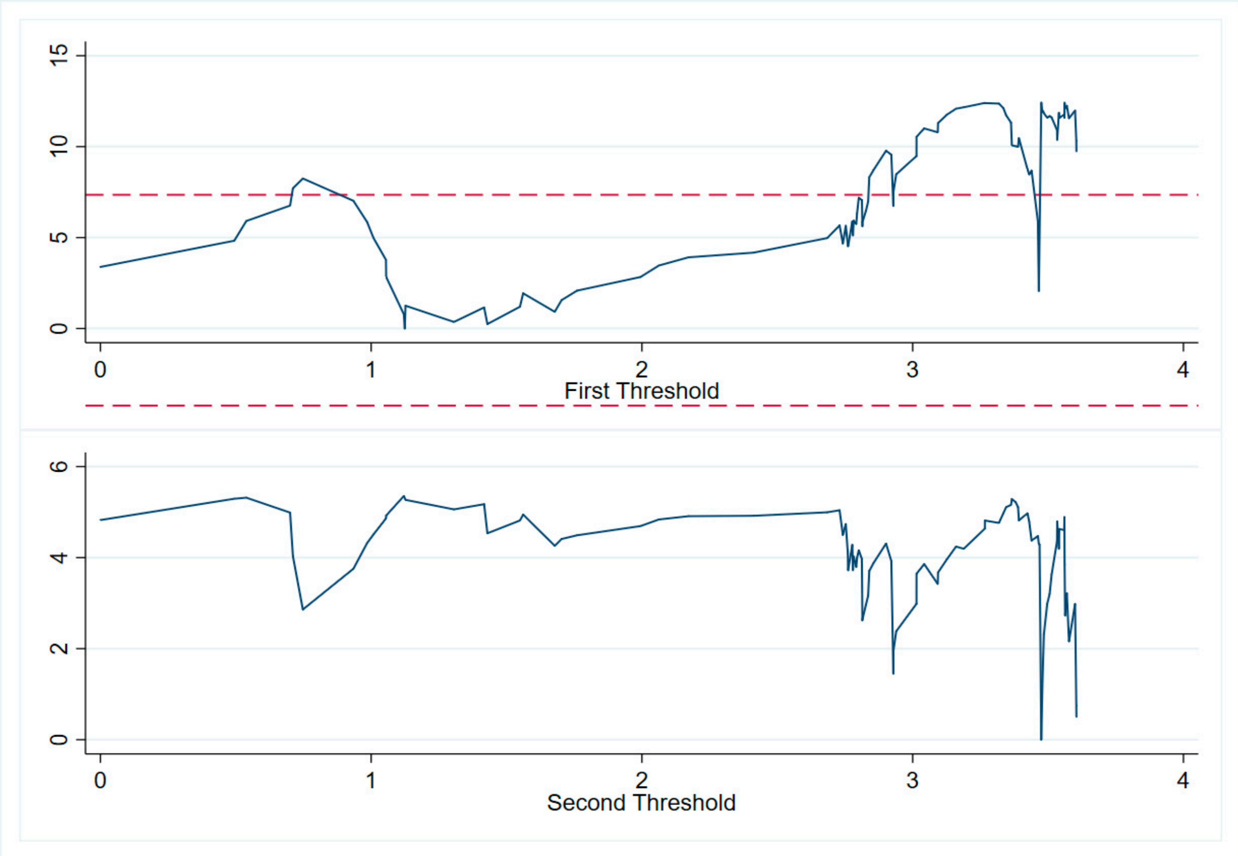

Figure 3. Likelihood ratio function graph panel B.

The estimated threshold values are 5.911 and 6.120, with corresponding 95% confidence intervals of [5.880–5.947] and [6.114–6.120], respectively. The likelihood ratio function graphs shows that there is a nonlinear threshold effect, using the dotted line when nonrenewable energy intensity is used as a threshold variable in both models.

4.3.2. Examining the Threshold's Estimated Results

The study aims to examine the relationship between renewable energy consumption, economic growth, and carbon emissions, taking into account the threshold variable of nonrenewable energy intensity. By analyzing the effect of these variables on carbon emissions at different levels of nonrenewable energy intensity, the study provides valuable insights into the environmental impact of renewable energy and economic growth. To ensure the robustness of the findings, the study employs fixed effect and threshold estimation techniques. The results, presented in Table 6, indicate distinct threshold levels, dividing the variable into high and low levels. At each threshold level, the effect of renewable energy consumption on carbon emissions is consistently negative. This implies that an increase in renewable energy consumption leads to a relative reduction in carbon emissions, despite the relatively low consumption of renewable energy in Africa and the proportionally low carbon emissions associated with renewable energy sources. This observation is consistent with the findings reported in the study conducted by [4].

Table 6. Results of fixed effects and PTR estimation using lnre as the explanatory variable (Panel A).

Variables	Fixed Effect	Threshold Model
lnre	−0.282 *** (−1.390)	−0.649 *** (d < 5.911) (−2.840) −0.556 *** (d > 5.911) (−2.450)
lnis	0.2432 *** (2.00)	0.127 *** (0.60)
lnto	0.021 ** (1.61)	0.656 ** (4.97)
lnps	0.709 *** (5.34)	0.320 *** (2.62)
lnurb	−0.827 *** (−6.31)	−0.444 *** (−3.64)
constant	−19.522 *** (−15.08)	−18.16 *** (−16.44)
R-squared	0.871	0.987
Number of obs.	1590	1590

Notes: ** and *** represent the significance level of 5% and 10%, respectively.

Specifically, when the threshold variable is at a high level, the coefficient estimate for the effect of renewable energy consumption on carbon emissions is −0.649. Similarly, when the threshold is at a low level, the coefficient estimate is −0.556. These negative and significant coefficients signify that the effect of renewable energy consumption on carbon emissions remains negative in both the high- and low-level phases. This suggests a nonlinear relationship, characterized by varying effects at different threshold levels.

These findings highlight the potential of renewable energy consumption in mitigating carbon emissions in Africa. Despite the current low levels of renewable energy consumption, the study emphasizes its positive impact on the environment. The nonlinear nature of the threshold effect further emphasizes the importance of considering the specific threshold levels when analyzing the relationship between renewable energy consumption, economic growth, and carbon emissions. Overall, these results provide valuable insights for policymakers and stakeholders in promoting renewable energy adoption and achieving sustainable development goals in Africa. The study demonstrates the potential of renewable energy as a key contributor to environmental preservation, and emphasizes the need for targeted policies to further enhance its positive impact.

Contrarily, in the results of Panel B, where lngdp is utilized as an explanatory variable, the coefficients of carbon emissions display a positive association at both split asymmetric threshold phases, as presented in Table 7. This indicates that, as the level of economic production increases in Africa, there is a corresponding increase in carbon emissions. These findings highlight the impact of nonrenewable energy sources, which are predominantly used in the production process in Africa and contribute significantly to carbon emissions. Notably, when the threshold value is set at a high threshold of 6.120, the coefficient of carbon emissions remains positive, suggesting that, even at higher levels of economic production, carbon emissions continue to rise. Similarly, the same positive association is observed at the low-level threshold. These results emphasize the need for effective measures to address the reliance on nonrenewable energy sources and promote the transition to renewable energy in the production process in Africa. The upward trend observed in the coefficient of carbon emissions at a later stage of the threshold indicates the insufficiency of the current efforts in transitioning from nonrenewable to renewable energy sources. This highlights the importance of implementing policies and initiatives to accelerate the adoption of renewable energy technologies and reduce the carbon intensity of economic activities in Africa.

Table 7. Results of fixed effects and PTR estimation using lngdp as the explanatory variable (Panel B).

Variables	Fixed Effect	Threshold Model
lngdp	0.651 *** (1.380)	0.136 *** (d < 6.120) (0.280) 0.054 *** (d > 6.120) (0.110)
lnis	0.113 *** (0.54)	0.295 *** (2.05)
lnto	−0.610 * (−5.03)	−0.473 *** (−3.82)
lnps	0.214 *** (1.76)	0.2034 *** (1.78)
lnurb	−0.69 *** (−4.69)	−0.481 *** (−11.32)
constant	−24.66 *** (−14.41)	−27.198 *** (−19.05)
R-squared within	0.875	0.925
Number of obs.	1590	1590

Notes: * and *** represent the significance level of 1% and 10%, respectively.

Additionally, the control variables in both Panel A and B exhibit significant negative and positive results. These findings suggest that other factors play a role in influencing carbon emissions in Africa. Understanding the impact of these control variables can provide valuable insights for policymakers in formulating targeted strategies to address environmental challenges and promote sustainable development.

The results of the two panels reveal a contrasting, yet expected, effect. The consumption of renewable energy is found to contribute to a reduction in carbon emissions in Africa, aligning with previous research findings [4,40,57]. Contrarily, according to [50], in the context of emissions related to consumption, there is a lack of conclusive evidence regarding decoupling economic growth.

However, the relationship between economic growth and environmental quality shows a significant positive association, indicating that economic growth is positively related to carbon emissions in Africa. It is worth noting that recent literature highlights the increasing adoption of renewable energies in Africa, and these developments can potentially impact carbon emissions. However, generalizing the relationship between renewable energy consumption, economic growth, and carbon emissions, without considering the diverse energy transition and development stages across regions and countries in Africa, may lead to biased results. Therefore, to gain a comprehensive understanding, this study further investigates these relationships within each specific region in Africa.

By analyzing the relationships at the regional level, the study aims to capture the nuances and variations in the impact of renewable energy consumption and economic growth on carbon emissions. This approach acknowledges the heterogeneity of energy systems, policy frameworks, and socio-economic factors across different regions in Africa. Such a detailed analysis will provide valuable insights into the specific dynamics of each region and enable policymakers to tailor strategies that address the unique challenges and opportunities associated with sustainable energy transitions.

In summary, this study recognizes the divergent effects of renewable energy consumption and economic growth on carbon emissions in Africa. It emphasizes the importance of analyzing these relationships at the regional level to account for variations in energy transition phases and development levels across different regions. By doing so, the study aims to contribute to a more accurate understanding of the complex interactions between renewable energy consumption, economic growth, and carbon emissions in Africa.

4.4. The Threshold Effects of the Grouped Regions

To further facilitate the regional differences, varying energies (renewable and non-renewable), and respective stages of development, this study examines the effect of both renewable energy consumption and economic growth (via the threshold variable) on all the five African region's carbon emissions. Due to the differences in resources and development, the results show obvious regional differences.

The threshold existence test was conducted on all five regions, with threshold variables of nonrenewable energy intensity. The results, as shown in Table A11 of Appendix A, and likelihood ratio function graphs in Figures A1–A10 of Appendix A, indicate that all the regions pass a single threshold effect, for both the model of renewable energy consumption and with economic growth as the explanatory variable. Table 8 presents the estimated threshold values of each region, with 95% confidence intervals.

Table 8. Estimated threshold values of grouped countries.

Group	Renewable Energy Consumption (Panel A)				Economic Growth (Panel B)			
	Threshold Model	Threshold Value	95% Conf. Int.		Threshold Model	Threshold Value	95% Conf. Int.	
			Lower	Upper			Lower	Upper
Central	Single	3.4791	3.3161	3.4846	Single	2.6256	2.4125	2.6846
Eastern	Single	6.183	6.182	6.185	Single	5.856	5.834	5.914
Northern	Single	6.5137	6.4744	6.5713	Single	6.8858	6.7310	6.9392
Southern	Single	4.428	4.374	4.436	Single	4.437	4.294	4.455
Western	Single	3.346	3.342	3.357	Single	3.0753	3.0102	3.2189

The impact of renewable energy consumption on carbon emissions in various African regions exhibits significant variation, influenced by the level of nonrenewable energy intensity. As depicted in Table 9, the majority of regions demonstrate a negative relationship between renewable energy consumption and carbon emissions. This negative coefficient highlights the influence of renewable energy consumption on the quality of the environment, as represented by carbon emissions in Africa. Given that a significant portion of greenhouse gas emissions in Africa is attributable to fossil fuel and nonrenewable energy consumption, the adoption of renewable energy sources holds the potential to reduce emissions and enhance environmental conditions. The negative coefficient signifies that an increase in the proportion of renewable energy consumption in Africa will result in a corresponding decrease in carbon emissions, thereby offering environmental benefits.

Table 9. The estimated threshold results of panel A and B.

Grouping	Threshold	Panel A		Panel B	
		Coefficients	Std. Dev.	Coefficients	Std. Dev.
Central	re * I(lnnre < r_1)	−0.364 * (d < 3.4791) (−1.49)	0.2449	0.767 *** (d < 2.6256) (4.19)	0.1832
	re * I(lnnre > r_1)	−0.308 ** (d > 3.4791) (−2.08)	0.2470	0.745 *** (d > 2.6256) (4.10)	0.1820
Eastern	re * I(lnnre < r_1)	−0.784 *** (d < 6.183) (−6.73)	0.1165	0.166 *** (d < 5.856) (3.92)	0.0425
	re * I(lnnre > r_1)	−0.668 *** (d > 6.183) (−5.95)	0.1123	0.179 *** (d > 5.856) (4.26)	0.0420
Northern	re * I(lnnre < r_1)	−0.996 * (d < 6.5137) (−4.97)	0.4425	0.0690 ** (d < 6.8858) (0.39)	0.1031
	re * I(lnnre > r_1)	−0.761 * (d > 6.5137) (−2.21)	0.3438	0.0408 ** (d > 6.8858) (0.95)	0.0471
Southern	re * I(lnnre < r_1)	−0.143 *** (d < 4.428) (−1.900)	0.3553	0.941 *** (d < 4.437) (4.63)	0.2032
	re * I(lnnre > r_1)	−0.030 * (d > 4.428) (−0.420)	0.2275	0.718 *** (d > 4.437) (5.20)	0.1382
Western	re * I(lnnre < r_1)	−0.887 ** (d < 3.346) (−3.01)	0.2949	0.251 * (d < 3.5307) (2.38)	0.1051
	re * I(lnnre > r_1)	−0.311 *** (d > 3.346) (−3.29)	0.0948	0.0804 * (d > 3.5307) (0.50)	0.1601

Notes: *, ** and *** represent the significance level of 1%, 5%, and 10%, respectively.

In the analysis conducted on Central Africa, using panel (A), the impact of renewable energy consumption on carbon emissions was examined by splitting the threshold variable into two levels: high and low. The resulting coefficients were −0.364 and −0.308, respectively. These coefficients indicate that a unit change in renewable energy consumption will have a negative effect on carbon emissions in Central Africa, with the respective coefficients representing the magnitude of this effect. This suggests that an increase in renewable energy consumption will lead to a significant improvement in the environmental conditions of Central Africa. Furthermore, the observed asymmetric phases of the effect highlight the presence of a nonlinear relationship. Each split threshold level demonstrates a distinct negative effect, indicating that the impact of renewable energy consumption on carbon emissions is not uniform across different levels.

Similar findings were observed in the remaining regions, where the effect of renewable energy consumption on carbon emissions was nearly identical, exhibiting the same asymmetric pattern. These results further support the notion that renewable energy consumption has a significant and beneficial impact on the environment across various regions, albeit with varying magnitudes and nonlinear effects.

The study, therefore, rejects the null hypotheses that renewable energy consumption has a nonlinear negative effect on environmental quality in Africa.

Similarly, the findings from panel (B), which incorporates economic growth represented by (GDP) as an explanatory variable, indicate a positive relationship between economic growth and environmental quality. However, it is important to note that, while the overall effect is positive, the coefficients associated with this relationship differ across regions. This disparity reflects the varying stages of development and the efforts undertaken by different African regions to mitigate carbon emissions.

Table 9 illustrates the varying coefficients, highlighting the threshold effects of economic growth on carbon emissions. In Central Africa, for instance, where the threshold variable is nonrenewable energy intensity, the coefficients of lngdp are 0.767 and 0.745 for high and low-level threshold regimes, respectively. Although positive in both cases, the presence of asymmetric effects is evident, as the coefficients differ at each regime phase. Similarly, in Northern, Southern, and Western Africa, the coefficients of lngdp are 0.0690 for high and 0.0408 for low, 0.941 for high and 0.718 for low, and 0.251 for high and 0.0804 for low, respectively. These discrepancies in coefficients at each regime indicate the asymmetric nature of the relationship between economic growth and carbon emissions. It implies that a unit increase in productivity is associated with the respective coefficients, underscoring that a proportional increase in production processes in Africa leads to a corresponding increase in carbon emissions, thereby deteriorating environmental quality.

This outcome can be largely attributed to the persistent reliance of the African production processes on nonrenewable energy consumption, causing an inertia in dependency. The results of the control variables for each region yield mixed outcomes, which are presented in Tables A6 and A7 of the Appendix A, providing further insights into the complexity of the relationship between economic growth, carbon emissions, and the control factors in African regions.

The study, therefore, rejects the null hypothesis that economic growth has a negative nonlinear effect on environmental quality.

5. Conclusions

This study aimed to explore the nonlinear relationship between renewable energy consumption, economic growth, and environmental quality, focusing on all African countries (which, to the best of our knowledge, pioneer research in Africa). To achieve this, a recently developed nonlinear approach (the panel threshold regression model) was employed, utilizing nonrenewable energy intensity as the threshold variable. The model allowed for an examination of the asymmetric effects of both renewable energy consumption and economic growth on environmental quality, specifically represented by carbon emissions. By splitting the threshold regimes into high-level and low-level (and mid-level, in the case of a double threshold), the model assessed the respective impacts of the explanatory variables within each regime on the explained variable. The selection of nonrenewable energy intensity as the threshold variable was justified by the predominance of nonrenewable energy consumption in Africa, thereby providing valuable insights into the continent's energy transition efforts and policies aimed at reducing greenhouse gas emissions.

In light of the research objectives, the study proposed two hypotheses. The first hypothesis suggested a nonlinear and negative relationship between renewable energy consumption and carbon emissions. This hypothesis acknowledged the potential for renewable energy consumption to play a pivotal role in mitigating carbon emissions and improving environmental conditions. The second hypothesis proposed a nonlinear and negative relationship between economic growth and environmental quality. Recognizing the intricate interplay between economic development and environmental impacts, this hypothesis aimed to uncover the nuanced effects of economic growth on environmental quality, considering both positive and negative aspects. By utilizing the panel threshold regression model and incorporating the threshold variable of nonrenewable energy intensity, this study aimed to contribute to the understanding of the nonlinear dynamics between renewable energy consumption, economic growth, and environmental quality in Africa.

The study findings reveal a nonlinear negative relationship between renewable energy consumption and environmental quality, applicable to both the combined African countries and the five distinct African regions. This indicates that the utilization of renewable energy in Africa has a beneficial impact, by reducing carbon emissions and improving environmental conditions. Specifically, at the higher regime, a unit change in renewable energy consumption is associated with a significant decrease of 0.649 in carbon emissions. Similarly, at the lower regime, a unit change in renewable energy consumption is linked to a substantial decrease of 0.556 in carbon emissions. These results support the presence of a negative asymmetric effect of renewable energy consumption on carbon emissions, underscoring the positive influence on the environment and contradicting the initial hypothesis. The study emphasizes the necessity for enhanced promotion and efforts in transitioning from nonrenewable to renewable energy consumption in Africa to ensure environmental sustainability.

In contrast, the results from the second panel, which employs economic growth as the explanatory variable, demonstrate a nonlinear positive relationship between economic growth and environmental quality. This suggests that an increase in the production process leads to a proportional increase in carbon emissions, in both the combined African countries and the five regions. Specifically, at the higher threshold, a unit increase in lngdp is associated with a 0.136 increase in carbon emissions, while, at the lower threshold regimes, a unit increase in lngdp is associated with a 0.054 increase in lnco2, thus exacerbating the environmental impact. These findings highlight the persistent dependency of African production processes on nonrenewable energy sources, resulting in a negative effect on the environment.

In the pursuit of both sustainable economic growth and greenhouse gas emission reduction, African countries are faced with a dual challenge. However, this study proposes that a focused and proactive approach to promoting renewable energy consumption and mitigating greenhouse gas emissions is crucial for achieving effective environmental quality and driving progressive economic development. Adequate investments should be directed towards renewable energy sources, coupled with heightened awareness and initiatives aimed at curbing greenhouse gas emissions. The involvement of various stakeholders, including governments, private entities, and international organizations, is paramount in supporting this transition towards clean energy and sustainable development. Financial assistance and collaborative efforts from these entities will play a pivotal role in facilitating the necessary transition and achieving the shared goals of clean energy and sustainable development.

6. Limitations and Future Work

The analysis may not fully consider the contextual factors specific to African countries, such as governance structures and regional policy frameworks disparities. These factors can significantly influence the relationship between the study variables. Also, the research covers data from 1990–2019 only. Future work should explore the influences of governance structures, regional policy frameworks, socio-economic conditions, and other relevant contextual variables on the energy-growth-environment mix. Also, alternative regression techniques beyond threshold regression analysis should be explored. It will be good for future work to extend the time period, in order to capture long-term trends and assess the dynamic nature of the relationship. These can provide a more comprehensive understanding of the complexities involved and contributed to targeted policy recommendations.

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Appendix A

Table A1. Central African descriptive statistics and correlation matrix.

	Mean	**Std. Dev.**	**Min.**	**Max.**	**lnCO$_2$**	**lnre**	**lngdp**	**lnei**	**lnurb**	**lnps**	**lnto**	**lnis**
lnCO$_2$	6.512	2.380	3.689	9.209	1.000							
lnre	3.891	1.193	1.264	4.588	−0.399	1.000						
lngdp	21.404	4.518	18.869	24.591	0.015	0.105	1.000					
lnei	0.955	1.419	3.770	8.048	0.167	0.151	0.193	1.000				
lnurb	1.353	1.581	2.079	4.187	−0.191	0.090	0.383	0.468	1.000			
lnps	14.896	1.749	−2.557	0.678	−0.267	0.286	0.800	−0.074	0.286	1.000		
lnto	0.439	0.357	3.723	4.422	0.485	−0.329	0.115	0.227	0.348	−0.131	1.000	
lnis	2.680	1.386	2.092	4.435	0.290	−0.163	0.294	−0.023	0.054	0.333	−0.021	1.000

Table A2. Eastern African descriptive statistics and correlation matrix.

	Mean	**Std. Dev.**	**Min.**	**Max.**	**lnCO$_2$**	**lnre**	**lngdp**	**lnei**	**lnurb**	**lnps**	**lnto**	**lnis**
lnCO$_2$	7.322	1.356	5.011	10.011	1.000							
lnre	4.326	0.362	3.183	4.582	0.162	1.000						
lngdp	23.283	1.308	20.867	25.301	0.856	−0.006	1.000					
lnei	2.547	0.765	0.809	4.282	−0.056	−0.265	−0.079	1.000				
lnurb	2.068	0.459	1.101	2.735	0.057	−0.127	0.198	0.533	1.000			
lnps	16.348	1.294	13.289	18.535	−0.040	−0.238	−0.145	0.141	−0.014	1.000		
lnto	−1.698	0.661	−3.522	0.988	0.782	0.618	0.628	−0.325	−0.153	−0.191	1.000	
lnis	2.865	0.355	1.807	4.115	0.124	−0.186	0.189	0.470	0.290	0.176	−0.021	1.000

Table A3. Northern African descriptive statistics and correlation matrix.

	Mean	**Std. Dev.**	**Min.**	**Max.**	**lnCO$_2$**	**lnre**	**lngdp**	**lnei**	**lnurb**	**lnps**	**lnto**	**lnis**
lnCO$_2$	24.963	0.837	23.591	26.478	1.0000							
lnre	0.275	0.156	0.066	0.622	−0.5122	1.0000						
lngdp	10.766	0.836	9.585	12.297	0.9945	−0.5378	1.0000					
lnei	2.465	0.381	1.703	3.135	−0.8465	0.4525	−0.8846	1.0000				
lnurb	4.495	0.047	4.400	4.590	0.8557	−0.5728	0.8917	−0.9778	1.0000			
lnps	3.063	0.123	2.883	3.245	0.9691	−0.6496	0.9660	−0.7815	0.8214	1.0000		
lnto	17.124	0.825	15.925	18.320	0.9482	−0.6770	0.9378	−0.7171	0.7670	0.9877	1.0000	
lnis	3.362	0.123	3.188	3.686	0.6827	−0.3522	0.7223	−0.8563	0.8374	0.6192	0.5482	1

Table A4. Southern African descriptive statistics and correlation matrix.

	Mean	Std. Dev.	Min.	Max.	$lnCO_2$	lnre	lngdp	lnei	lnurb	lnps	lnto	lnis
$lnCO_2$	8.1509	1.7560	5.0106	13.0124	1.000							
lnre	3.5821	1.1401	−0.3425	4.5465	0.052	1.000						
lngdp	22.9890	1.4356	20.2101	26.6058	0.940	0.170	1.000					
lnei	3.5316	0.6524	1.5942	4.4790	0.310	−0.356	0.220	1.000				
lnurb	2.4512	0.4441	1.0396	3.5877	0.704	−0.311	0.677	0.317	1.000			
lnps	15.4862	1.7153	11.1492	17.9106	0.603	0.675	0.729	−0.201	0.161	1.000		
lnto	3.2504	0.4283	0.0000	4.2866	0.255	0.169	0.245	0.175	0.373	0.102	1.000	
lnis	0.6279	0.3292	0.1284	1.7667	−0.257	−0.332	−0.281	0.164	0.092	−0.467	0.063	1.000

Table A5. Western African descriptive statistics and correlation matrix.

	Mean	Std. Dev.	Min.	Max.	$lnCO_2$	lnre	lngdp	lnei	lnurb	lnps	lnto	lnis
$lnCO_2$	8.877	1.439	6.446	11.651	1.000							
lnre	4.222	0.232	3.684	4.516	0.222	1.000						
lngdp	23.785	1.502	21.208	26.885	0.952	0.247	1.000					
lnei	3.254	0.481	1.853	4.010	0.053	−0.886	0.091	1.000				
lnurb	2.854	0.159	2.542	3.154	−0.619	−0.338	−0.657	0.075	1.000			
lnps	16.750	1.093	15.144	18.988	0.979	0.340	0.978	−0.038	−0.689	1.000		
lnto	0.379	0.213	0.105	1.150	−0.322	−0.208	−0.391	−0.005	0.693	−0.375	1.000	
lnis	3.082	0.248	2.619	3.630	0.589	−0.007	0.511	0.115	−0.643	0.555	−0.427	1.000

Table A6. Panel unit root test (CIPS) for central Africa.

	Level					First Difference				
	Statistics	Prob.	1%	5%	10%	Statistics	Prob.	1%	5%	10%
$lnCO_2$	−0.96	0.985	−2.16	−1.98	−1.88	−5.47 ***	0.000	−2.16	−1.98	−1.88
lnre	−1.399	0.610	−2.16	−1.98	−1.88	−5.24 ***	0.000	−2.16	−1.98	−1.88
lngdp	−1.517	0.451	−2.16	−1.98	−1.88	−5.38 ***	0.000	−2.16	−1.98	−1.88
Lnei	−0.952	0.974	−2.16	−1.98	−1.88	−5.47 ***	0.000	−2.16	−1.98	−1.88
lnurb	−0.95	0.98	−2.16	−1.98	−1.88	−1.30	0.74	−2.16	−1.98	−1.88
lnps	0.40	1.00	−2.16	−1.98	−1.88	−1.33	0.703	−2.16	−1.98	−1.88
Lnto	−1.88	0.102	−2.16	−1.98	−1.88	−6.82 ***	0.000	−2.16	−1.98	−1.88
Lnis	−1.376	0.675	−2.16	−1.98	−1.88	−5.77 ***	0.000	−2.16	−1.98	−1.88

Notes: *** represent the significance level of 10%.

Table A7. Panel unit root test (CIPS) for eastern Africa.

	Level					First Difference				
	Statistics	Prob.	1%	5%	10%	Statistics	Prob.	1%	5%	10%
$lnCO_2$	−1.79	0.249	−2.46	−2.18	−2.04	−5.37 ***	0.000	−2.46	−2.18	−2.04
Lnre	−1.20	0.738	−2.46	−2.18	−2.04	−4.82 ***	0.000	−2.46	−2.18	−2.04
lngdp	0.167	1.000	−2.46	−2.18	−2.04	−3.75 ***	0.000	−2.46	−2.18	−2.04
lnei	−1.70	0.337	−2.46	−2.18	−2.04	−4.939 ***	0.000	−2.46	−2.18	−2.04
lnurb	−0.14	0.999	−2.46	−2.18	−2.04	−2.16 *	0.098	−2.46	−2.18	−2.04
lnps	0.280	1.000	−2.46	−2.18	−2.04	−0.854	0.931	−2.46	−2.18	−2.04
lnto	−1.698	0.454	−2.46	−2.18	−2.04	−6.522 ***	0.000	−2.46	−2.18	−2.04
lnis	−1.74	0.274	−2.46	−2.18	−2.04	−4.68 ***	0.000	−2.46	−2.18	−2.04

Notes: *, and *** represent the significance level of 1% and 10%, respectively

Table A8. Panel unit root test (CIPS) for northern Africa.

	Level					First Difference				
	Statistics	**Prob.**	**1%**	**5%**	**10%**	**Statistics**	**Prob.**	**1%**	**5%**	**10%**
$lnCO_2$	−1.585	0.485	−2.46	−2.18	−2.04	−4.809 ***	0.000	−2.46	−2.18	−2.04
lnre	−1.407	0.548	−2.46	−2.18	−2.04	−4.844 ***	0.000	−2.46	−2.18	−2.04
lngdp	−1.808	0.270	−2.46	−2.18	−2.04	−7.403 ***	0.000	−2.46	−2.18	−2.04
Lnei	−2.571	0.027	−2.46	−2.18	−2.04	−6.246 ***	0.000	−2.46	−2.18	−2.04
lnurb	−0.883	0.893	−2.46	−2.18	−2.04	−1.417	0.532	−2.46	−2.18	−2.04
lnps	−0.115	1.000	−2.46	−2.18	−2.04	−2.005	0.209	−2.46	−2.18	−2.04
Lnto	−2.099	0.178	−2.46	−2.18	−2.04	−6.583 ***	0.000	−2.46	−2.18	−2.04
Lnis	−1.851	0.226	−2.46	−2.18	−2.04	−5.870 ***	0.000	−2.46	−2.18	−2.04

Notes: *** represent the significance level of 10%.

Table A9. Panel unit root test (CIPS) for southern Africa.

	Level					First Difference				
	Statistics	**Prob.**	**1%**	**5%**	**10%**	**Statistics**	**Prob.**	**1%**	**5%**	**10%**
$lnCO_2$	−5.841	0.087	−2.04	−1.90	−1.81	−12.09 ***	0.000	−2.04	−1.90	−1.81
Lnre	−4.524	0.290	−2.04	−1.90	−1.81	−10.352 ***	0.000	−2.04	−1.90	−1.81
lngdp	−1.222	0.896	−2.04	−1.90	−1.81	−5.06 ***	0.000	−2.04	−1.90	−1.81
lnei	−1.590	0.579	−2.04	−1.90	−1.81	−6.800 ***	0.000	−2.04	−1.90	−1.81
lnurb	−3.697	0.002	−2.04	−1.90	−1.81	−1.851	0.087	−2.04	−1.90	−1.81
lnps	1.634	1.000	−2.04	−1.90	−1.81	−2.577 ***	0.000	−2.04	−1.90	−1.81
lnto	−1.832	0.126	−2.04	−1.90	−1.81	−5.772 ***	0.000	−2.04	−1.90	−1.81
lnis	−2.027	0.07	−2.04	−1.90	−1.81	−3.212 ***	0.000	−2.04	−1.90	−1.81

Notes: *** represent the significance level of 10%.

Table A10. Panel unit root test (CIPS) for western Africa.

	Level					First Difference				
	Statistics	**Prob.**	**1%**	**5%**	**10%**	**Statistics**	**Prob.**	**1%**	**5%**	**10%**
$lnCO_2$	−1.712	0.327	−2.46	−2.18	−2.04	−5.468 ***	0.000	−2.46	−2.18	−2.04
lnre	−1.387	0.628	−2.46	−2.18	−2.04	−5.207 ***	0.000	−2.46	−2.18	−2.04
lngdp	−0.469	0.997	−2.46	−2.18	−2.04	−3.617 ***	0.000	−2.46	−2.18	−2.04
lnei	−1.713	0.325	−2.46	−2.18	−2.04	−5.564 ***	0.000	−2.46	−2.18	−2.04
lnurb	−1.554	0.892	−2.46	−2.18	−2.04	−1.744	0.302	−2.46	−2.18	−2.04
lnps	−0.871	0.977	−2.46	−2.18	−2.04	−1.353	0.652	−2.46	−2.18	−2.04
lnto	−1.649	0.347	−2.46	−2.18	−2.04	−4.674 ***	0.000	−2.46	−2.18	−2.04
lnis	−1.944	0.120	−2.46	−2.18	−2.04	−5.298 ***	0.000	−2.46	−2.18	−2.04

Notes: *** represent the significance level of 10%.

Table A11. Threshold existence test of grouped countries.

Grouping	**Explanatory Vrb.**	**Threshold Test**	***p*-Value**	**F-Value**	**Critical Value**		
					10%	**5%**	**1%**
Central	Renewable Energy	Single	0.0133	11.88 ***	7.4114	8.2178	12.3153
	Economic Growth	Single	0.0067	9.01 ***	5.5907	6.7870	7.8144
Eastern	Renewable Energy	Single	0.000	29.270 ***	15.823	17.257	20.908
	Economic Growth	Single	0.0752	17.600 *	16.365	21.255	23.430
Southern	Renewable Energy	Single	0.0767	34.12 *	30.7511	38.797	64.0811
	Economic Growth	Single	0.017	33.460 **	21.296	26.159	37.537
Northern	Renewable Energy	Single	0.000	32.428 ***	9.6621	11.7239	16.6521
	Economic Growth	Single	0.054	9.705 **	7.0855	7.8209	13.0780
Western	Renewable Energy	Single	0.0000	38.93 ***	14.284	17.385	21.1899
	Economic Growth	Single	0.0033	41.58 ***	24.2727	27.6713	37.9884

Notes: *, ** and *** represent the significance level of 1%, 5%, and 10%, respectively.

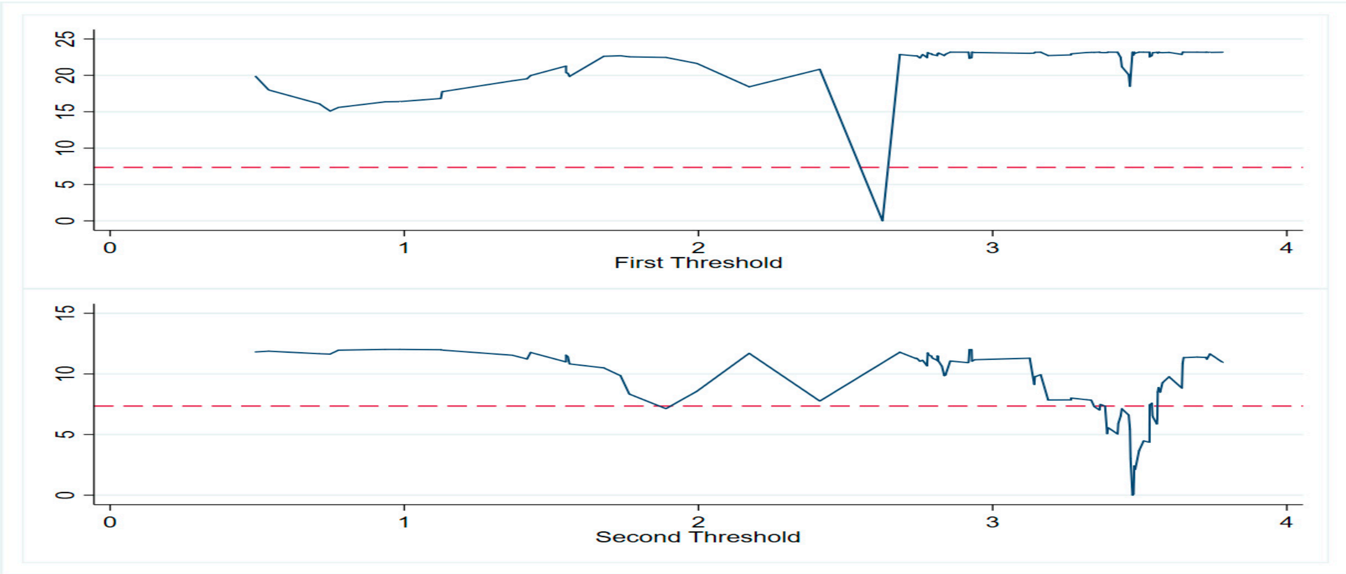

Figure A1. Panel A, likelihood ratio function (central Africa).

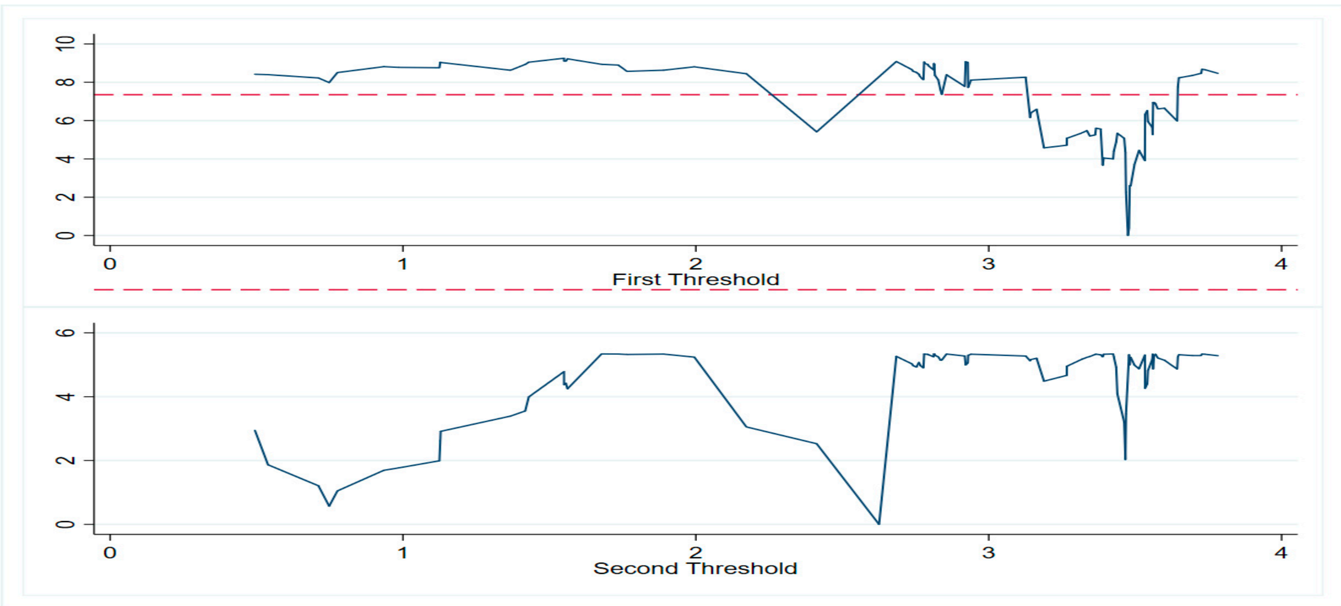

Figure A2. Panel B, likelihood ratio function (central Africa).

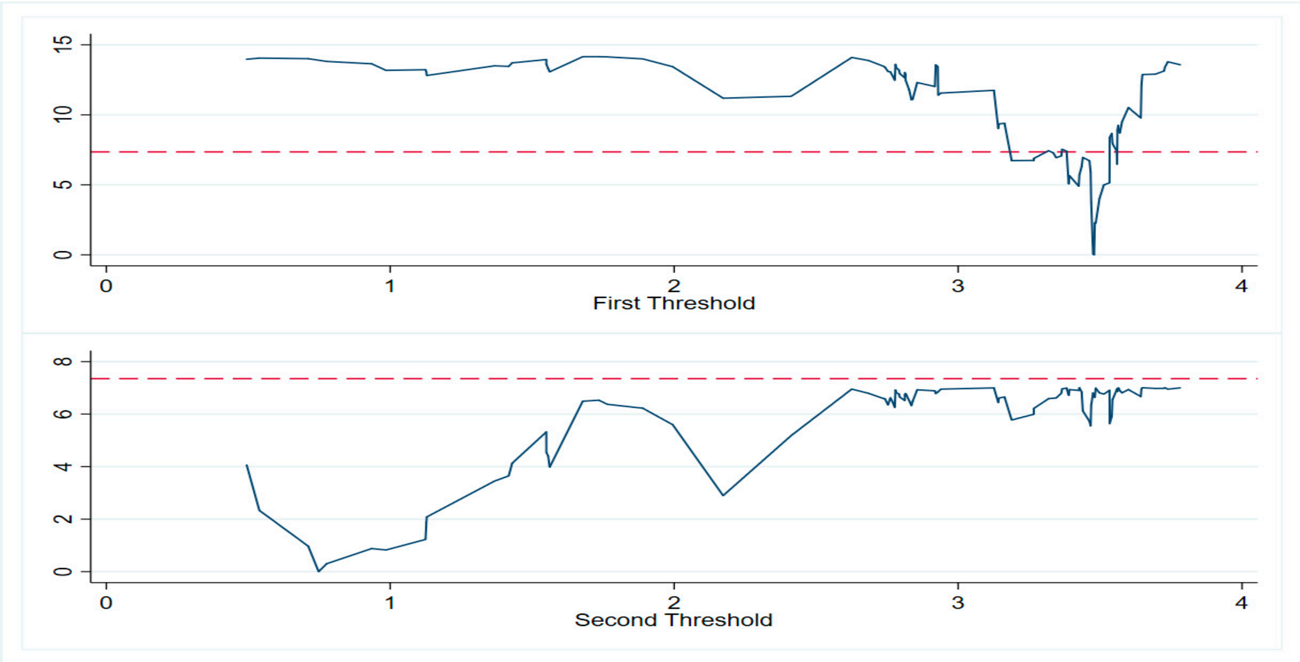

Figure A3. Likelihood ratio function (eastern Africa) Panel A.

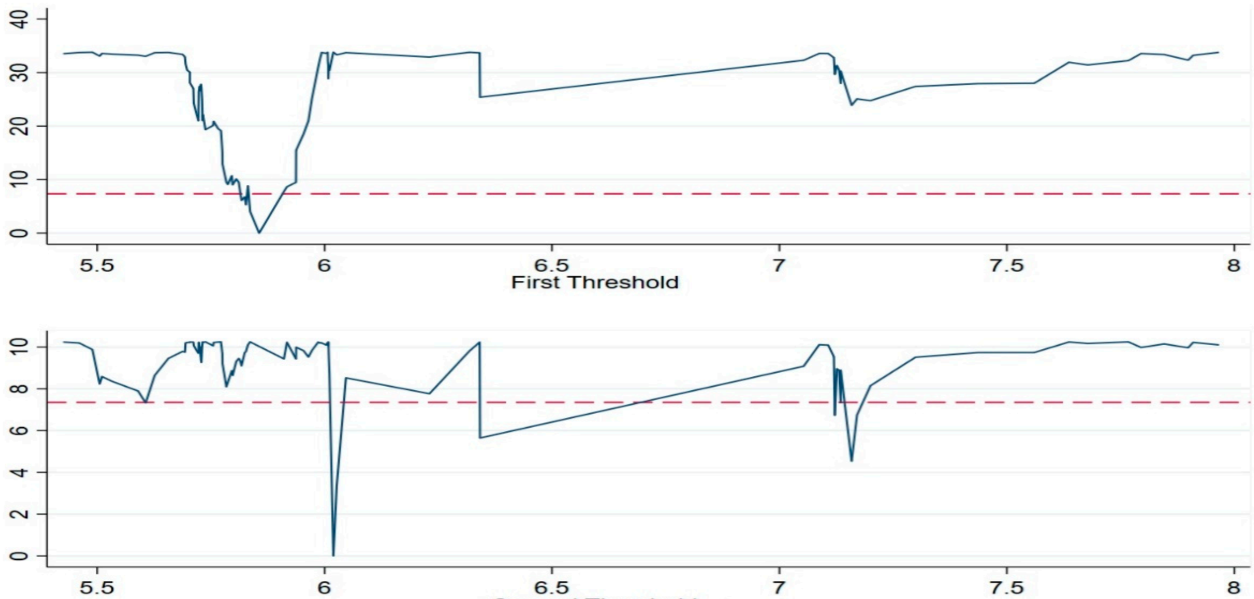

Figure A4. Likelihood ratio function (eastern Africa) Panel B.

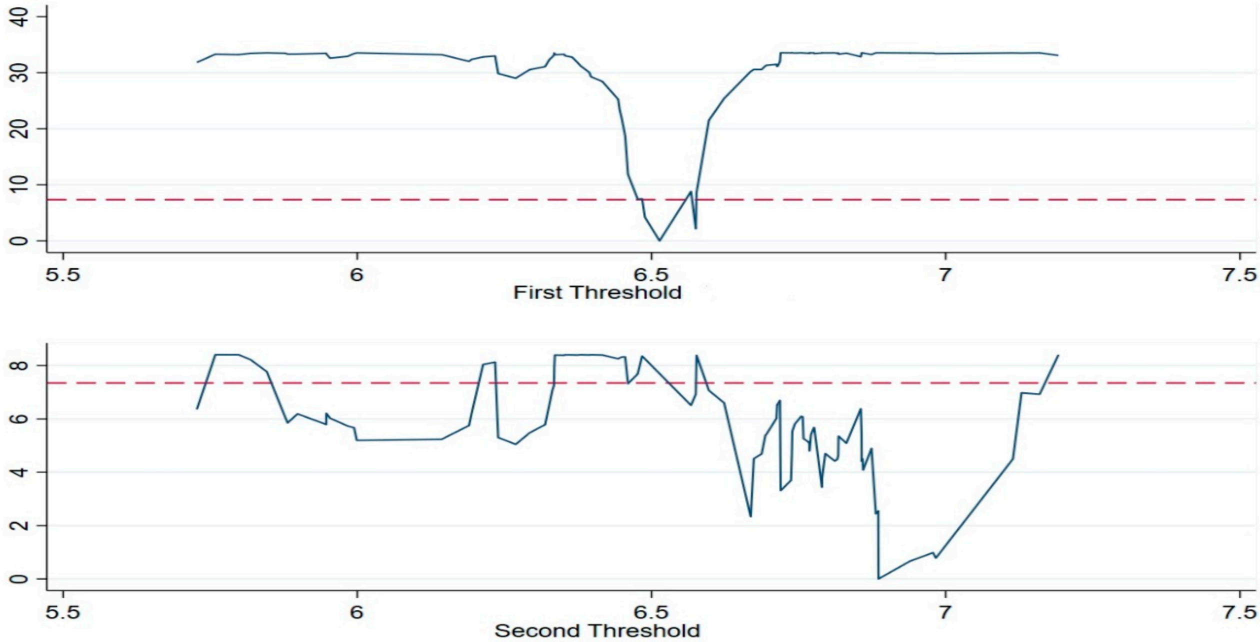

Figure A5. Likelihood ratio function (northern Africa) Panel A.

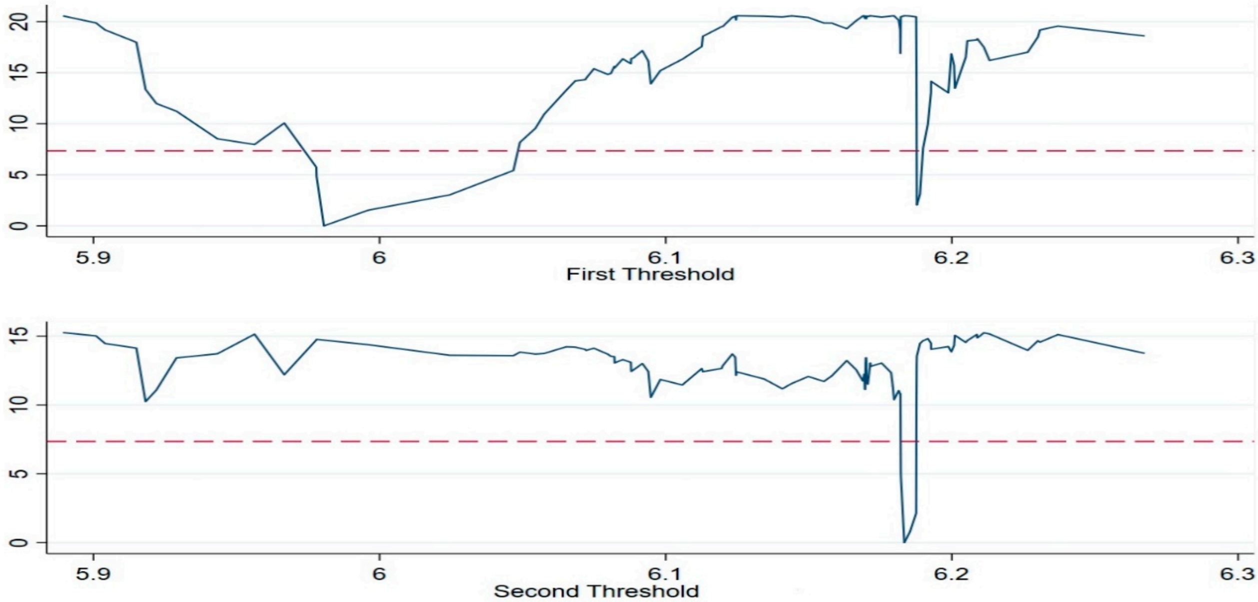

Figure A6. Likelihood ratio function (northern Africa) Panel B.

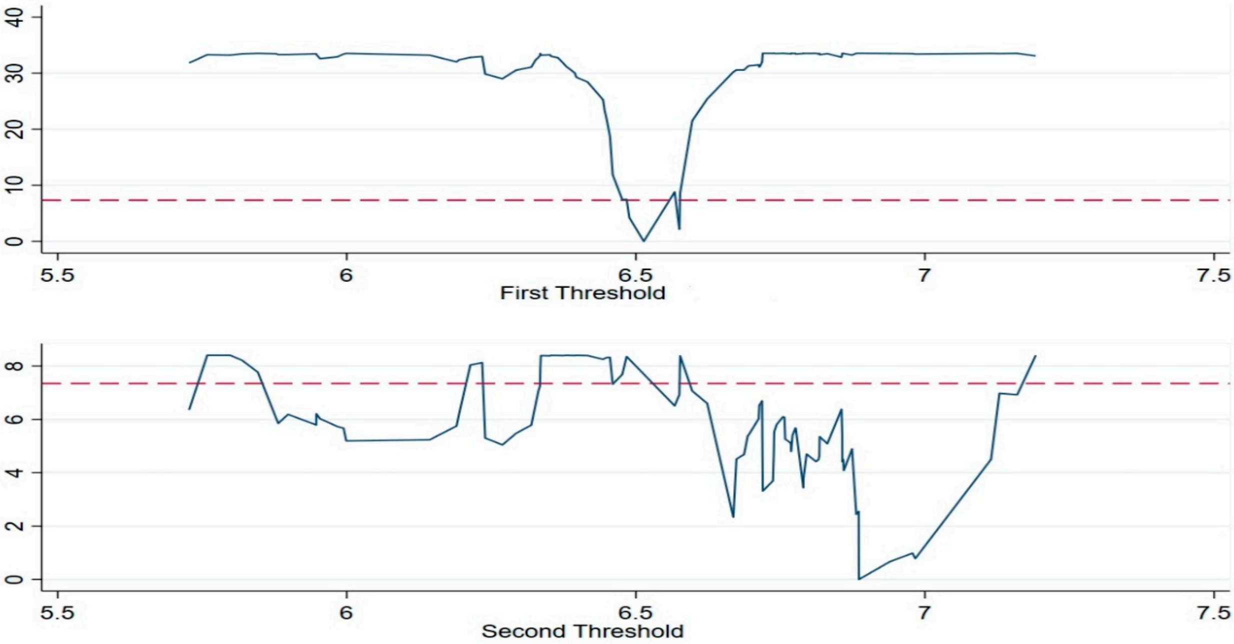

Figure A7. Likelihood ratio function (southern Africa) Panel A.

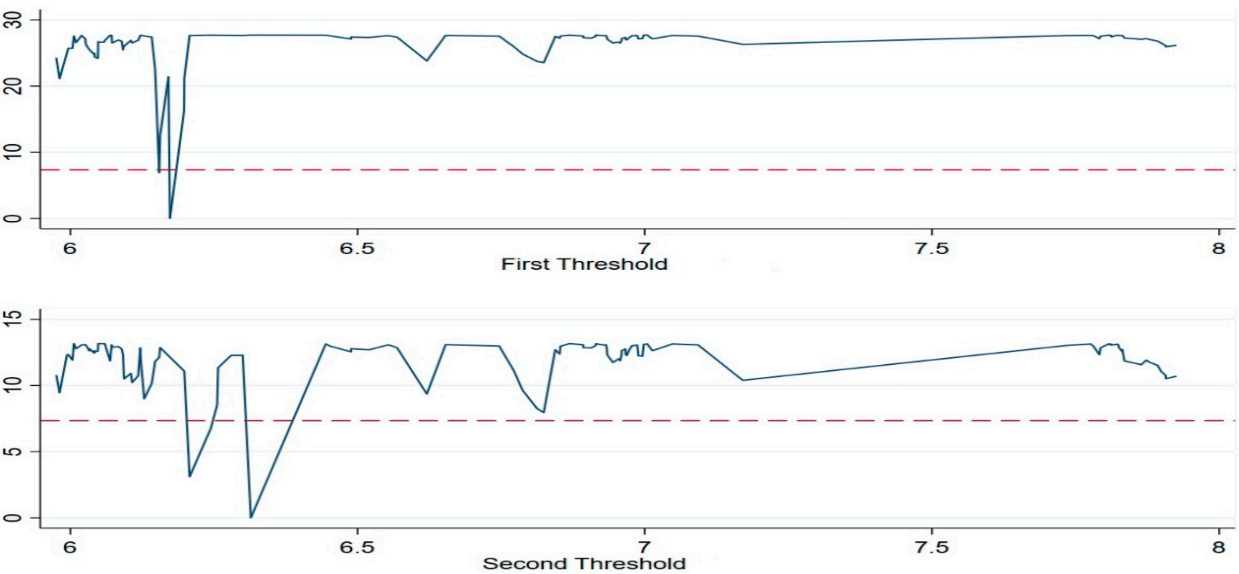

Figure A8. Likelihood ratio function (southern Africa) Panel B.

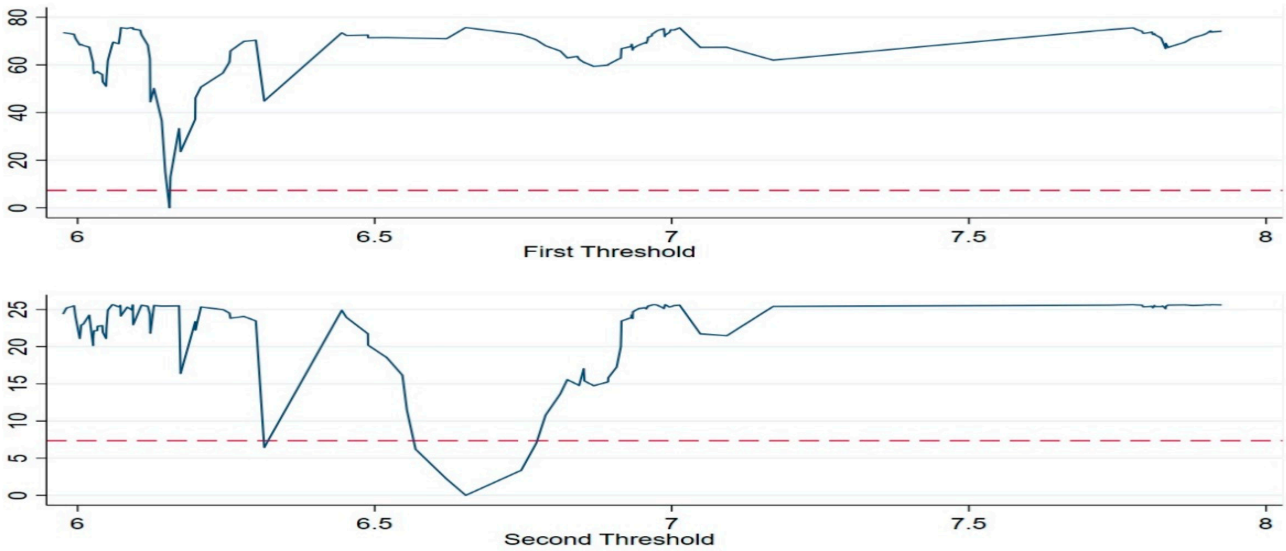

Figure A9. Likelihood ratio function (western Africa) Panel A.

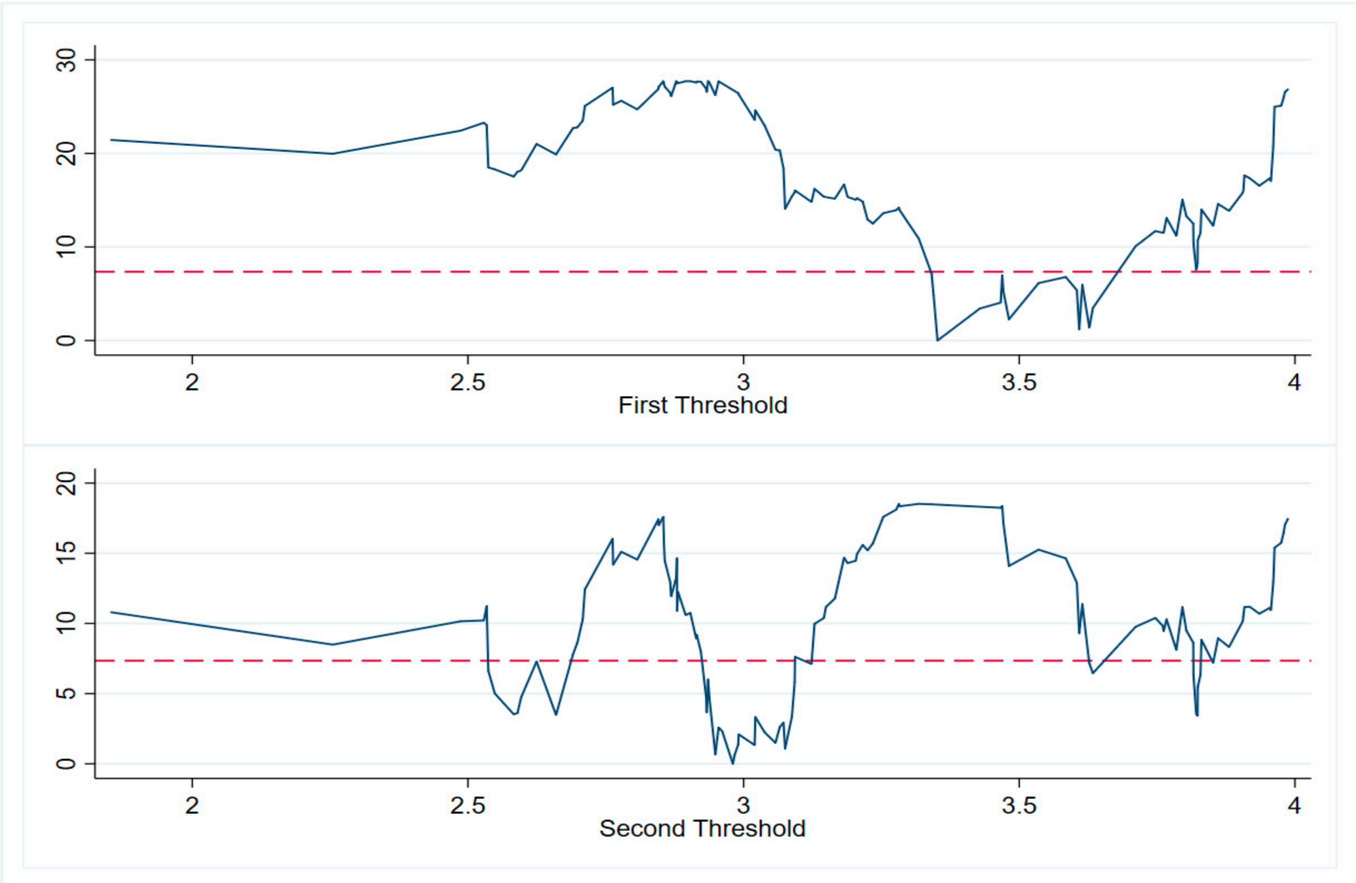

Figure A10. Likelihood ratio function (western Africa) Panel B.

Table A12. Estimated threshold effect of control variables for Panel A.

Group	Control Variables with lnre Model				Constant	RSqr.
	lnis	lnto	lnps	lnurb		
Central	0.212 ** (1.98)	−0.055 (−0.77)	0.341 *** (3.40)	−0.073 *** (−0.76)	3.952 *** (21.46)	0.541
Eastern	0.589 *** (9.02)	0.268 *** (7.86)	0.383 *** (7.15)	0.9286 *** (7.24)	2.912 ** (2.67)	0.742
Northern	0.651 * (0.80)	−1.294 * (−2.26)	2.0226 ** (2.69)	1.603 * (1.01)	0.231 * (0.02)	0.7704
Southern	0.629 (0.75)	0.373 ** (2.75)	1.040 *** (4.23)	−0.201 (−0.56)	−7.775 * (−2.38)	0.5419
Western	0.566 ** (0.15)	−0.486 ** (−4.83)	0.457 ** (5.64)	0.545 * (0.025)	−1.548 * (−5.489)	0.7221

Notes: *, ** and *** represent the significance level of 1%, 5%, and 10%, respectively.

Table A13. Estimated threshold effect of control variables for Panel B.

Group	Control Variables with lngdp Model				Constant	RSqr.
	lnis	lnto	lnps	lnurb		
Central	0.063 * (0.63)	−0.041 * (−0.55)	0.1337 (1.30)	−0.016 (−0.17)	17.8 *** (5.2)	0.9241
Eastern	0.589 *** (8.46)	0.354 *** (10.08)	0.320 *** (4.98)	0.419 ** (2.92)	−4.015 *** (−4.47)	0.7235
Northern	0.855 *** (6.48)	0.445 * (9.552)	0.568 * (3.548)	0.562 * (3.644)	−2.254 ** (−6.22)	0.854
Southern	0.083 (1.090)	0.003 * (1.090)	−0.729 ** (−2.080)	−0.023 (−0.070)	−8.362 *** (−2.900)	0.6304
Western	0.215 * (1.79)	−0.079 * (−0.43)	2.235 *** (7.50)	−0.2662 * (−0.61)	−22.753 *** (−6.97)	0.8049

Notes: *, ** and *** represent the significance level of 1%, 5%, and 10%, respectively.

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