www.devbankng.com

Development Bank of Nigeria
RC 1215724
...Financing Sustainable Growth

WORKING PAPER SERIES

234, 2025

RENEWABLE ENERGY, INNOVATIONS AND ENVIRONMENTAL SUSTAINABILITY IN SUB-SAHARAN AFRICA: THE ENVIRONMENTAL KUZNETS CURVE, POLICY THRESHOLDS AND THRESHOLDS FOR COMPLEMENTARY POLICIES

Forthcoming: Renewable Energy

Emmanuel K. Manu
UNE Business School, Faculty of Science, Agriculture,
Business and Law, University of New
England, Armidale, NSW, Australia
E-mails: emanu2@myune.edu.au / emak82589@gmail.com

Simplice A. Asongu
(Corresponding authors)
School of Economics, University of Johannesburg,
Johannesburg, South Africa
E-mails: asongusimplice@yahoo.com, asongus@afridev.org

Abstract

Amid growing environmental challenges and development pressures, this study examines the dynamic relationship between renewable energy consumption, innovation, and environmental degradation in 24 Sub-Saharan African countries from 2000 to 2021. Using mixed-effects and logistic quantile regression models, we test the Environmental Kuznets Curve (EKC) hypothesis across carbon dioxide and methane emissions. The analysis confirms an EKC pattern, identifying critical turning points of 0.049 kt for CO_2, 0.054 kt CO_2-equivalent for methane, and 0.137% of GDP for industrialisation where emissions begin to increase as income levels rise. Innovation, proxied by non-resident patent activity, exhibits a non-linear effect: initially contributing to higher emissions at lower quantiles but significantly reducing emissions at higher quantiles, reflecting the time-lagged environmental benefits of technological diffusion. The study further reveals heterogeneous impacts of GDP and industrialisation across the emissions distribution, suggesting that blanket policy interventions may be ineffective. Instead, we identify context-specific policy thresholds for renewable energy and innovation that can enhance environmental sustainability. These findings underscore the need for integrated, innovation-driven energy strategies tailored to the region's development stage, institutional capacity, and emission profiles.

Keywords: Innovations; Environmental Kuznets curve; environmental degradation; renewable energy deployment; Sub-Saharan Africa

1. Introduction

Sub-Saharan Africa (SSA) has witnessed a rapid escalation in environmental degradation, with carbon dioxide (CO_2) emissions nearly doubling over the past two decades compared to a modest 20% rise from 1990 to 2000 [1]. Methane (CH_4) emissions have also surged, increasing by 300 kilotons of CO_2 equivalent between 2000 and 2020, up from 100 kilotons in the previous decade [2]. These alarming trends underscore the region's vulnerability to environmental deterioration, elevating the need for sustainable policy responses. Within this context, the relationship between renewable energy, innovation, and environmental degradation has emerged as a focal area of research, especially in regions like SSA where development goals must be reconciled with ecological imperatives. [3], who explore the divergent impacts of energy policies across African economies, and [4], who emphasize regional disparities in clean energy access and innovation readiness, both affirm the pressing nature of this debate.

Renewable energy is widely recognized as a vital component of climate mitigation and sustainable development strategies. [5] highlight its carbon-reducing potential in diverse economies, [6] underscores the enabling role of policy and financial frameworks, while [7] document varied renewable energy effects in lower-income settings. Innovation, particularly environmentally oriented innovation, also plays a transformative role. [8] assess eco-innovation's productivity effects. However, the relationship among these factors is neither linear nor straightforward. The Environmental Kuznets Curve (EKC) hypothesis posits that environmental degradation initially worsens with economic growth before declining beyond a certain income threshold. [10] test this hypothesis across multiple pollutants; [5] reveals significant sectoral and regional differences; and [7] find that EKC turning points vary substantially by country, urging caution in generalization.

Against this backdrop, this study investigates how renewable energy consumption and innovation particularly through non-resident patent activity affect carbon dioxide and methane emissions in SSA. [11] highlight the importance of energy access in driving inclusive development, while [12] call attention to spatial and sectoral disparities in Africa's innovation ecosystems. SSA vast renewable energy potential especially solar, hydro, and wind presents opportunities to decarbonize its rapidly growing energy systems. [13] link renewables to long-term energy security, whereas [14] identify persistent barriers to adoption, including infrastructural and institutional limitations. At the same time, innovations in agriculture, waste management, and green technologies are creating new resilience pathways. [6] provides case studies on emerging innovation hubs, while [8] point to their role in reducing emissions and bolstering local capacity.

Nevertheless, the region's diversity economically, institutionally, and geographically means that these interactions are unlikely to be homogeneous. [15] stress national disparities in environmental policy effectiveness, while [16] document uneven distribution of technological capabilities. Additionally, the imperative for economic growth and poverty alleviation may sometimes clash with environmental objectives, making it vital to understand how synergies between renewable energy and innovation can be harnessed to overcome this trade-off.

This study seeks to address three core questions: (i) What is the impact of renewable energy consumption on environmental degradation in SSA? (ii) Does innovation mitigate emissions, and if so, is there a threshold beyond which its effects become more significant? (iii) Is there evidence supporting the EKC hypothesis in the region?

Despite increasing interest in the EKC framework, a notable gap remains. Very few studies identify clear turning points for both CO_2 and methane emissions in SSA, and fewer still explore the interaction effects between renewable energy and innovation. To fill this gap, our research empirically estimates these turning points 0.049 kilotons for CO_2, 0.054 kilotons of CO_2 equivalent for methane, and 0.137 percent of GDP for industrialization thereby offering concrete policy benchmarks. Furthermore, this study explores how renewable energy and innovation jointly influence emissions outcomes, providing insights into their complementarity. Methodologically, we employ mixed-effects and panel quantile regression techniques, both suited for capturing unobserved heterogeneity and distributional variation across countries.

In summary, this paper makes three distinct contributions. First, it identifies empirical EKC thresholds for both carbon dioxide and methane emissions in SSA. Second, it examines the synergistic effects of renewable energy and innovation on emissions mitigation. Third, it enhances methodological rigor through the application of techniques capable of addressing regional diversity and endogeneity. Collectively, these contributions provide timely evidence to guide sustainable development strategies in one of the most environmentally and economically vulnerable regions in the world.

The remainder of the study is organised as follows. Section 2 covers the theoretical background, empirical literature and the corresponding testable hypotheses whereas Section 3 discusses the data and methodology. The empirical results are presented and discussed in Section 4. Section 5 concludes with implications and further research directions.

2. Theoretical background, empirical literature and testable hypotheses

2.1 Theoretical background

In the pursuit of enhancing environmental sustainability in SSA, four core theoretical strands underpin this study: innovation systems, technological transitions, energy policy, and the Environmental Kuznets Curve (EKC).

First, [17], in his work on Policies for the Energy Technology Innovation System (ETIS), emphasizes the strategic role of institutional frameworks and technology diffusion in accelerating clean energy transitions offering a roadmap relevant for SSA's underdeveloped energy infrastructure and limited innovation systems. Second, [18], who introduce a network-based conceptual framework for system building, provide a refined lens on how innovation networks especially those leveraging local and global actors can promote sustainable development. This aligns with SSA's need for collaborative innovation to overcome environmental constraints. Third, [19] presents a multi-level perspective on socio-technical transitions, showing how technological change is embedded in broader societal processes. His framework is especially relevant for SSA, where renewable energy adoption is deeply influenced by institutional inertia, consumer norms, and policy path dependency. Fourth, the EKC theory, originating from [20] and later adapted for environmental economics, posits an inverted U-shaped relationship between economic growth and environmental degradation. [21] apply this to carbon emissions, illustrating how low-income countries initially experience rising pollution before benefiting from structural and policy reforms that reduce emissions. [22], along with [23], highlight that the EKC turning point differs by pollutant type and national context, challenging assumptions of universality.

Additional studies reinforce this variability. [24] emphasizes the significance of energy mix in shifting the EKC curve, while [25] show how policy quality and innovation capacity alter the emission-growth relationship. [26] stress the role of renewable energy deployment in accelerating the post-turning-point decline in emissions. [27] build on this by showing how income thresholds differ across African economies, making a region-specific EKC analysis essential. Therefore, while the EKC provides a foundational hypothesis, its application in SSA requires a disaggregated and empirically tested approach, considering factors such as renewable energy, innovation, and structural economic dynamics. Following [28], who advocate for tailored thresholds in environmental policymaking, this study adopts a regionally grounded perspective to test for both linear and non-linear effects, and for interactions among core variables.

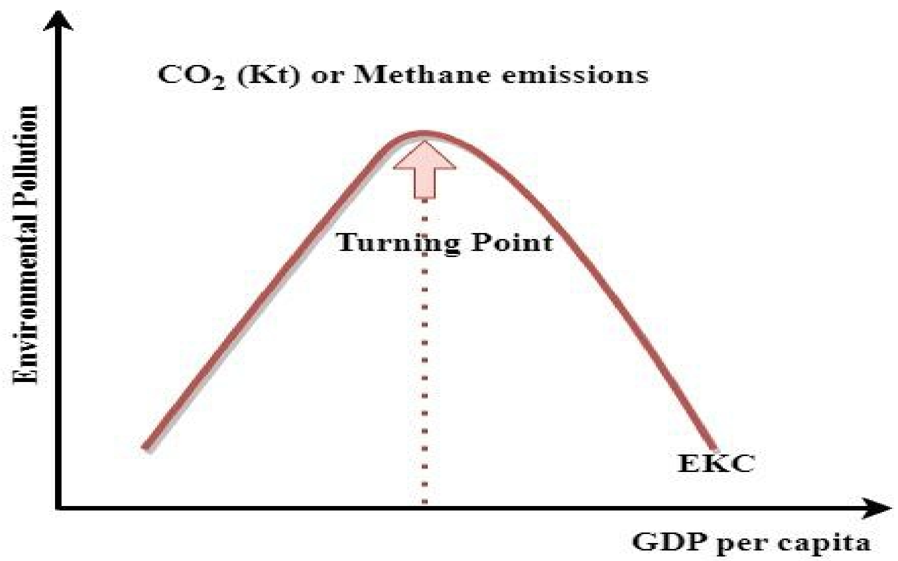

Figure 1. Environmental Kuznets Curve depicted an inverted U-shaped curve.

H1a: There is evidence of the turning point in the Environmental Kuznets Curve relationship for Sub-Saharan Africa indicating that higher income is associated with reduced environmental degradation.

H1b: There is evidence of an Environmental Kuznets Curve relationship in Sub-Saharan Africa, indicating that as income levels rise due to economic development, environmental degradation initially worsens, but beyond a certain income threshold (turning point), it starts to improve.

2.2 Empirical literature and testable hypotheses

The adoption of renewable energy sources and the advancement of innovations have become critical pillars in SSA strategy to tackle environmental degradation while promoting inclusive economic growth. A growing body of empirical literature has examined these dynamics, revealing both opportunities and tensions that shape the sustainability agenda within the region.

Studies within SSA have illustrated the complex nexus between economic growth and environmental quality. For instance, [29], in analysing air quality indicators, shows that industrialization intensifies environmental deterioration in highly urbanized settings, while [30] link water pollution to increased economic activity, underscoring how growth can compromise ecosystem services. In contrast, [22] demonstrate that the enforcement of environmental regulation can weaken the growth–pollution link, suggesting a decoupling trajectory. Similarly, [31] emphasized how institutional enforcement capacity determines whether environmental policies succeed in shifting development onto a low-carbon path. Complementing these perspectives, [32] and [33] reveal that the effectiveness of environmental regulation during growth hinges on policy stringency and governance quality, adding further refine to the development–degradation debate.

Several region-specific studies offer deeper insights into the environmental challenges confronting SSA. [34] and [35], employing satellite-based land cover data, trace patterns of land use change and vegetation loss, providing a landscape-level view of environmental degradation. In public health research, [36] highlight how indoor air pollution—primarily from biomass fuels—disproportionately affects rural populations, making energy transition a matter of health equity. [15], [37] distinguish between country-level patterns in the environmental impacts of growth, while [38] focuses on water safety, emphasizing the governance dimensions of resource management. [39], using geospatial techniques, links industrial pollution to adverse health outcomes, offering evidence for spatial inequalities in environmental exposure. [40] explore how land degradation affects agricultural productivity, highlighting a feedback loop between ecosystem decline and rural poverty.

On innovation, [41] find that environmental regulation spurs firm-level eco-innovation in European markets, showing how external policy drivers can steer private sector behavior. [42] report that eco-innovative firms exhibit superior productivity and competitiveness, making a case for innovation as a dual economic environmental lever. [43], [44] analyze how policy instruments such as taxes and subsidies shape the direction and pace of green innovation, underscoring the role of targeted interventions. Lastly, [45] reveal sectoral divergences in innovation drivers across manufacturing and services, signaling that a one-size-fits-all approach may fail in promoting innovation across economic segments.

Collectively, this literature confirms the critical importance of renewable energy and innovation in addressing SSA's sustainability challenge. Yet, most studies either focus on individual environmental indicators or fail to account for the interaction between innovation and clean energy adoption. There is limited empirical work on threshold effects, such as those implied by the EKC, or on how non-resident innovation (e.g., through patent flows) contributes to emissions mitigation.

Based on the literature we formulate the following hypotheses:

Hypothesis 2: The adoption of renewable energy sources in SSA leads to a measurable reduction in emissions and a positive impact on environmental quality.

Hypothesis 3: The promotion of innovations in SSA enhances the development and deployment of renewable energy technologies.

3. Data model and methodology

This study aims to assess the EKC, as well as identify thresholds and complementary policy levers involving renewable energy and innovation dynamics to promote environmental sustainability. We conducted an empirical analysis spanning the years 2000 to 2021, using data from [46] for 24 SSA. The sample periodicity varies depending on data availability at the time of the study. To address issues related to data distribution and scale, we employed both mixed-effects and panel quantile regression models. Mixed-effects modeling offers distinct advantages over traditional ordinary least squares (OLS) estimates, particularly in capturing both fixed effects (representing overall average trends) and random effects (reflecting country-specific variations). This dual structure allows for a more understanding of cross-country heterogeneity, which is especially relevant in the African context where institutional, economic, and environmental differences are substantial. Moreover, mixed-effects models are well-suited for analyzing nested or hierarchical panel data, enhancing both the robustness and interpretability of results. By integrating both fixed and random components, the approach provides a flexible analytical framework that strengthens generalizability.

Our primary investigation explores the relationship between economic development proxied by GDP and environmental degradation, with a focus on two major greenhouse gases: carbon dioxide (CO_2) and methane (CH_4). Renewable energy consumption, encompassing both general renewable energy use and renewable electricity, is included following [47], who emphasize renewable capacity expansion in emerging regions, and [48], who specifically examine renewable energy dynamics in SSA. Innovation is proxied by non-resident and resident patent counts, consistent with [37], who highlights the relevance of intellectual property indicators in capturing innovation diffusion across African economies. The dependent variables CO_2 and CH_4 emissions are analysed based on [49], who documents emission patterns and the drivers of methane output in African energy systems. To capture nonlinearities and turning points in the economic growth–environmental degradation nexus, the analysis includes GDP and its squared term to test the EKC hypothesis. A quantile regression is applied to account for conditional distributional effects across different levels of emissions intensity, thereby complementing the mean-focused results of the mixed-effects model.

More insights into the variables, including descriptive statistics and the Jarque–Bera test results for normality, are presented in Table 1. This comprehensive empirical framework allows for a deeper understanding of the interaction between innovation, renewable energy, and environmental sustainability in the context of SSA evolving development landscape.

Table 1. Variable and descriptive statistics

Variable	**Mnemonics**	Mean	Std. dev.	Min	Max	Skewness	Kurtosis	J.B test	P-value	Source
Carbon emission	CO_2 (kt)	8.437	1.569	5.500	13.013	0.913	4.2128	105.691	0.110	WDI (2022)
Methane emissions	CH4 (kt of CO_2 equivalent)	8.956	1.890	4.283	11.952	-0.936	3.4422	81.44	0.120	WDI (2022)
Renewable energy consumption	REC (% of total final energy consumption)	3.882	1.010	-0.342	4.588	-2.399	8.8711	1264.824	0.130	WDI (2022)
Renewable electricity	REELECT (% of total electricity output)	3.268	1.774	-5.423	4.964	2.004	7.353	770.554	0.100	WDI (2022)
Patent non-resident	Non-resident patent applications are from applicants outside the relevant State or region (PN)	3.532	1.922	-1.099	8.910	0.552	3.556	33.694	0.000	WDI (2022)
Patent resident	Resident patent applications are those for which the first-named applicant or assignee is a resident of the State or region concerned (PR)	2.940	1.807	0.000	6.911	0.532	2.350	34.220	0.000	WDI (2022)
GDP	GDP (constant 2015 US$)	23.500	1.653	18.833	26.974	0.394	3.366	16.652	0.120	WDI (2022)
Industrialization	Industry (including construction), value added (% of GDP)	3.114	0.364	1.997	4.278	0.343	3.246	11.693	0.000	WDI (2022)

Note: WDI is World Development indicators, where J.B test denotes Jarque-Bera test. For the datasets with J.B p-values of 0.110, 0.120, and 0.130 (greater than 0.05), we fail to reject the null hypothesis. This suggests that the residuals follow a normal distribution.

3.1 Environmental Kuznets Curve (EKC) Theory

We employ a model that integrates key variables to empirically assess the EKC hypothesis in the context of renewable energy, innovation, and environmental degradation across SSA. This approach draws on the framework established by [50], who apply EKC modeling to examine nonlinear environmental responses to economic expansion, and [27], who emphasize region-specific EKC patterns in low-income economies. These studies support the relevance of adapting the EKC model to account for SSA unique developmental trajectory and structural characteristics. Accordingly, the model is formulated to include economic development indicators (GDP and GDP²), renewable energy variables, and proxies for innovation to capture both linear and nonlinear dynamics in the pollution–growth relationship. The specific model specifications used in this study are presented in Equation (1) and Equation (2), which correspond to carbon dioxide (CO_2) emissions and methane (CH_4) emissions, respectively.

$$ln(CO_{it})=\beta_0+\beta_1 ln(GDP)_{it}+\beta_2 ln(GDP)_{it}\hat{}2+\beta_3 ln(REC)_{it}+\beta_4 ln(I)_{it}+\beta_5 X_{it}+\varepsilon_{it} \quad (1)$$

$$ln(Methane_{it})=\beta_0+\beta_1 ln(GDP)_{it}+\beta_2 ln(GDP)_{it}\hat{}2+\beta_3 ln(REC)_{it}+\beta_4 ln(I)_{it}+\beta_5 X_{it}+\varepsilon_{it} \quad (2)$$

where $ln(CO_{it})$ and $ln(Methane_{it})$ represent the natural logarithm of carbon emissions and methane emissions respectively, for country *i* in year *t*. $ln(GDP)_{it}$ is the natural logarithm of GDP per capita for country *i* in year *t*. $ln(RED)_{it}$ denotes the natural logarithm of renewable energy consumption for country *i* in year *t*. $ln(EI)_{it}$ is the natural logarithm of innovation indicators (e.g., patents related to environmental technologies) for country i in year t. X_{it} includes additional control variables, such as industrialisation that may affect carbon dioxide emissions and the relationships in question. β_0 represents the intercept, capturing the baseline level of carbon dioxide emissions when all other variables are zero. β_1 measures the linear relationship between $ln(GDP)$ and $ln(CO)$, testing the initial direction of the Environmental Kuznets Curve. β_2 captures the quadratic (non-linear) relationship between $ln(GDP)^2_{it}$ and $ln(GDP)$, examining the turning point in the Environmental Kuznets Curve. β_3 represents the effect of renewable energy consumption $ln(REC)$ on carbon dioxide emissions, examining whether increased use of renewable energy reduces emissions. β_4 measures the impact of innovations $ln(EI)$ on carbon dioxide emissions, assessing whether innovations in environmental technologies influence emissions. ε_{it} represents the error term, capturing the unexplained variation in carbon dioxide emissions particularly in regions like SSA where data gaps and institutional weaknesses limit environmental accountability—is essential for robust modelling, as underscored by [3], who highlight the role of contextual challenges in emissions management, and [4], who emphasize the need for improved policy targeting and responsible resource use.

The turning point of the EKC involves the quadratic relationship between economic development (often measured as Gross Domestic Product per capita) and an environmental indicator (such as carbon emissions and methane emissions). The turning point represents the GDP per capita at which environmental degradation starts to decrease after initially increasing with economic growth, as apparent in Equation (3).

$$E = a + b(GDP) + c(GDP)^2 \quad (3)$$

where *E* is the environmental indicator (e.g., carbon emissions and industrialisation). Gross Domestic Product (GDP) is the economic development variable (GDP per capita). a, b, and c are coefficients estimated from empirical data.

The turning point is calculated as follows in Equation (4):

$$\text{Turning Point or GDP Threshold} = \left|\frac{\text{Unconditional impact}}{2 \times \text{Conditional impact}}\right| = \left|\frac{b}{(2 \times c)}\right| \qquad (4)$$

where *b* represents the coefficient of the linear term GDP in the regression. *c* represents the coefficient of the squared term $(GDP)^2$ in the regression. The turning point GDP can be estimated by plugging the values of these coefficients from the regression results into the formula which is in absolute value.

3.2 Econometric model

We specify an econometric model incorporating mixed-effects estimations, following the approach outlined by [51], who provide a robust framework for modelling hierarchical and longitudinal data structures, to explore the relationship between carbon dioxide emissions, Gross Domestic Product per capita, renewable energy consumption, innovations, and control variables as shown in Equation (5):

$$ln(CO_{it})=\beta_0+\beta_1 ln(GDP)_{it}+\beta_2 ln(GDP)_{it}\text{^}2+\beta_3 ln(REC)_{it}+\beta_4 ln(I)_{it}+\beta_5 X_{it} + \varepsilon_{it} tv \qquad (5)$$

The incorporating mixed effects for both cross-sectional units *(i)* and time periods *(t)*, the model can be written as follows in Equation (6):

$$ln(CO_{it})=\beta_0+\beta_1 ln(GDP)_{it}+\beta_2 ln(GDP)_{it}\text{^}2+\beta_3 ln(REC)_{it}+\beta_4 ln(I)_{it}+\beta_5 X_{it} + u_i + \varepsilon_{it} \qquad (6)$$

where u_i is the random effect at the country level (cross-sectional unit). εit is the error term or residual. The inclusion of random effects at the country level (ui) accounts for unobserved heterogeneity across countries that might not be captured by the included independent variables. This mixed-effects approach is suitable for panel data where we have multiple countries observed over several time periods.

We incorporate an interaction effect between renewable energy and innovation *(I)* in our model for carbon dioxide emissions, we extend the previously suggested model as follows in Equation (7):

$$ln(CO_{it})=\beta_0+\beta_1 ln(GDP)_{it}+\beta_2 ln(GDP)_{it}\text{^}2+\beta_3 ln(REC)_{it}+\beta_4 ln(I)_{it}+ \beta_5 (REC_{it} \times I_{it})+\beta_6 X_{it} + u_i + \varepsilon_{it} \qquad (7)$$

Where $(REC_{it} \times I_{it})$is the interaction term between renewable energy and innovations, which captures how the joint effect of these two variables impacts carbon dioxide emissions. The inclusion of the interaction term allows us to investigate whether the combined effect of renewable energy and innovations on carbon dioxide emissions is different from the sum of their individual effects. This can provide insights into whether these two factors interact synergistically or antagonistically in their influence on environmental outcomes.

3.3 Robustness test

The study employs logistic quantile regression as a robustness test to examine the relationship between our variables, drawing on [52], who demonstrate its effectiveness in modeling conditional quantiles of bounded outcomes, and we outline the subsequent model specification in Equation (8).

$$Pr(Y_{it} \leq y \mid X_{it}) = \Phi(\alpha(y) + \beta_1 ln(GDP)_{it} + \beta_2 (ln(GDP)_{it})^2 + \beta_3 (lnREC_{it}) + \beta_4 ln(I_{it}) + \beta_5 X_{it} \quad (8)$$

where Y_{it} is a binary indicator variable, 1 indicates high carbon dioxide emissions and 0 indicates low carbon dioxide emissions. Φ represents the standard logistic cumulative distribution function. (α(y) is a quantile-specific intercept. In this model, we estimate the probability that carbon dioxide emissions are high (Y_{it}=1) as a function of our independent variables using logistic quantile regression. This allows us to explore how changes in our independent variables influence the probability of high carbon dioxide emissions at different quantiles of the distribution, providing insights into the relationship's robustness across different segments of the data. We estimate this model at various quantiles (e.g., 0.25, 0.50, 0.75 and 0.95) to examine how the effects of our variables vary across different parts of the carbon dioxide emissions distribution. This can help us assess whether the relationship between economic factors, renewable energy, innovations, and carbon dioxide emissions holds at different levels of emissions intensity. In other words, quantile regression accounts for initial levels of the outcome variables that can influence the responsiveness of the outcome variable to the independent variables of interest [53].

4. Empirical Results and Discussion

Based on the benchmark results presented in Table 2, it is evident that the direct influence of renewable energy consumption (REC) and renewable electricity on carbon dioxide and methane emissions holds significant importance in the context of SSA. The coefficient associated with REC is statistically significant and negative, indicating that a one-unit increase in REC leads to an approximate 33.8% reduction in carbon dioxide emissions at the 5% level. This finding affirms the substantial role of renewable energy initiatives in enhancing environmental quality, as shown in [3], who underscore how renewable uptake in SSA improves air quality, and [4], who emphasize its link to regional emission reductions.

Consequently, policymakers across the region should prioritize investments in solar, wind, and hydropower technologies to support a transition toward a cleaner energy mix. However, while REC significantly impacts CO_2 emissions, its coefficient for methane emissions remains statistically insignificant. This suggests that REC alone may not effectively curb methane emissions—a potent greenhouse gas. This echoes the argument made by [48], who note methane requires targeted interventions beyond general clean energy strategies, and aligns with [54], who call for sector-specific methane abatement policies in SSA. Policymakers should, therefore, complement REC with tailored strategies such as methane-capture technologies and stricter regulations in agriculture and waste sectors.

Similarly, the coefficient for renewable electricity is both statistically significant and negative, implying a 10.9% reduction in CO_2 emissions with increased renewable electricity generation. This further underscores the importance of expanding grid access to clean electricity and enhancing the efficiency of renewable power distribution networks. Targeted infrastructure development and policy incentives would accelerate this transition.

Beyond energy use, the study explores the role of innovation in mitigating emissions. The coefficient for patent non-resident (PN) is significantly negative, indicating that innovations sourced from outside the region contribute to a 10.1% reduction in CO_2 emissions. This finding supports [13], who show how cross-border knowledge transfer boosts green innovation in SSA, and [55], who highlight that non-resident patents serve as vital inputs for low-carbon growth in developing economies. This underlines the importance of integrating foreign technology into local environmental strategies.

In contrast, patent resident (PR) also exhibits a statistically significant and negative relationship with carbon dioxide emissions, yielding a 15% reduction. This result points to the critical role of domestic innovation capacity in advancing environmental goals. The finding aligns with [56], who explore localized innovation ecosystems in SSA, and [48], who emphasize the transformative effect of empowering local inventors. Policy strategies should foster collaboration between resident and non-resident innovators to enhance eco-technology diffusion, improve local absorptive capacity, and facilitate inclusive innovation ecosystems.

Nonetheless, similar to the renewable energy findings, the influence of innovation variables—both PN and PR—on methane emissions remains statistically insignificant. This indicates that while innovations are valuable for reducing CO_2 emissions, their impact on CH_4 is limited or indirect. Addressing methane effectively will require complementary policies, such as enforcing emission caps in agriculture and waste management and incentivizing the development and diffusion of methane-capture technologies. Regular impact assessments, as recommended in [3], will be vital for adapting these strategies over time.

Table 2. Mixed effect results

Dependent var.	Carbon emission						Methane emission					
	1	2	3	4	5	6	7	8	9	10	11	12
Renewable energy	-0.338**	0.040**	0.037	0.037*	0.008	-0.022***	0.000	0.020***	-0.003***	-0.012***	0.004	0.033*
	(0.107)	(0.015)	(0.032)	(0.016)	(0.009)	(0.007)	(0.129)	(0.004)	(0.001)	(0.003)	(0.008)	(0.017)
Renewable electricity	-0.109*	0.171***	0.138*	0.138*	0.531***	0.093**	-0.039	0.169**	-0.035***	0.110**	-0.010	1.021***
	(0.048)	(0.029)	(0.062)	(0.069)	(0.062)	(0.030)	(0.058)	(0.053)	(0.008)	(0.035)	(0.114)	(0.245)
Patent non-resident	-0.101*	0.009	0.010	0.010	0.001	0.004	-0.031	-0.146***	0.001	-0.092***	-0.037	-0.326***
	(0.041)	(0.006)	(0.007)	(0.005)	(0.002)	(0.003)	(0.050)	(0.010)	(0.002)	(0.009)	(0.026)	(0.055)
Patent resident	0.150**	0.056***	0.052***	0.052***	0.203***	-0.262***	0.222***	0.032***	-0.004***	-0.043***	-0.006	0.076*
	(0.049)	(0.003)	(0.008)	(0.004)	(0.031)	(0.024)	(0.060)	(0.008)	(0.002)	(0.006)	(0.017)	(0.037)
Gross domestic	-0.055	-0.010*	0.015*	0.015**	-0.022**	0.022***	-0.187**	0.094***	0.001	-0.007	0.027	0.060
product	(0.049)	(0.005)	(0.008)	(0.003)	(0.006)	(0.003)	(0.059)	(0.016)	(0.002)	(0.013)	(0.034)	(0.075)
Industrialization	-0.062	0.034**	-0.014	-0.014	-0.002	-0.003	0.887***	0.000	-0.001	0.010**	0.005	-0.033*
	(0.158)	(0.010)	(0.022)	(0.016)	(0.003)	(0.055)	(0.190)	(0.004)	(0.001)	(0.003)	(0.008)	(0.019)
	11.560***	-1.645***	0.221***	-6.324***	-0.095	5.069***	9.344***	-6.000***	-0.130	-2.04*1	-0.166	5.355***
Constant	(1.334)	(0.288)	(0.045)	(1.348)	(0.632)	(0.094)	(1.607)	(0.448)	(0.228)	(1.196)	(0.179)	(0.156)
Wald chi2	52.80	54.00	56.65	58.85	59.67	45.69	52.60	54.64	52.86	56.87	58.56	57.32
Prob > chi2	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Note: The notation for significance levels in the presented results is as follows: * denotes p-values below 0.10, ** signifies p-values below 0.05, and *** indicates p-values below 0.01.

To put the result in context, the findings emphasize that renewable energy and innovation both contribute significantly to reducing CO_2 emissions in SSA. However, methane emissions require a different policy toolkit. A multi-pronged approach combining clean energy expansion, domestic and foreign innovation, and methane-specific regulation offers the most viable path toward climate resilience in the region.

4.1 Examining if the Threshold (Turning point) of the Environmental Kuznets Curve exists in Sub-Saharan Africa

Based on the results presented in Table 3, the presence of a threshold or turning point in the EKC can be inferred, supporting Hypothesis 1a. The results confirm an inverted U-shaped relationship between economic development, measured by Gross Domestic Product (GDP), and environmental degradation suggesting that while initial economic growth increases environmental stress, further development beyond a certain point contributes to environmental improvement. This dual-phase relationship aligns with theoretical expectations. Specifically, [10], who test the EKC for multiple pollutants across developing regions, and [57], who investigate nonlinear energy-growth-environment dynamics, both assert that economic growth can initially worsen but later alleviate environmental degradation depending on structural shifts and policy evolution. These findings raise pertinent questions about how renewable energy deployment and innovation adoption interact with economic development to influence the EKC path in SSA.

The regression results reveal that the coefficient of GDP (-1.182) is statistically significant and negative, implying that at early stages of economic development, increases in GDP are associated with reductions in CO_2 emissions. This reflects the initial phase of the EKC where better resource management, increased environmental awareness, or marginal increases in clean energy adoption begin to yield positive environmental returns. This interpretation is consistent with [11], who document improvements in green outcomes during initial growth spurts in SSA, and [12], who emphasize that early-stage growth often leverages underutilized green resources.

Conversely, the positive and significant coefficient for GDP^2 (12.127) indicates a turning point, beyond which economic expansion contributes to higher carbon emissions. This reflects the later stage of the EKC, where factors such as industrial expansion, fossil fuel dependence, and urban congestion may offset earlier environmental gains. [58], who find a similar EKC shape in West African economies, and [59], who stress that weak institutions can accelerate environmental degradation in later growth stages, support this interpretation.

Taken together, these coefficients validate the presence of the EKC in SSA and provide an empirical foundation to calculate the specific GDP level at which environmental outcomes shift from improvement to deterioration. The following section outlines the estimation of this turning point using the derived model parameters.

$$\text{Carbon Dixoide Turning Point or GDP Threshold} = \left|\frac{-1.182}{(2 \times 12.127)}\right| = 0.049 \quad (9)$$

TSo, the estimated turning point in GDP, where the Environmental Kuznets Curve may exhibit its transition from decreasing to increasing environmental degradation, is approximately 0.049. This suggests that the turning point occurs at a relatively low level of GDP.

Also, the coefficient of GDP (-6.596) on methane emissions: The significant and negative coefficient of GDP indicates that as GDP increases, there is a decrease in methane emissions. This suggests that, initially, economic growth is associated with reduced methane emissions, which aligns with the first phase of an Environmental Kuznets Curve. Coefficient of the square term of GDP (60.840) on methane emissions: The significant and positive coefficient of the square term of GDP implies that there is a turning point in economic development (GDP) beyond which higher GDP levels promote an increase in methane emissions. This aligns with the second phase of an Environmental Kuznets Curve, where further economic growth starts to have adverse effects on the environment, specifically in terms of methane emissions.

We estimate the specific GDP level at which the turning point occurs for methane emissions, we use a similar calculation as before:

$$\text{Methane Turning Point or GDP Threshold} = \left|\frac{-6.596}{(2 \times 60.840)}\right| = 0.054 \quad (10)$$

So, based on these coefficients, the estimated turning point in GDP, where the transition from decreased to increased methane emissions may occur, is approximately 0.054. This suggests that the turning point for methane emissions is also at a relatively low level of GDP. These coefficients indicate a pattern like the presence of an EKC for carbon dioxide emissions in Sub-Saharan Africa. Coefficient of Industrialization (-11.001) on carbon dioxide Emissions: The significant and negative coefficient of industrialization suggests that as industrialization increases, there is a decrease in carbon dioxide emissions. This aligns with the first phase of an EKC, where industrialization initially leads to reduced carbon dioxide emissions due to the adoption of cleaner technologies or more efficient industrial processes. Coefficient of the square term of industrialization (40.166) on carbon dioxide emissions: The significant and positive coefficient of the square term of industrialization indicates that there is a turning point in industrialization beyond which higher levels of industrialization promote an increase in carbon dioxide emissions. This aligns with the second phase of an Environmental Kuznets Curve, where further industrialization begins to have adverse effects on the environment, specifically in terms of carbon dioxide emissions as countries experience industrialization and urbanization, environmental degradation tends to increase [58].

We estimate the specific level of industrialization at which the turning point occurs for carbon dioxide emissions as:

$$\text{Carbon Dixoide Turning Point or Industrialization Threshold} = \left|\frac{-11.001}{(2\times 40.166)}\right| = 0.137$$
(11)

So, based on these coefficients, the estimated turning point in industrialization—where the transition from decreased to increased carbon dioxide emissions is likely to occur—is approximately 0.137. This threshold signifies the critical level of industrial development at which environmental degradation begins to rise again, reflecting the second phase of the EKC. This finding supports the broader hypothesis that both carbon dioxide and methane emissions follow an inverted U-shaped relationship with income. For instance, [60], who analyze emissions behavior in rapidly industrializing Asian economies, confirm that economic growth initially mitigates emissions before reversing the trend beyond a certain threshold. Similarly, [61], who incorporate renewable energy and technological progress into the EKC model, demonstrate how income-environment dynamics are influenced by clean energy uptake and innovation thresholds. [62] further validate the inverted U-pattern in the context of developing economies, emphasizing that energy-intensive industrial activities contribute to the environmental rebound as income rises.

Together, these studies reinforce the empirical validity of the EKC in SSA and emphasize the need for carefully targeted policy interventions once these thresholds are crossed.

4.2 Examining if the EKC theory exist in Sub-Saharan Africa

The results presented in Table 3 confirm the existence of the EKC in SSA, thereby supporting Hypothesis 1b. The estimated coefficients for Gross Domestic Product (GDP) and industrialization (IDUS) provide compelling evidence on the dynamics of carbon dioxide and methane emissions in the region.

Starting with carbon dioxide, the negative coefficient for GDP (−1.182) indicates that in the early stages of economic development, increases in GDP are associated with reductions in carbon dioxide emissions. This outcome aligns with the first phase of the EKC, where economic growth is accompanied by improved environmental quality—typically driven by shifts toward cleaner practices and the adoption of more efficient technologies. Conversely, the positive and highly significant coefficient of the squared GDP term (GDP^2 = 12.127) signals the presence of a turning point: beyond this level of development, further GDP growth leads to increased emissions, reflecting the second phase of the EKC. This finding resonates with the argument by [63], who identify economic thresholds beyond which pollution intensifies, and [27], who emphasize the transitional nature of growth-environment dynamics in emerging economies.

Turning to industrialization, the results further reinforce the EKC framework. The negative and statistically significant coefficient for industrialization (IDUS = −11.001) suggests that early industrial expansion is linked to declining emissions—likely due to the adoption of cleaner production methods and improved efficiency. However, the positive and significant coefficient on the squared industrialization term ($IDUS^2 = 40.166$) identifies a critical threshold beyond which additional industrial growth results in heightened carbon dioxide emissions. This mirrors the inverted U-shaped relationship proposed in the EKC literature and supports the notion that industrial development initially aids sustainability but may later contribute to environmental degradation if not properly managed.

Shifting focus to methane emissions, a similar EKC pattern emerges. The coefficient for GDP (−6.596) is both significant and negative, implying that in the early phase of development, economic expansion reduces methane emissions—consistent with environmental improvements seen in early growth stages. However, the squared GDP term ($GDP^2 = 60.840$) is significantly positive, suggesting a turning point where further economic advancement reverses these gains, causing a rise in methane emissions. This outcome supports findings by [61], who underscore that greenhouse gas responses vary across pollutants and may intensify after certain growth thresholds are surpassed.

For industrialization and methane emissions, the relationship is less clear-cut. While the coefficient for IDUS (−4.079) is negative, it lacks statistical significance, indicating no strong evidence of a direct relationship. Similarly, the squared term ($IDUS^2 = 18.302$), though positive, is also statistically insignificant. Nevertheless, the positive sign suggests a potential EKC-type turning point that may emerge under alternative model specifications or longer-term data series. These point to the need for further investigation into sector-specific methane dynamics, particularly as data quality and coverage improve across the region.

Table 3. Environmental Kuznets Curve results

Dependent var.	**Carbon emissions**		**Methane emission**	
$LnCO_2$	-0.182***	(0.043)	-0.320***	(0.042)
Renewable energy	-0.288**	(0.089)	-0.295**	(0.105)
Renewable electricity	-0.156**	(0.052)	-0.035	(0.061)
Patent-non resident	-0.116*	(0.047	0.067	(0.056)
Patent resident	0.123*	(0.051)	0.191**	(0.060)
Gross domestic product	-1.182**	(2.011)	-6.596**	(2.377)
Gross domestic product^2	12.127**	(19.246)	60.840**	(22.746)
Industrialisation	-11.001*	(5.534)	-4.079	(6.619)
Industralisation^2	40.166*	(19.286)	18.302	23.050
Constant	6.052	(50.910)	-147.029*	60.230
Wald chi2	84.47		115.71	
Prob > chi2	0.000		0.000	
Log likelihood	-906.605		-991.439	

Note: The notation for significance levels in the presented results is as follows: * denotes p-values below 0.10, ** signifies p-values below 0.05, and *** indicates p-values below 0.01. These levels are applied to coefficients associated with variables such as GDP, GDP squared, industrialization (IDUS), and industrialization squared ($IDUS^2$), reflecting their impact on both carbon dioxide (CO_2) and methane emissions.

Collectively, these results suggest that the EKC hypothesis holds in SSA, at least for carbon dioxide and, to a lesser extent, methane emissions. They also highlight the importance of identifying policy-relevant thresholds to inform the timing and design of sustainability interventions. As [61] emphasize, region-specific EKC analyses are critical for developing adaptive and inclusive environmental policies. These findings urge SSA policymakers to not only pursue growth but to proactively integrate environmental safeguards that prevent the rebound effects typically observed beyond key development thresholds.

4.3 Examining if renewable energy and innovations influences environmental degradation in Sub-Saharan Africa (Interaction effect)

To deepen the understanding of how innovation complements clean energy in shaping environmental outcomes, we explore the interaction effects between renewable energy and patents (both non-resident and resident) in the SSA context. Models 1–4 examine these interactions with carbon dioxide emissions as the dependent variable, while Models 5–8 shift the focus to methane emissions.

A key finding emerges in the interaction between renewable energy consumption (REC) and patent non-resident (PN), where the coefficient (−0.121) is negative and statistically significant at the 5% level. This suggests that a unit increase in the combined effect of REC and PN is associated with a 12.1% reduction in carbon dioxide emissions. This interaction implies that innovation spillovers from foreign inventors can reinforce the environmental benefits of renewable energy deployment. As noted by [8], non-resident innovation can serve as a conduit for technological upgrades in low-innovation economies, while [9] emphasize its role in cross-border eco-technology diffusion. These findings point to the value of fostering partnerships that enable the transfer of clean technologies to the region. Policymakers should prioritize creating an enabling environment for such international collaboration, including support for patent facilitation, technical licensing, and regional innovation hubs.

When examining the interaction between renewable electricity (REELECT) and patent non-resident (PN), we observe a similarly encouraging pattern. The coefficient (−0.063) is both statistically significant and negative, indicating that each unit increase in their combined effect contributes to a 6.3% reduction in carbon dioxide emissions. This supports earlier arguments that renewable electricity, when coupled with external innovation, can accelerate decarbonization. [37] highlight the effectiveness of foreign innovation in reducing emissions when supported by domestic clean energy investments. Additionally, [64] show that patent inflows improve technology readiness in African countries, and [65] calls for integrated innovation-energy strategies as part of Africa's transition plans. These findings collectively strengthen the case for integrating renewable electricity policy with international innovation partnerships.

In contrast, the interaction between REC and patent resident (PR) yields a coefficient of +0.139, which is statistically significant at the 1% level and positively signed. This finding indicates that a unit increase in REC and PR together results in a 13.9% increase in carbon dioxide emissions. While counterintuitive, this suggests that domestic innovation, as currently practiced, may not yet be sufficiently environmentally aligned or may focus on sectors with a higher emissions footprint. As [37] explain, resident innovations in developing regions may prioritize industrial expansion over environmental performance, and [66] cautions that local innovation often lacks green orientation unless supported by environmental regulation and institutional oversight.

This observation should prompt reflection on the types of innovation being supported within the region. While resident patent activity is a sign of creative capacity, aligning these efforts with clean energy and low-emissions goals will require deliberate policy efforts. This includes environmental standards in R&D funding, investment in green research centers, and fostering collaboration between universities, energy ministries, and private firms.

Table 4. Interaction effect

Dependent var.	**Carbon emission**				**Methane emission**			
	1	2	3	4	5	6	7	8
Renewable energy	0.119	-0.024	-0.736***	0.005	0.435*	-0.095***	-0.453**	-0.236***
	(0.200)	(0.003)	(0.115)	(0.004)	(0.242)	(0.014)	(0.1365)	(0.052)
Renewable electricity	0.027**	0.015	-0.002***	-0.258***	0.632*	0.139*	-0.010*	-0.109
	(0.030)	(0.066)	(0.000)	(0.064)	(0.301)	(0.080)	(0.005	(0.077)
Patent non-resident (PN)	0.395**	0.133**	-0.084***	0.045*	0.414*	0.166**	-0.496***	0.111
	(0.138)	(0.050)	(0.015)	(0.019)	(0.168)	(0.060)	(0.097)	(0.093)
Patent resident (PR)	-0.050***	0.022***	-0.452**	0.033	-0.129***	-0.031	-0.4957**	-0.018
	(0.016)	(0.003)	(0.140)	(0.078)	(0.035)	(0.018)	(0.1667)	(0.021)
REC×PN	**-0.121****				**-0.099***			
	(0.036)				**(0.044)**			
REELECT×PN		**-0.063*****				**-0.052****		
		(0.016)				**(0.019)**		
REC×PR			**0.139*****				**0.1793*****	
			(0.034)				**(0.0406)**	
REELECT×PR				**0.027**				**0.028**
				(0.019)				**(0.023)**
GDP	-0.009	-0.031	0.005	-0.069	-0.105*	-0.094*	-0.1210**	-0.167***
	(0.044)	(0.042)	(0.050)	(0.049)	(0.053)	(0.050)	(0.0595)	(0.059)
INDUS	-0.053	0.145	-0.173	0.159	0.858***	0.789***	0.7594**	0.846***
	(0.160)	(0.131)	(0.157)	(0.135)	(0.194)	(0.158)	(0.1863)	(0.161)
NE of PN	-0.074	-0.072			0.029	-0.004		

Threshold of PN	na	na			4.575	2.673		
NE of REC	na		-0.327		0.085		0.074	
Threshold of REC	3.264		3.251		4.181		2.764	
NE of PR			0.087	na			0.200	na
Threshold of PR			5.295	na			2.526	na
NE of REELECT		na		na		-0.044		na
Threshold of REELECT		2.111		na		3.192		na
Constant	8.599*** (1.431)	8.747*** (1.206)	11.599*** (1.307)	9.904*** (1.263)	6.100*** (1.735)	7.497*** (1.456)	9.8599** (1.5550)	9.208*** (1.505)
Wald chi2	50.38	47.14	58.18	41.33	43.09	45.28	73.06	53.79
Prob > chi2	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Log likelihood	-962.481	-963.965	-958.944	-966.646	-1064.216	-1063.205	-1050.713	-1059.317

Mean values of interactive variables are: REC, 3.882; REELECT, 3.268; PN, 3.532; PR, 2.940. The range of the interactive variables are: REC, -0.342 to 4.588; REELECT, -5.423 to 4.964; PN, -1.099 to 8.910; PR, 0.000 to 6.911. na: not applicable because at least one estimated coefficient needed for the computation of net effects is not significant.

In an attempt to avoid the pitfalls of interactive regressions that are documented in [67], in the light of extant contemporary interactive regressions literature [68], net effects and thresholds of the considered moderating variables and channels are computed, respectively. The computations are tailored such that for each interactive pair, two thresholds and two net effects are apparent, especially when the corresponding estimated coefficients required for the computations are significant. To illustrate this perspective with an example, let us consider the fourth column or third specification of Table 3. In the attendant column, both the net effects and thresholds of renewable energy (REC) and patent from residents (PR) are computed. It follows that in the corresponding computations when REC is considered a moderator, PR is the channel and hence, the net effect of PR and threshold of REC are computed. In the same vein, when PR is the moderating or policy variable and REC the main mechanism, the net effect of REC and threshold of PR are computed. For instance, in the related column, the net effect of REC is: -0.327 ([2.940 × 0.139] + [-0.736]). In the corresponding computation, the mean value of PR is 2.940, the interactive or conditional effect of REC is 0.139 while the unconditional effect of REC -0.736. The corresponding PR threshold is 5.295 (0.736/0.139). The computation insights of net effects and thresholds are consistent with contemporary literature on interactive regressions [69], [70]. Moreover, for the policy threshold to be policy-relevant, it should be situated within the PR statistical range. Hence, the computed critical mass is relevant to policy makers because the PR threshold of 5.295 is within the minimum and maximum values of PR which are respectively, 0.000 to 6.911, as apparent in the summary statistics.

In the light of the above, the fact that net effects and thresholds are computed for both pairs of variables implies that some variables can be complemented to improve environmental quality (i.e., by means of reducing carbon dioxide and methane emissions) upon certain thresholds of the moderating variables while for other interactive pairs, complementary policies are needed once the policy thresholds are reached in order to promote environmental quality. Consistent with the extant threshold literature [71], [72], the policy prescriptions underlying the interactive regressions are discussed two main strands, notably: policy thresholds and thresholds for complementary policies. On the front of policy thresholds: (i) renewable energy and renewable electricity can effectively moderate patents from non-residents to reduce carbon dioxide and methane emissions when critical policy thresholds of renewable energy and renewable electricity are reached (i.e., first, second, fifth and sixth specifications of Table 3). (ii) Patents from non-residents can effectively moderate renewable energy and renewable electricity to reduce methane emissions when critical policy thresholds of patent from non-residents are reached (i.e., fifth and sixth specifications of Table 3).

With respect to thresholds for complementary policies: (i) while renewable energy can effectively moderate patents from residents to reduce carbon dioxide and methane emissions, there are critical thresholds of renewable energy that once reached, complementary policies are needed to promote environmental sustainability (i.e., third and seventh specifications of Table 3). (ii) Whereas patent from residents can robustly moderate renewable energy to reduce carbon and methane emissions, there are thresholds of patents from residents that once reached, complementary policy is worthwhile to reduce carbon dioxide and methane emissions (i.e., third and seventh specification of Table 3). It follows that, above the relevant thresholds for complementary policies, the interaction becomes a necessary but not a sufficient condition for environmental sustainability while below the attendant thresholds, the interaction reflects a sufficient and necessary condition for the promotion of environmental sustainability.

In our study of Sub-Saharan Africa, we identify significant interactions between renewable energy, patents, and emissions. The combination of renewable energy (REC) and patent non-resident (PN) emphasizes the potential for synergy in promoting renewable energy and innovations. The interaction of renewable electricity and patent non-resident (PN) underscores the importance of prioritizing renewable electricity technologies and fostering innovations. However, the interaction between renewable energy (REC) and patent resident (PR) highlights the necessity of balanced policies that harmonize economic development with environmental sustainability. These findings emphasize the significance of encouraging innovations and technology transfer while integrating renewable energy into Sub-Saharan Africa's energy mix to drive sustainable economic growth and environmental conservation.

4.4 Examining if renewable energy and innovations influence environmental degradation in Sub-Saharan Africa (Robustness)

To assess the robustness of our findings, we employ quantile regression, which offers several analytical advantages over conventional mixed-effects models—particularly in a context marked by skewed data and distributional heterogeneity, such as Sub-Saharan Africa. As established by [73], quantile regression provides robust estimates less influenced by outliers, making it suitable for data with non-normal distributions. Further, [74] emphasize its ability to estimate conditional quantiles, offering refined view across the distribution of the dependent variable. This is critical in understanding how predictors affect not just average emissions but also their behavior at different emission intensities. Additionally, [75] highlights quantile regression's strength in modeling heteroscedasticity and nonlinear relationships an advantage when evaluating environmental indicators in diverse socioeconomic settings.

Our quantile-specific analysis across the 25th, 50th, 75th, and 95th percentiles reveal significant variation in the effects of renewable energy and innovation. At the 75th quantile, renewable energy consumption (REC) is highly significant (1% level), with a coefficient indicating a 58.2% reduction in carbon dioxide emissions. This result confirms that REC becomes increasingly effective at higher emission levels, offering a powerful tool for decarbonization among high-emission sectors or countries. Policymakers should consider scaling up REC-focused interventions in these zones through subsidies, targeted infrastructure support, and public-private partnerships.

Regarding renewable electricity (REELECT), consistent significance is observed across the 25th (−12.9%), 50th (−5.6%), and 75th (−6.4%) quantiles. This demonstrates the broad applicability of REELECT in reducing emissions across varying contexts. [76], who explore the strategic role of decentralized electricity systems, and [77], who underscore infrastructure readiness and grid reliability, support the argument for investing in robust and inclusive energy access systems as a foundation for clean growth in Africa.

The effects of non-resident patent innovation (PN) on emissions present intriguing dynamics. At the 25th quantile, PN shows a positive and significant effect (9.1%), potentially reflecting the emissions-intensive nature of early-stage industrial technologies. However, at the 75th and 95th quantiles, the coefficients become negative and significant (−2.6% and −86.6%), indicating strong emissions-reducing potential at higher levels of economic complexity or institutional capacity. These findings align with [78], who cautions about the transitional emissions cost of innovation adoption, and [58], who demonstrate how foreign technology can become a vehicle for emissions mitigation when matched with local absorptive capacity.

In contrast, resident patent innovation (PR) exhibits consistently positive and significant effects on carbon dioxide emissions at the 25th (6.7%) and 95th (35.1%) quantiles. These results raise important questions about the environmental alignment of resident innovation. In many cases, innovation may be oriented toward productivity rather than sustainability goals. As [37] note, domestic innovations in emerging economies may initially favor economic competitiveness over environmental performance. Similarly, [66] underscores the need for strong regulatory frameworks to reorient local innovation systems toward environmental goals.

The influence of GDP also varies meaningfully across quantiles. At the 25th and 95th percentiles, GDP exhibits a significant and negative relationship with carbon dioxide emissions (−9.6% and −12.2%), suggesting that at both low and high levels of economic output, structural efficiencies or environmental policy reforms may drive emissions reductions. These findings are consistent with [79], who highlight the dual role of economic growth as both a driver and mitigator of environmental harm, depending on the policy context and development stage.

For industrialization (IDUS), a significant and positive effect (+) is only observed at the 25th quantile, suggesting that early industrial development in low-income settings may drive emissions. However, the relationship is insignificant at the 50th, 75th, and 95th quantiles, indicating a more complex and possibly non-linear relationship in mature economies. These results align with [80], who suggest that industrialization's environmental impacts depend on technological pathways, and [81], who emphasize the need for sustainable industrial planning in low-income countries.

This robustness analysis reaffirms the asymmetric effects of renewable energy and innovation across the emissions distribution in Sub-Saharan Africa. Renewable energy—particularly at higher quantiles—plays a decisive role in reducing carbon emissions, while the effectiveness of innovation varies by source and context. Non-resident innovation shows promise in high-emission sectors, whereas resident innovation may require realignment with green objectives. The results underscore the need for refined, quantile-specific policy interventions that account for heterogeneity in development, innovation systems, and energy access. Collaborative frameworks, guided by both international technology partnerships and local institutional strengthening, remain essential for aligning economic development with environmental sustainability in Sub-Saharan Africa.

Table 5 Logistic quantile results

Variable	q25	q50	q75	q95	q25	q50	q75	q95
	0.076	-0.065	-0.582***	-0.175	0.390**	-0.191	-1.006***	-0.820
REC	(0.055)	(0.101)	(0.105)	(0.474)	(0.145)	(0.141)	(0.162)	(0.726)
	-0.129***	-0.056**	0.064***	-0.507	-0.077**	0.087*	0.240***	-0.003
REELECT	(-0.012)	(0.020)	(0.015)	(0.428)	(0.033)	(0.037)	(0.050)	(0.202)
	0.091*	0.026	-0.061*	-0.866***	0.170**	-0.074	-0.061	-0.193**
PN	(0.036)	(0.025)	(0.028)	(0.186)	(0.084)	(0.059)	(0.058)	(0.055)

	0.067*	0.033	0.047	0.351***	0.282***	0.150**	0.090*	0.225**
PR	(0.034)	(0.030)	(0.033)	(0.098)	(0.057)	(0.043)	(0.042)	(0.070)
	-0.096**	-0.003	0.065	-0.122**	-0.234***	-0.087	-0.145	-0.437**
GDP	(0.033)	(0.021)	(0.057)	(0.068)	(0.046)	(0.073)	(0.092)	(0.103)
	0.439**	0.067	-0.202	-0.670	1.442***	0.170	-0.320*	-0.696**
INDUS	(0.156)	(0.178)	(0.204)	(0.461)	(0.314)	(0.252)	(0.174)	(0.252)
	-0.959	-0.554	1.362	12.126***	-3.315**	2.290	9.318***	18.709**
_cons	(0.964)	(0.768)	(1.358)	(2.700)	(1.616)	(2.001)	(2.316)	(3.020)

Note: Bounded Outcome: carbon emissions (5.5004415, 13.013214) and methane emissions (4.2829489,11.951663).

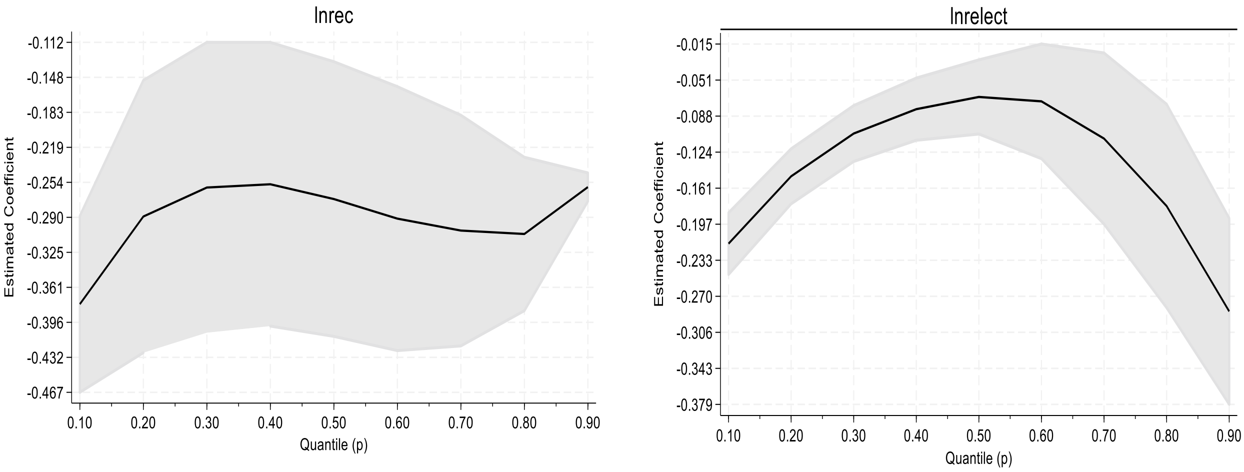

Figure 2. Shows the quantile graph of the effect of renewable energy consumption on CO_2.

From Figure 2, we observed varying effects of REC and r REELECT on carbon dioxide emissions across different quantiles in Sub-Saharan Africa. Notably, REC exhibited a statistically significant reduction in emissions, particularly in the upper quantiles of the distribution, suggesting that its impact intensifies in higher-emission contexts. This underscores REC critical role in decarbonizing the region's most polluting sectors. In parallel, REELECT consistently demonstrated a negative and significant impact on carbon dioxide emissions across multiple quantiles, reinforcing its broad applicability and effectiveness in emissions mitigation across diverse national settings. These findings resonate with [82], who emphasize the transregional nature of air pollutants, arguing that renewable energy policies must transcend borders due to shared environmental externalities. Similarly, [83] highlight the transnational diffusion of renewable energy benefits, noting that reductions in carbon emissions in one country can yield spillover effects in neighboring regions. These studies collectively affirm the importance of regionally coordinated renewable energy investments. Accordingly, policymakers across SSA are encouraged to prioritize the adoption and scaling of renewable electricity sources, particularly solar and wind, in both high- and low-emission areas. Targeted infrastructure development, cross-border energy trade, and harmonized regulatory frameworks will be essential to fully harness the emissions-reducing potential of renewable electricity across the region.

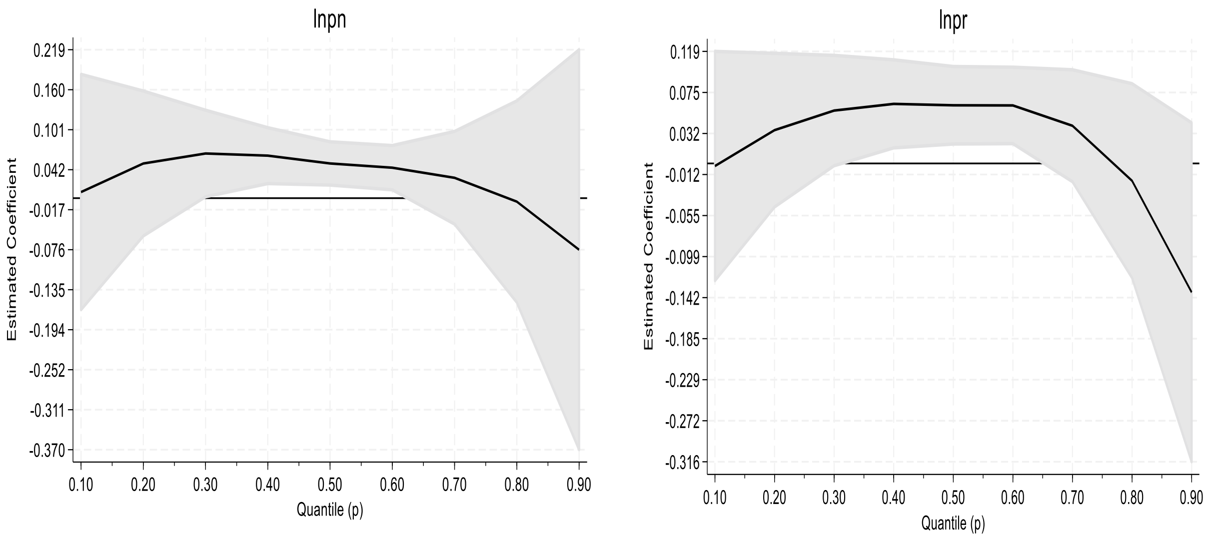

Figure 3. Shows the quantile graph of innovations on carbon dioxide

Figure 3 shows that the impact of Patent Non-Resident (PN) on carbon dioxide emissions varies significantly across different quantiles. PN leads to an increase in carbon dioxide emissions, but at some point, it significantly reduces emissions. This shift suggests that the effect of PN depends on the emission intensity of the region or sector. The transition from increasing to decreasing emissions highlights the potential of innovations to reduce emissions, particularly in higher-emission areas or industries. Policymakers should prioritize the adoption of eco-friendly technologies in regions or sectors with higher emissions, facilitating this through incentives and technology transfer programs.

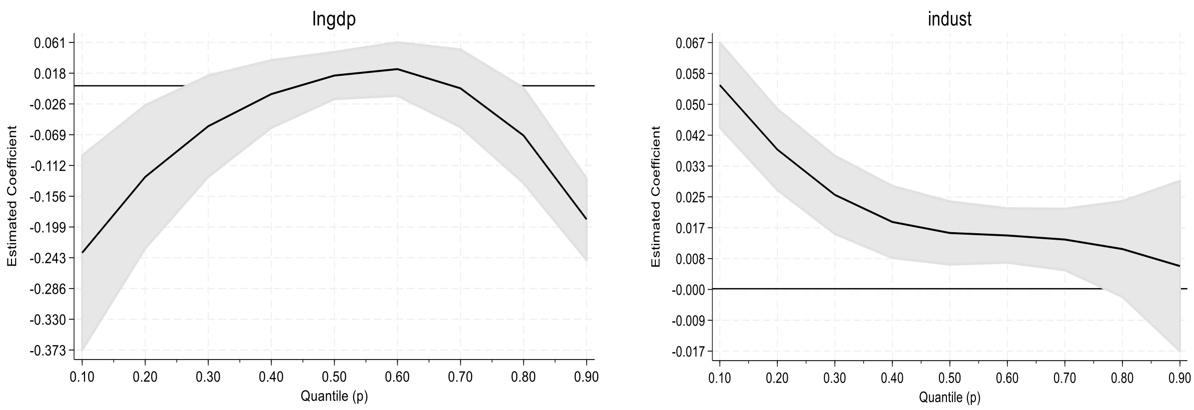

Figure 4. Shows the quantile graph of potential growth on carbon dioxide.

Figure 4 shows the influence of GDP and industrialization on carbon dioxide emissions across different quantiles. GDP has a significant negative effect on carbon dioxide emissions, indicating emissions reduction. Conversely, the effect of industrialization is significant and positive. This suggests that addressing the environmental impact of industrialization should be a priority at lower levels of development, but its impact becomes less clear as countries progress. Policymakers should prioritize sustainable and green industrialization practices to ensure economic growth does not lead to increased emissions as countries develop. Figures 5, 6 and 7 in Appendix b also illustrate the contingency of the findings.

5. Conclusion and Implications

5.1 Conclusion

This study examined the relationship between economic growth, renewable energy, innovation, and environmental degradation in Sub-Saharan Africa, focusing on carbon dioxide (CO_2) and methane (CH_4) emissions from 2000 to 2021 across 24 countries. The results provide strong empirical support for the Environmental Kuznets Curve (EKC) hypothesis, which posits a non-linear relationship between GDP and environmental degradation. Using mixed-effects and panel quantile regression models, we found that emissions initially decline with economic growth but rise beyond identified turning points, signaling a trade-off between higher income and environmental outcomes. Our findings confirm Hypothesis 1, indicating a U-shaped EKC relationship for both CO_2 and CH_4. Specifically, turning points were observed at relatively low GDP levels 0.049 kilotons for CO_2, 0.054 kilotons of CO_2 equivalent for methane, and 0.137 percent of GDP for industrialization—suggesting that the transition from emission reduction to environmental burden occurs earlier in the development process than in high-income countries. Hypothesis 2 is also supported, as renewable energy and electricity exhibit consistent emissions-reducing effects across all quantiles, with stronger impacts observed at higher emission levels. Hypothesis 3 is partially confirmed: non-resident innovation (patents) increases emissions at lower quantiles but begins to reduce them at higher quantiles, reflecting a nonlinear effect dependent on technological maturity and absorptive capacity. Moreover, interactive regressions reveal the existence of policy thresholds and thresholds for complementary policies. For instance, renewable energy and electricity must reach minimum critical levels before they can significantly moderate the environmental impact of non-resident patents. Similarly, innovation—both resident and non-resident—must exceed certain thresholds to enhance the emissions-reducing effects of renewable energy. Once these thresholds are surpassed, the introduction of complementary policies becomes essential to sustain positive synergies between clean energy and innovation. These results provide refined insight into the region's development-environment trade-offs and inform the sequencing of climate and innovation policy interventions.

5.2 Practical Implications

The identification of EKC turning points and emission-reducing thresholds offers several practical implications for policymaking in Sub-Saharan Africa. First, during the initial stages of economic growth—when emissions tend to decline—governments should embed sustainability into infrastructure planning, industrial policy, and energy expansion strategies. This phase provides a strategic window to lock in green growth pathways before emissions intensify beyond the EKC threshold. Second, renewable energy investments must be prioritized. Given their consistent emissions-reducing effects across both low- and high-emission contexts, expanding access to solar, wind, hydroelectric, and clean cooking technologies is imperative. These interventions should be accompanied by energy policy reforms that improve grid reliability and expand off-grid solutions, particularly for rural areas. Third, innovation policy should be strategically aligned with climate goals. Since patent activity—especially from non-residents—only reduces emissions after reaching critical levels, governments must actively facilitate technology transfer, invest in research and development, and provide innovation incentives. Beyond achieving these policy thresholds, complementary reforms such as subsidies, education initiatives, and institutional strengthening will be necessary to sustain environmental gains. Fourth, policymakers must prepare for post-threshold dynamics, where interactions between renewable energy and innovation become necessary but not sufficient conditions for sustainability. At this stage, integrated climate and industrial policy packages are required to maintain emissions reductions and avoid rebound effects. Sector-specific focus, particularly in agriculture and manufacturing, can yield more targeted and cost-effective outcomes. Finally, coordinated regional strategies and partnerships with international actors will be crucial in accelerating green transitions. Multilateral support for climate finance, capacity building, and technology transfer can help countries in SSA reach and maintain the critical thresholds identified in this study.

5.3 Theoretical Implications

From a theoretical standpoint, this study advances the Environmental Kuznets Curve framework by introducing dynamic threshold effects and accounting for multi-dimensional environmental indicators. The identification of turning points for both CO_2 and CH_4 challenges the notion of a universal EKC and underscores the importance of regional context. In Sub-Saharan Africa, the EKC manifests at relatively low levels of GDP, suggesting that economic-environmental trade-offs arise earlier than anticipated and must be addressed sooner in the development trajectory. The results also reinforce the need to consider pollutant-specific behavior within EKC analyses. While CO_2 and CH_4 are both greenhouse gases, their trajectories in response to growth, innovation, and renewable energy diverge. This highlights the importance of adopting a multi-pollutant approach in environmental economic modeling, rather than assuming a uniform response across emissions. Moreover, this study extends EKC theory by integrating interactive effects and identifying nonlinear thresholds. The effectiveness of renewable energy and innovation in reducing emissions depends not only on their presence but on reaching minimum scale and intensity levels. Once these levels are surpassed, the nature of their interaction changes, requiring a shift from basic deployment to strategic policy coordination. This enriches EKC modeling by introducing a dynamic, staged framework for understanding environmental transitions.

5.4 Future Applied Research

Several avenues exist for future research to build on these findings. First, disaggregated EKC analyses should be conducted at the sectoral level to identify which economic activities contribute most to emissions and where interventions may be most effective. For example, agriculture's role in methane emissions may differ substantially from the industrial sector's CO_2 output. Second, future studies should address limitations related to endogeneity. Although our models control for unobserved heterogeneity and distributional differences, challenges such as reverse causality, measurement error, and omitted variable bias persist. Methodological advancements—such as structural equation modeling, dynamic panel models, or system dynamics—can enhance causal inference and strengthen policy guidance. Third, researchers should explore the long-term stability of the identified EKC turning points. This includes evaluating the effects of global economic shocks, pandemics, or major environmental events on the shape and direction of the curve. Understanding whether these turning points are transient or enduring can help policymakers design more resilient and adaptable policies. Fourth, future research should investigate the social and equity dimensions of environmental change. As countries transition toward sustainability, it is critical to assess how benefits and burdens are distributed across income groups, genders, and geographic areas. Doing so will contribute to more inclusive climate strategies. Lastly, future work should integrate climate adaptation into EKC frameworks. As Sub-Saharan Africa faces increasing climate risks, studies should assess how resilience strategies—such as flood protection or drought-resistant agriculture—interact with emissions and economic growth. This would allow for more comprehensive assessments of sustainability in the region.

Acknowledgement

The authors are highly indebted to the editors and reviewers for constructive comments. AI (i.e., ChatGPT) was used to rephrase some parts of the theoretical literature and the Appendix Table 3 on the cross-sectional dependence test.

References

[1] World Bank, "CO2 emissions (kt) - Sub-Saharan Africa. The World Bank (Accessed: 26/02/2024)," 2023.

[2] World Bank, "Methane emissions (kt of CO2 equivalent) - Sub-Saharan Africa. The World Bank. (Accessed: 26/02/2024)," 2023.

[3] M. Appiah, S. Ashraf, A. K. Tiwari, B. A. Gyamfi, and S. T. Onifade, "Does financialization enhance renewable energy development in Sub-Saharan African countries?," *Energy Econ*, vol. 125, p. 106898, Sep. 2023, doi: 10.1016/j.eneco.2023.106898.

[4] M. Musah, B. A. Gyamfi, P. A. Kwakwa, and D. Q. Agozie, "Realizing the 2050 Paris climate agreement in West Africa: the role of financial inclusion and green investments," *J Environ Manage*, vol. 340, p. 117911, Aug. 2023, doi: 10.1016/j.jenvman.2023.117911.

[5] M. A. Destek and A. Sinha, "Renewable, non-renewable energy consumption, economic growth, trade openness and ecological footprint: Evidence from organisation for economic Co-operation and development countries," *J Clean Prod*, vol. 242, p. 118537, Jan. 2020, doi: 10.1016/j.jclepro.2019.118537.

[6] IRENA, "Bracing for climate impact: Renewables as a climate change adaptation strategy," in *International Renewable Energy Agency*, Abu Dhabi, 2022.

[7] N. Saqib and M. Usman, "Are technological innovations and green energy prosperity swiftly reduce environmental deficit in China and United States? Learning from two sides of environmental sustainability," *Energy Reports*, vol. 10, pp. 1672–1687, Nov. 2023, doi: 10.1016/j.egyr.2023.08.022.

[8] A. L. Cántaro Márquez, G. F. Miranda Vásquez, and D. Ángeles Barrantes, "Analysis of Eco-Innovations in Peruvian Accommodation Establishments," *Sustainability*, vol. 15, no. 8, p. 6700, Apr. 2023, doi: 10.3390/su15086700.

[9] A. L. Cántaro Márquez, G. F. Miranda Vásquez, and D. Ángeles Barrantes, "Analysis of Eco-Innovations in Peruvian Accommodation Establishments," *Sustainability*, vol. 15, no. 8, p. 6700, Apr. 2023, doi: 10.3390/su15086700.

[10] M. A. AlKhars, S. Alwahaishi, M. R. Fallatah, and A. Kayal, "A literature review of the Environmental Kuznets Curve in GCC for 2010–2020," *Environmental and Sustainability Indicators*, vol. 14, p. 100181, Jun. 2022, doi: 10.1016/j.indic.2022.100181.

[11] M. O. Agboola, F. V. Bekun, and U. Joshua, "Pathway to environmental sustainability: Nexus between economic growth, energy consumption, CO2 emission, oil rent and total natural resources rent in Saudi Arabia," *Resources Policy*, vol. 74, p. 102380, Dec. 2021, doi: 10.1016/j.resourpol.2021.102380.

[12] C. Pérez and O. Claveria, "Natural resources and human development: Evidence from mineral-dependent African countries using exploratory graphical analysis," *Resources Policy*, vol. 65, p. 101535, Mar. 2020, doi: 10.1016/j.resourpol.2019.101535.

[13] G. S. Chen, E. K. Manu, and D. Asante, "Achieving environmental sustainability in Africa: The role of financial institutions development on carbon emissions,"

Sustainable Development, vol. 31, no. 5, pp. 3272–3290, Oct. 2023, doi: 10.1002/sd.2584.

[14] E. K. Manu, G. S. Chen, and D. Asante, "Regional heterogeneities in the absorptive capacity of renewable energy deployment in Africa," *Renew Energy*, vol. 193, pp. 554–564, Jun. 2022, doi: 10.1016/j.renene.2022.05.019.

[15] M. Donkor, Y. Kong, and E. K. Manu, "Natural resource abundance, governance, and government expenditure: Empirical insights from environmental sustainability," *Sustainable Development*, Aug. 2024, doi: 10.1002/sd.3116.

[16] E. K. Manu and S. A. Asongu, "The impact of environmental policy, technological innovations, and digitalisation: Does context matter in natural resource management in Sub-Sahara Africa?," *Extr Ind Soc*, vol. 22, p. 101608, Jun. 2025, doi: 10.1016/j.exis.2024.101608.

[17] A. F. A. K. S. G. M. H. K. J. L. M. L. N. G. F. N. and C. W. Grubler, "Policies for the energy technology innovation system (ETIS)," 2012.

[18] J. Musiolik, J. Markard, and M. Hekkert, "Networks and network resources in technological innovation systems: Towards a conceptual framework for system building," *Technol Forecast Soc Change*, vol. 79, no. 6, pp. 1032–1048, Jul. 2012, doi: 10.1016/j.techfore.2012.01.003.

[19] F. W. Geels, "Reconceptualising the co-evolution of firms-in-industries and their environments: Developing an inter-disciplinary Triple Embeddedness Framework," *Res Policy*, vol. 43, no. 2, pp. 261–277, Mar. 2014, doi: 10.1016/j.respol.2013.10.006.

[20] S. Kuznets, "The American Economic Association," *American Economic Review*, vol. 90, no. 3, pp. i–vi, Jun. 1995, doi: 10.1257/aer.90.3.i.

[21] S. Saint Akadiri, A. A. Alola, U. V. Alola, and C. S. Nwambe, "The role of ecological footprint and the changes in degree days on environmental sustainability in the USA," *Environmental Science and Pollution Research*, vol. 27, no. 20, pp. 24929–24938, Jul. 2020, doi: 10.1007/s11356-020-08884-0.

[22] W. Fan and Y. Hao, "An empirical research on the relationship amongst renewable energy consumption, economic growth and foreign direct investment in China," *Renew Energy*, vol. 146, pp. 598–609, Feb. 2020, doi: 10.1016/j.renene.2019.06.170.

[23] Y. Pan, F. Dong, and C. Du, "Is China approaching the inflection point of the ecological Kuznets curve? Analysis based on ecosystem service value at the county level," *J Environ Manage*, vol. 326, p. 116629, Jan. 2023, doi: 10.1016/j.jenvman.2022.116629.

[24] T. S. (2020) Adebayo, "Revisiting the EKC hypothesis in an emerging market: An application of ARDL-based bounds and wavelet coherence approaches," *SN Appl Sci*, vol. 2, no. 12, pp. 1–15., 2020.

[25] K. K. Gokmenoglu and N. Taspinar, "Testing the agriculture-induced EKC hypothesis: the case of Pakistan," *Environmental Science and Pollution Research*, vol. 25, no. 23, pp. 22829–22841, Aug. 2018, doi: 10.1007/s11356-018-2330-6.

[26] A. Rauf, X. Liu, W. Amin, I. Ozturk, O. U. Rehman, and M. Hafeez, "Testing EKC hypothesis with energy and sustainable development challenges: a fresh evidence from belt and road initiative economies," *Environmental Science and Pollution Research*, vol. 25, no. 32, pp. 32066–32080, Nov. 2018, doi: 10.1007/s11356-018-3052-5.

[27] D. Tenaw and A. D. Beyene, "Environmental sustainability and economic development in sub-Saharan Africa: A modified EKC hypothesis," *Renewable and Sustainable Energy Reviews*, vol. 143, p. 110897, Jun. 2021, doi: 10.1016/j.rser.2021.110897.

[28] W. Ohemeng, K. Ofori-Boateng, E. Kwame Agyapong, and J. Darmoe, "Environmental risk and growth in foreign direct investment: Is the composition of FDI in sub-Saharan Africa a speculative type?," *Cogent Economics & Finance*, vol. 11, no. 2, Jun. 2023, doi: 10.1080/23322039.2023.2243695.

[29] S. A. Sarkodie, "The invisible hand and EKC hypothesis: what are the drivers of environmental degradation and pollution in Africa?," *Environmental Science and Pollution Research*, vol. 25, no. 22, pp. 21993–22022, Aug. 2018, doi: 10.1007/s11356-018-2347-x.

[30] B. Mishra, P. Kumar, C. Saraswat, S. Chakraborty, and A. Gautam, "Water Security in a Changing Environment: Concept, Challenges and Solutions," *Water (Basel)*, vol. 13, no. 4, p. 490, Feb. 2021, doi: 10.3390/w13040490.

[31] L. Li and A. Taeihagh, "An in-depth analysis of the evolution of the policy mix for the sustainable energy transition in China from 1981 to 2020," *Appl Energy*, vol. 263, p. 114611, Apr. 2020, doi: 10.1016/j.apenergy.2020.114611.

[32] J. Eom, M. Hyun, J. Lee, and H. Lee, "Increase in household energy consumption due to ambient air pollution," *Nat Energy*, vol. 5, no. 12, pp. 976–984, Sep. 2020, doi: 10.1038/s41560-020-00698-1.

[33] W. Shen, S. Li, Y. Zhuang, J. He, H. Liu, and L. Zhang, "Phosphorus use efficiency has crossed the turning point of the environmental kuznets curve: Opportunities and challenges for crop production in China," *J Environ Manage*, vol. 326, p. 116754, Jan. 2023, doi: 10.1016/j.jenvman.2022.116754.

[34] M. Musah, Y. Kong, I. A. Mensah, S. K. Antwi, and M. Donkor, "The link between carbon emissions, renewable energy consumption, and economic growth: a heterogeneous panel evidence from West Africa," *Environmental Science and Pollution Research*, vol. 27, no. 23, pp. 28867–28889, Aug. 2020, doi: 10.1007/s11356-020-08488-8.

[35] S. Stavropoulos, R. Wall, and Y. Xu, "Environmental regulations and industrial competitiveness: evidence from China," *Appl Econ*, vol. 50, no. 12, pp. 1378–1394, Mar. 2018, doi: 10.1080/00036846.2017.1363858.

[36] A. Sood *et al.*, "ERS/ATS workshop report on respiratory health effects of household air pollution," *European Respiratory Journal*, vol. 51, no. 1, p. 1700698, Jan. 2018, doi: 10.1183/13993003.00698-2017.

[37] G. C. S. A. Emmanuel K Manu, "Do environmental regulations and technological innovation enhance environmental well-being in sub-Saharan Africa? ," *Bus Strategy Environ*, 2024.

[38] J. Ayelazuno, "Oil wealth and the well-being of the subaltern classes in Sub-Saharan Africa: A critical analysis of the resource curse in Ghana," *Resources Policy*, vol. 40, pp. 66–73, Jun. 2014, doi: 10.1016/j.resourpol.2013.06.009.

[39] T. Dinkelman, "The Effects of Rural Electrification on Employment: New Evidence from South Africa," *American Economic Review*, vol. 101, no. 7, pp. 3078–3108, Dec. 2011, doi: 10.1257/aer.101.7.3078.

[40] T. Amare *et al.*, "Remediation of acid soils and soil property amelioration via Acacia decurrens-based agroforestry system," *Agroforestry Systems*, vol. 96, no. 2, pp. 329–342, Feb. 2022, doi: 10.1007/s10457-021-00721-8.

[41] V. Costantini, F. Crespi, G. Marin, and E. Paglialunga, "Eco-innovation, sustainable supply chains and environmental performance in European industries 1 1We gratefully acknowledge the support by the European Union's Horizon 2020 research and innovation programme under grant agreement No. 649186 – ISIGrowth. The comments and suggestions by three anonymous referees are also acknowledged. The usual disclaimers apply.," *J Clean Prod*, vol. 155, pp. 141–154, Jul. 2017, doi: 10.1016/j.jclepro.2016.09.038.

[42] C. Ghisetti, A. Marzucchi, and S. Montresor, "The open eco-innovation mode. An empirical investigation of eleven European countries," *Res Policy*, vol. 44, no. 5, pp. 1080–1093, Jun. 2015, doi: 10.1016/j.respol.2014.12.001.

[43] K. Rennings, "Redefining innovation — eco-innovation research and the contribution from ecological economics," *Ecological Economics*, vol. 32, no. 2, pp. 319–332, Feb. 2000, doi: 10.1016/S0921-8009(99)00112-3.

[44] K. Rennings, A. Ziegler, K. Ankele, and E. Hoffmann, "The influence of different characteristics of the EU environmental management and auditing scheme on technical environmental innovations and economic performance," *Ecological Economics*, vol. 57, no. 1, pp. 45–59, Apr. 2006, doi: 10.1016/j.ecolecon.2005.03.013.

[45] OECD, "OECD Environmental Performance Reviews: Turkey Highlights 2019 OECD Environmental Performance Review Programme, ," 2019.

[46] W. D. Indicators, "World Bank," *Online Database. World Bank (2020), Africa's Future and the World Bank's Support to It, Washington, D.C*, 2022.

[47] A. Jäger-Waldau, M. Szabó, N. Scarlat, and F. Monforti-Ferrario, "Renewable electricity in Europe," *Renewable and Sustainable Energy Reviews*, vol. 15, no. 8, pp. 3703–3716, Oct. 2011, doi: 10.1016/j.rser.2011.07.015.

[48] M. Donkor, Y. Kong, E. K. Manu, A. H. Ntarmah, and F. Appiah-Twum, "Economic Growth and Environmental Quality: Analysis of Government Expenditure and the Causal Effect," *Int J Environ Res Public Health*, vol. 19, no. 17, p. 10629, Aug. 2022, doi: 10.3390/ijerph191710629.

[49] A. F. Djoumessi Djoukouo, "Relationship between methane emissions and economic growth in Central Africa countries: Evidence from panel data," *Glob Transit*, vol. 3, pp. 126–134, 2021, doi: 10.1016/j.glt.2022.02.001.

[50] N. Aminu, N. Clifton, and S. Mahe, "From pollution to prosperity: Investigating the Environmental Kuznets curve and pollution-haven hypothesis in sub-Saharan Africa's industrial sector," *J Environ Manage*, vol. 342, p. 118147, Sep. 2023, doi: 10.1016/j.jenvman.2023.118147.

[51] A. Gałecki and T. Burzykowski, “Linear Mixed-Effects Model,” 2013, pp. 245–273. doi: 10.1007/978-1-4614-3900-4_13.

[52] M. Bottai, B. Cai, and R. E. McKeown, “Logistic quantile regression for bounded outcomes,” *Stat Med*, vol. 29, no. 2, pp. 309–317, Jan. 2010, doi: 10.1002/sim.3781.

[53] I. Khan, I. Muhammad, A. Sharif, I. Khan, and X. Ji, “Unlocking the potential of renewable energy and natural resources for sustainable economic growth and carbon neutrality: A novel panel quantile regression approach,” *Renew Energy*, vol. 221, p. 119779, Feb. 2024, doi: 10.1016/j.renene.2023.119779.

[54] C. Haibo and E. K. Manu, “The impact of banks’ financial performance on environmental performance in Africa,” *Environmental Science and Pollution Research*, vol. 29, no. 32, pp. 49214–49233, Jul. 2022, doi: 10.1007/s11356-022-19401-w.

[55] E. K. Manu, G. S. Chen, and S. Adomako, “Do environmental regulations and technological innovation enhance environmental well-being in sub-Saharan Africa?,” *Bus Strategy Environ*, Apr. 2024, doi: 10.1002/bse.3772.

[56] M. Musah, “Financial inclusion and environmental sustainability in Ghana: application of the dynamic ARDL estimator,” *Environmental Science and Pollution Research*, vol. 29, no. 40, pp. 60885–60907, Aug. 2022, doi: 10.1007/s11356-022-19994-2.

[57] M. A. Destek and S. A. Sarkodie, “Investigation of environmental Kuznets curve for ecological footprint: The role of energy and financial development,” *Science of The Total Environment*, vol. 650, pp. 2483–2489, Feb. 2019, doi: 10.1016/j.scitotenv.2018.10.017.

[58] S. Saint Akadiri, A. A. Alola, A. C. Akadiri, and U. V. Alola, “Renewable energy consumption in EU-28 countries: Policy toward pollution mitigation and economic sustainability,” *Energy Policy*, vol. 132, pp. 803–810, Sep. 2019, doi: 10.1016/j.enpol.2019.06.040.

[59] S. Erdogan, I. Okumus, and A. E. Guzel, “Revisiting the Environmental Kuznets Curve hypothesis in OECD countries: the role of renewable, non-renewable energy, and oil prices,” *Environmental Science and Pollution Research*, vol. 27, no. 19, pp. 23655–23663, Jul. 2020, doi: 10.1007/s11356-020-08520-x.

[60] N. Aziz, A. Sharif, A. Raza, and K. Jermsittiparsert, “The role of natural resources, globalization, and renewable energy in testing the EKC hypothesis in MINT countries: new evidence from Method of Moments Quantile Regression approach,” *Environmental Science and Pollution Research*, vol. 28, no. 11, pp. 13454–13468, Mar. 2021, doi: 10.1007/s11356-020-11540-2.

[61] U. K. Pata, M. T. Kartal, S. Erdogan, and S. A. Sarkodie, “The role of renewable and nuclear energy R&D expenditures and income on environmental quality in Germany: Scrutinizing the EKC and LCC hypotheses with smooth structural changes,” *Appl Energy*, vol. 342, p. 121138, Jul. 2023, doi: 10.1016/j.apenergy.2023.121138.

[62] A. Rashid Gill, K. K. Viswanathan, and S. Hassan, “The Environmental Kuznets Curve (EKC) and the environmental problem of the day,” *Renewable and Sustainable Energy Reviews*, vol. 81, pp. 1636–1642, Jan. 2018, doi: 10.1016/j.rser.2017.05.247.

[63] C. Işık, S. Ongan, and D. Özdemir, "Testing the EKC hypothesis for ten US states: an application of heterogeneous panel estimation method," *Environmental Science and Pollution Research*, vol. 26, no. 11, pp. 10846–10853, Apr. 2019, doi: 10.1007/s11356-019-04514-6.

[64] A. H. Ntarmah, Y. Kong, and E. K. Manu, "Investigating the dynamic relationships between credit supply, economic growth, and the environment: empirical evidence of sub-regional economies in Sub-Saharan Africa," *Environmental Science and Pollution Research*, vol. 28, no. 5, pp. 5786–5808, Feb. 2021, doi: 10.1007/s11356-020-10875-0.

[65] P. Shipalana, "Green Finance Mechanisms in Developing Countries: Emerging Practice," 2020.

[66] P. A. Kwakwa, "The carbon dioxide emissions effect of income growth, electricity consumption and electricity power crisis," *Management of Environmental Quality: An International Journal*, vol. 32, no. 3, pp. 470–487, May 2021, doi: 10.1108/MEQ-11-2020-0264.

[67] T. Brambor, W. R. Clark, and M. Golder, "Understanding Interaction Models: Improving Empirical Analyses," *Political Analysis*, vol. 14, no. 1, pp. 63–82, Jan. 2006, doi: 10.1093/pan/mpi014.

[68] V. S. Tchamyou, S. A. Asongu, and N. M. Odhiambo, "The Role of ICT in Modulating the Effect of Education and Lifelong Learning on Income Inequality and Economic Growth in Africa," *African Development Review*, vol. 31, no. 3, pp. 261–274, Sep. 2019, doi: 10.1111/1467-8268.12388.

[69] S. A. Asongu and S. le Roux, "The Role of Mobile Money Innovations in the Effect of Inequality on Poverty and Severity of Poverty in Sub-Saharan Africa," *Information Systems Frontiers*, Aug. 2023, doi: 10.1007/s10796-023-10427-0.

[70] V. S. Tchamyou, J. Somé, and S. A. Asongu, "The African Continental Free Trade Area and Financial Development for Female Labour Force Participation in Africa," *Forum for Social Economics*, pp. 1–15, Dec. 2023, doi: 10.1080/07360932.2023.2297169.

[71] S. A. Asongu and N. M. Odhiambo, "The green economy and inequality in Sub-Saharan Africa: Avoidable thresholds and thresholds for complementary policies," *Energy Exploration & Exploitation*, vol. 39, no. 3, pp. 838–852, May 2021, doi: 10.1177/0144598720984226.

[72] S. A. Asongu and N. M. Odhiambo, "Mobile technology supply factors and mobile money innovation: thresholds for complementary policies," *Journal of Banking Regulation*, vol. 23, no. 3, pp. 288–301, Sep. 2022, doi: 10.1057/s41261-021-00167-z.

[73] R. Koenker, "Quantile regression ," *Cambridge university press*, vol. 38, 2005.

[74] M. Geraci and M. Bottai, "Quantile regression for longitudinal data using the asymmetric Laplace distribution," *Biostatistics*, vol. 8, no. 1, pp. 140–154, Jan. 2007, doi: 10.1093/biostatistics/kxj039.

[75] B. R. N. Brian S. Cade, "A gentle introduction to quantile regression for ecologists," *Frontiers in Ecology and the Environment* , vol. 1, no. 8, pp. 339–452, Oct. 2003.

[76] Y. Liu, J. Zhu, E. Y. Li, Z. Meng, and Y. Song, "Environmental regulation, green technological innovation, and eco-efficiency: The case of Yangtze river economic belt in China," *Technol Forecast Soc Change*, vol. 155, p. 119993, Jun. 2020, doi: 10.1016/j.techfore.2020.119993.

[77] J. Ma *et al.*, "Digitalization in response to carbon neutrality: Mechanisms, effects and prospects," *Renewable and Sustainable Energy Reviews*, vol. 191, p. 114138, Mar. 2024, doi: 10.1016/j.rser.2023.114138.

[78] K. Pinzón, "Dynamics between energy consumption and economic growth in Ecuador: A granger causality analysis," *Econ Anal Policy*, vol. 57, pp. 88–101, Mar. 2018, doi: 10.1016/j.eap.2017.09.004.

[79] Z. Ao, R. Fei, H. Jiang, L. Cui, and Y. Zhu, "How can China achieve its goal of peaking carbon emissions at minimal cost? A research perspective from shadow price and optimal allocation of carbon emissions," *J Environ Manage*, vol. 325, p. 116458, Jan. 2023, doi: 10.1016/j.jenvman.2022.116458.

[80] F. Chien, M. Sadiq, M. A. Nawaz, M. S. Hussain, T. D. Tran, and T. Le Thanh, "A step toward reducing air pollution in top Asian economies: The role of green energy, eco-innovation, and environmental taxes," *J Environ Manage*, vol. 297, p. 113420, Nov. 2021, doi: 10.1016/j.jenvman.2021.113420.

[81] R. Pang, D. Zheng, M. Shi, and X. Zhang, "Pollute first, control later? Exploring the economic threshold of effective environmental regulation in China's context," *J Environ Manage*, vol. 248, p. 109275, Oct. 2019, doi: 10.1016/j.jenvman.2019.109275.

[82] G. Halkos and K. Tsilika, "Understanding transboundary air pollution network: Emissions, depositions and spatio-temporal distribution of pollution in European region," *Resour Conserv Recycl*, vol. 145, pp. 113–123, Jun. 2019, doi: 10.1016/j.resconrec.2019.02.014.

[83] E. K. Manu, W. Xuezhou, I. O. Paintsil, S. Gyedu, and A. H. Ntarmah, "Financial development and economic growth nexus in Africa," *BUSINESS STRATEGY & DEVELOPMENT*, vol. 3, no. 4, pp. 506–521, Dec. 2020, doi: 10.1002/bsd2.113.

Appendix a.

Appendix Table 1. Correlation matrix

Carbon emission	1							
Methane emissions	0.7485	1						
Renewable energy	-0.2491	-0.1845	1					
Renewable electricity	-0.2311	-0.1087	0.6305	1				
Patent non-resident	0.0248	0.0442	-0.2705	-0.1551	1			
Patent resident	0.0616	0.0401	0.0893	0.0611	0.4696	1		
GDP	-0.0513	-0.1144	0.2613	0.1107	0.1832	0.5481	1	
Industrialization	0.1726	0.1725	-0.0067	-0.1587	0.1064	0.2298	0.3593	1

Note: The significance of the test statistics at different levels (1%, 5%) indicates the degree of statistical confidence in these findings.

Appendix Table 2. Cointegration

Kao	Statistic	p-value	**Westerlund**	Statistic	p-value
Modified Dickey–Fuller t	-1.722*	0.043		2.001	0.022
Dickey–Fuller t	-1.901*	0.029			
Augmented Dickey–Fuller t	-2.762**	0.003			
Unadjusted modified Dickey–Fuller t	-2.161*	0.015			
Unadjusted Dickey–Fuller t	-2.134*	0.016			
Pedroni					
Modified Phillips–Perron t	4.818***	0.000			
Phillips–Perron t	-2.549**	0.005			
Augmented Dickey–Fuller t	-1.855*	0.032			

Note: The significance of the test statistics at different levels (1%, 5%) indicates the degree of statistical confidence in these findings.

Appendix Table 3. Unit root test and cross-sectional dependency test

The significant results obtained from the cross-sectional dependence test, particularly regarding carbon and methane emissions, have profound implications for understanding how common exogenous or externally driven policies, such as the **UN Sustainable Development Goals (SDGs) and the African Union (AU) Agenda 2063** on sustainable development, could impact sampled countries in Sub-Saharan Africa. Three main policies are apparent.

Firstly, both the UN SDGs and AU Agenda 2063 prioritize environmental sustainability and climate action as fundamental components of their overarching development frameworks. The significant values of **(-12.764 and -20.507**) at **1% levels** of cross-sectional dependence among carbon and methane emissions across the 24 Sub-Saharan African countries highlights the interconnectedness of environmental challenges within the region. This underscores the importance of aligning national policies with the objectives outlined in the international and regional agendas to address shared environmental concerns effectively.

Secondly, the results suggest that policies targeting emissions reduction and environmental sustainability in one Sub-Saharan African country can have spill-over effects on neighboring nations due to cross-sectional dependence. Therefore, achieving the ambitious targets set forth in the UN SDGs and AU Agenda 2063 requires not only strong national policies but also enhanced regional cooperation and coordination. Shared challenges like mitigating carbon and methane emissions necessitate collaborative efforts among Sub-Saharan African countries to develop harmonized policies and strategies that promote sustainable development while minimizing adverse environmental impacts.

Last, the significant cross-sectional dependence underscores the importance of resource allocation and capacity building initiatives to support SSA countries in implementing effective environmental policies. By recognizing the interconnected nature of environmental challenges, international organizations, development partners, and governments can prioritize investments in areas such as renewable energy infrastructure, technology transfer, and institutional capacity building. These investments can empower Sub-Saharan African countries to address environmental issues collectively while advancing broader development objectives outlined in the UN SDGs and AU Agenda 2063.

In conclusion, the significant results from the cross-sectional dependence test highlight the imperative for Sub-Saharan African countries to align their policies with international and regional sustainability agendas like the UN SDGs and AU Agenda 2063. By fostering policy coherence, regional cooperation, and targeted investments, Sub-Saharan African countries can address shared environmental challenges more effectively and advance sustainable development across the region.

Appendix Table 3. Unit root test and cross-sectional dependency test

Variables	CS test		CIPS	
	Test Statistic	Cross-sectional dependence?	(First difference)	Stationary?
Carbon emission	-12.764***	Yes	-13.093***	Yes
Methane emissions	-20.507***	Yes	-17.427***	Yes
Renewable energy	-9.056***	Yes	-9.0687***	Yes
Renewable electricity	-9.600***	Yes	-9.8752***	Yes
Patent non-resident	-6.279***	Yes	-3.280***	Yes
Patent resident	-8.2614***	Yes	-4.8368***	Yes
GDP	-16.5342***	Yes	-13.6469***	Yes
Industrialization	-13.5474***	Yes	-12.7326***	Yes

Note: The significance of the test statistics at different levels (1%, 5%) indicates the degree of statistical confidence in these findings.

Appendix b.

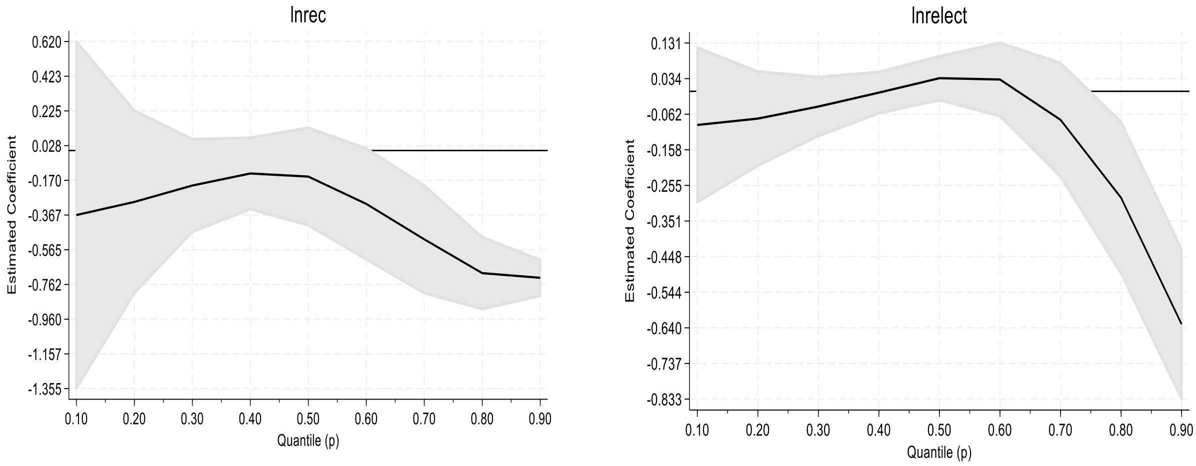

Figure 5. shows the quantile graph of renewable energy deployment on CO_2.

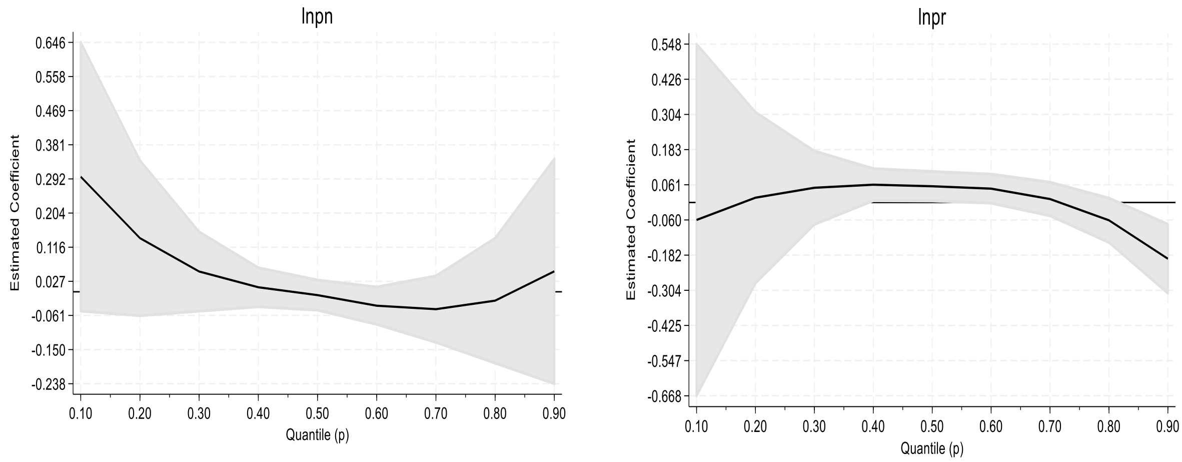

Figure 6. shows the quantile graph of the effect of CO_2 on innovations.

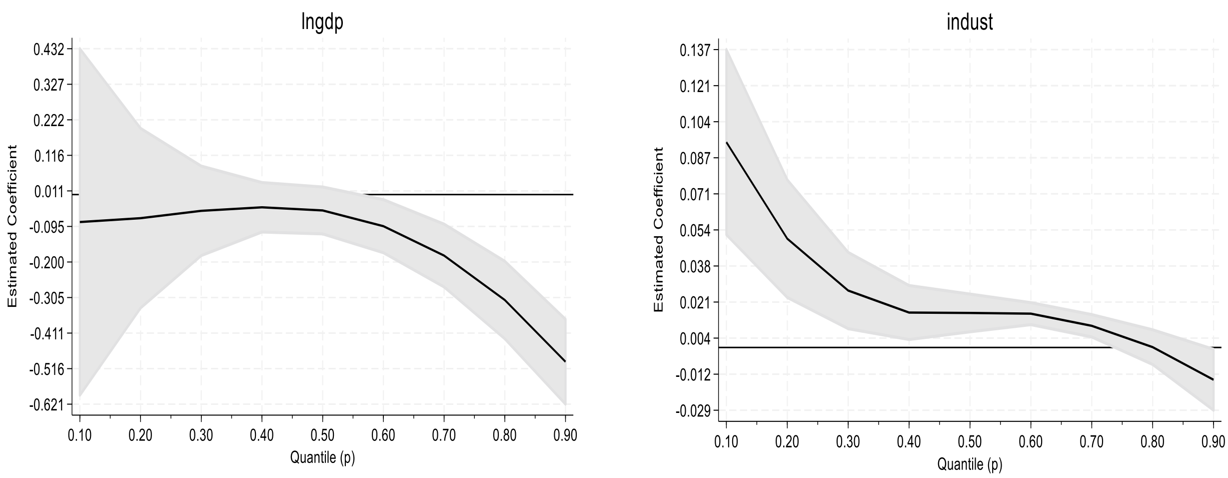

Figure 7. shows the quantile graph of the potential growth channel on CO_2.

List of countries

Angola, Botswana, Burkina Faso, Burundi, Cape Verde, Dem. Rep. of Congo, Cote d'Ivoire, Ethiopia, Ghana, Kenya, Madagascar, Mauritius, Mozambique, Namibia, Nigeria, Rwanda, Sao Tome and Principe, Seychelles, South Africa, Sudan, Tanzania, Uganda, Zambia, Zimbabwe.