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Renewable energy and economic performance in developing countries: The role of climate change

Énergies renouvelables et performance économique dans les pays en développement : le rôle du changement climatique

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Abstract

The objective of this paper is to explore the extent to which climate change influences the relationship between renewable energy consumption and economic performance in 84 developing countries from 1990 to 2018. Using fixed-effects models with Driscoll-Kraay residual adjustment, system GMM and Pooled OLS for analysis and robustness checks, the results show a significant U-shaped relationship between renewable energy consumption and economic performance. Below a threshold of 97% of total energy consumption, an increase in renewable energy is associated with a decline in economic performance, whereas above this threshold, it contributes to its improvement. When climate change interacts with renewable energy, this threshold drops to 74%, suggesting that an energy mix combining renewable and non-renewable sources leads to faster gains in economic performance. These results support energy transition policies aimed at reducing the effects of climate change whilst stimulating economic growth in developing countries.

Keywords: Economic performance; Renewable energy; Climate change; Driscol-Kraay, System GMM.

Résumé

L'objectif de cet article est d'examiner dans quelle mesure le changement climatique influence la relation entre la consommation d'énergies renouvelables et la performance économique dans 84 pays en développement de 1990-2018. À l'aide du modèle à effets fixes avec ajustement des résidus de Driscoll-Kraay, GMM en système et moindres carrés groupés pour les tests de robustesse, les résultats mettent en évidence une relation significative en forme de U entre la consommation d'énergies renouvelables et la performance économique. En dessous d'un seuil de 97 % de la consommation totale d'énergie, une hausse des énergies renouvelables est associée à une baisse de la performance économique, tandis qu'au-delà de ce seuil, elle contribue à son amélioration. Lorsque le changement climatique interagit avec les énergies renouvelables, ce seuil baisse à 74 %, suggérant qu'un mix énergétique combinant sources renouvelables et non renouvelables favorise plus rapidement les gains de performance économique. Ces résultats soutiennent les politiques de transition énergétique visant à réduire les effets du changement climatique tout en stimulant la croissance économique dans les pays en développement.

Mots clés: Performance économique; énergie renouvelable; changement climatique; Driscoll-Kraay ; GMM en système.

Introduction

The issues of global warming and the energy transition are at the heart of scientific and political concerns in this century. It is widely accepted that the use of fossil fuels is the main cause of the greenhouse gas emissions responsible for global warming. The consequences of CO_2 emissions on economic growth, health, investment and migration, amongst other things, require global action to address them. The measures undertaken aim to reduce CO2 emissions whilst improving environmental quality. Among the solutions identified to reduce CO2 emissions is the use of renewable energy (see Lei et al.,2022; Balsalobre-Lorente et al., 2023a; Zuhal & Göcen, 2025). The multilateral approach to combating climate change, from the Kyoto Protocol to the Paris Agreement, has resulted in very little real commitment, yet CO2 emissions continue to degrade our shared environment. The World Bank report (2007) highlights that CO2 emissions are the primary driver of climate change, accounting for 58.8% of greenhouse gas emissions.

Asumadu-Sarkodie & Owusu (2016) argue that due to the pace of economic growth in some developing countries, the majority of CO2 emissions will emanate from these countries. It therefore becomes necessary to take into account emissions that already cause health problems, migration, and sometimes social tensions. In the literature, studies have examined the effects of renewable energy consumption on economic performance (Sadorsky, 2009; Apergis and Payne, 2011; Menya & Wolde-Rufael, 2010; Tiwari, 2011, and Baek, 2016). Most of these studies generate mixed and non-conclusive results. These studies have also based their analysis on a linear model, whereas Yao et al. (2024) suggest that the relationship between renewable energy and economic performance may be non-linear (quadratic). A second group of authors establishes the link between CO_2 emissions and economic performance; among these authors are Kaika & Zervas (2013), Jebli et al., (2016), Lopez-Menendez et al. (2014), and Bölük & Mert (2015). These authors based their analysis on the inverted U-shaped relationship proposed by Kuznets (1955) and generalised by Grossman and Krueger (1991, 1995). Most of these studies also reach mixed conclusions.

More recently, studies have also focused on a new approach based on the Kuznets environmental curve: the renewable energy Kuznets curve model (Yao et al., 2024). According to this approach, the decline in environmental quality at the start of economic performance could be attributed to a low level of renewable energy consumption (the downward phase of the curve). Subsequently, following an increase in renewable energy consumption, environmental quality improves (the upward phase of the curve) as does

economic performance. This argument points to a U-shaped relationship between renewable energy consumption and economic performance (Nabaweesi et al.,2024 et Pata et al., 2025). Although the renewable energy Kuznets curve (REKC) hypothesis has been tested bilaterally in some studies, it remains a novel approach that has been scarcely explored in the literature covering a large sample of developing countries.

At a time when environmental sustainability, climate resilience, and the transition to cleaner energy systems have become central policy concerns, a more comprehensive analysis is required. This underscores the importance of investigating the contribution of renewable energy consumption to economic performance, as well as assessing how the interaction between carbon dioxide (CO_2) emissions and renewable energy influences economic outcomes in developing countries. Such an approach can provide valuable insights into the pursuit of sustainable development and the design of effective energy and environmental policies. This paper, therefore, seeks to fill this gap by analyzing the direct and indirect (via climate change) impacts of renewable energy consumption on economic performance. The rest of the paper presents a literature review, methodology, and finally, sections four and five present the economic policy implications and the conclusion, respectively.

1. Literature review

The literature on the relationship between energy use and economic growth has generally been organized around four major hypotheses: the growth hypothesis, the conservation hypothesis, the neutrality hypothesis, and the feedback hypothesis. Collectively, these perspectives suggest that inadequate energy consumption often reflects low levels of economic development and may constrain productivity, industrial expansion, and overall economic progress.

Despite their contributions, many of these studies treat energy consumption as a homogeneous input and pay limited attention to the specific sources from which energy is generated. Consequently, they often overlook the distinct role that renewable energy can play in shaping economic outcomes. This omission is particularly important given the growing significance of renewable energy in both developed and developing economies. By failing to differentiate between renewable and non-renewable energy sources, previous research may provide an incomplete understanding of the energy–growth nexus.

The issue of environmental sustainability, energy transition, and therefore sustainable development is at the heart of contemporary discussions. Hence the need to examine the link between renewable energy and economic performance, on the one hand, and the interaction

between CO2 emissions and renewable energy on the economic performance of developing countries, on the other.

In this context, Rafindadi & Ozturk (2017) conducted their study on the relationship between renewable energy consumption and economic development in Germany. The method used was ARDL and VECM (Vector Error Correction) and structural break in the unit root test on quarterly data from Q1 1970 to Q4 2013 and on the variables GDP per capita, renewable energy consumption per capita, real capital per capita and labor per capita. They found that in the long run with the ARDL method, a 1% increase in renewable energy consumption increases economic development by 0.2194%. They also had the same positive results with the VECM method, but with different coefficients. Similarly, the result of causality was the same (positive), so they concluded the presence of a bidirectional relationship between GDP and renewable energy consumption.

The research of Jebli & Youssef (2015) on the relationship between renewable and non-renewable electrical energy and international trade for a panel of 69 countries by deploying the panel cointegration method and Granger causality on the variables of GDP, total renewable and non-renewable electrical energy, export and import, capital stock (gross fixed capital formation) and labor, the study period was from 1980 to 2010, results in an absence of causal relationship between GDP and consumption of renewable electrical energy in the short term. On the other hand, in the long term, they note a bidirectional causality between these two variables. Chang et al., (2015), for their part, used the panel method with a heterogeneous model and Granger causality to study the relationship between renewable energy and economic development for the seven G7 countries over a period from 1990 to 2011. The authors found a unidirectional relationship from renewable energy consumption to GDP.

For Inglesi-Lotz (2016), who examined the link between renewable energy consumption and economic development for the case of 34 OECD countries over the period 1990-2010, using the variables GDP, GDP per capita, total renewable energy consumption, the share of renewable energy in total energy consumption, gross capital formation, labor, and research and development (R&D) expenditures, the author used a Cobb-Douglas production model and arrived at the following results: a long-term equilibrium relationship between the variables. The author also found that a 1% increase in renewable energy consumption will increase GDP by 0.105% and GDP per capita by 0.1%. However, a 1% increase in the share of renewable energy in total energy consumption will increase GDP by 0.089% and GDP per capita by 0.09%.

Kahia et al. (2016) analyzed the influence of renewable and non-renewable energy on economic development for two groups of MENA countries over the period 1980–2012. The first group consisted of 13 countries, and the second group of five countries that use renewable energy in their energy production cycle. The authors apply the FMOLS (panel cointegration) method, Granger causality, and the pair-wise correlation model to the variables of GDP, consumption of renewable and non-renewable electricity, gross fixed capital formation, and labor. They conclude that there is a cointegration relationship for both groups of MENA countries. In the long run, they find for both groups of countries together (the entire panel) that a 1% increase in renewable energy consumption will increase GDP by 0.058%. Also, they observe a bidirectional causality between GDP and renewable energy for the case of the second group (i.e., the group of 5 MENA countries).

Amri (2017a), studies the economic development factor (GDP), renewable energy consumption, capital stock, labor and trade factor for the case of 72 developed and emerging countries over the study period 1990-2012. He uses the two-stage generalized method of moments (GMM) and concludes a bidirectional relationship between income or GDP and renewable energy consumption. Armeanu et al., (2017) tested the hypothesis that renewable energy can contribute to achieving sustainable economic development. A study based on 28 European countries and the authors used the panel cointegration method and Granger causality on data from 2003 to 2014. The variables retained in the analysis are GDP per capita, renewable energy production and its forms (hydroelectricity, wind, geothermal, etc.), energy dependence (countries that depend on energy imports), greenhouse gas emissions, nitrogen gas emissions, research and development (R&D) expenditures and labor. They concluded the existence of a positive influence of renewable energy on economic development and also a unidirectional relationship from GDP to renewable energy production.

However, it is noted that renewable energies do not only have a strictly positive relationship with economic performance. Indeed, the existence of factors such as the production cost of these types of energies can lead to a lack of significant or even negative relationship with economic activity. In this perspective, we can note the work of Bhattacharya et al. (2016) who, by conducting the study on the contribution of renewable energies in the process of economic development for 38 countries over the period 1991-2012 and using the panel cointegration method (FMOLS and DOLS) and heterogeneous causality on the variables of GDP, gross fixed capital formation, labor, consumption of renewable and non-renewable

energies, they conclude that in the long term renewable energies must be included in the energy production cycle to secure the factor of sustainable development and the stability of economic development overall. Then, by analyzing the causality between the GDP variable and renewable energy, they found, firstly, a positive relationship for the case of countries such as Austria, Bulgaria, Canada, Chile, China, the Czech Republic, Denmark, Finland, France, Germany, Greece, Italy, Kenya, South Korea, Morocco, the Netherlands, Norway, Peru, Poland, Portugal, Romania, Spain and Great Britain. On the other hand, secondly, for the case of India, Ukraine and the USA, they found that there was a negative relationship between GDP and renewable energy consumption.

Lekana (2019), focused on CEMAC countries for the period 1990 and 2015 and used three error correction models in panel data (MG PMG and DFE) and two causality approaches (Engel and Granger causality and Dumitrescu and Hurlin causality). The results showed that the consumption of renewable energy has a positive long-term effect, but a negative short-term effect on the economic growth of these countries. Similarly, Biloa el al. (2019), studied the link between the consumption of renewable energy and well-being (GDP/capita) in French-speaking countries. By mobilizing a dynamic model (FMOLS, DOLS), the authors conclude that there is an overall negative relationship in the area studied over the period 1991-2015.

Wang et al. (2023) explored the impact of the digital economy on carbon emissions and renewable energy development using panel data for 67 countries from 2005–2019. Their results show that there is an inverted U-shaped relationship between the digital economy and carbon emissions, which is consistent with the Environmental Kuznets Curve (EKC) hypothesis, and a U-shaped relationship with renewable energy consumption, which is consistent with the Renewable energy Kuznets Curve (REKC) hypothesis.

Nabaweesi et al. (2024) studied the validity of the modern renewable energy-environmental Kuznets curve (REKC) while considering the relevance of financial development in the consumption of modern renewable energy in East Africa Community (EAC) from 1996 to 2019, and employing the ARDL-PMG, they find that the REKC hypothesis is supported for modern renewable energy consumption in the EAC region.

Yao et al. (2024), drawing on the Kuznets environmental curve, examined the U-shaped relationship between renewable energy use and economic growth. Using two panel datasets covering 17 major developing and developed countries, as well as six geo-economic regions

of the world from 1990 to 2014, and employing a dynamic model (FMOLS, DOLS), they conclude that the renewable energy Kuznets curve (REKC) exists.

Pata et al. (2025) examine the renewable energy Kuznets curve (REKC) and the environmental Kuznets curve (EKC) in the United States, using time series based on the Fourier method from 1973 to 2022. The authors find a U-shaped relationship between renewable energy and economic performance, as well as evidence for the existence of the environmental Kuznets curve.

The REKC U-shaped relationship between renewable energy consumption and the economic performance is based on the hythesis that there is a negative relationship between economic growth and renewable energy consumption in the early phases of development. This is because during this developmental stage, the expense associated with the consumption of renewable energy sources (photovoltaic, wind power, hydropower, etc.) exceeds that of fossil fuels. As economies continue to expand and approach a specific economic performance threshold, the costs associated with renewable energy sources begin to decrease (Gielen et al. (2019). At this point, countries tend to increase their consumption of renewable energy to cut carbon emissions and enhance environmental sustainability.

It should be noted that, although some studies highlight the absence of a link or a negative link between renewable energy and economic performance, the majority of the studies reviewed suggest that the expansion of renewable energy not only improves countries' economic performance but also helps to slow down environmental degradation.

Regarding the link between CO2 emissions and economic activity, particularly the environmental Kuznets curve, extensive studies have been conducted. Some of them confirm the existence of the inverted U-shaped relationship between income and environmental degradation, while others find no such relationship. Among these studies, we note Lazăr et al. (2019), who examined the relationship between pollution and growth in eleven Central and Eastern European (CEE) countries. The results reveal a growing nonlinear link between GDP and CO2 overall in these countries. However, at the disaggregated level of each country, the relationship between GDP and CO2 is characterized by great diversity, namely: N, inverted N, U, inverted U, monotonic or no statistical relationship. Thus, despite an overall upward trend, some countries in the studied group managed to achieve both higher GDP and lower CO2 emissions. The authors conclude that, from a political perspective, EU decision-makers could pay more attention to these countries and modify the current single environmental

policy to take into account national heterogeneities in order to support economic growth without harming the environment.

It is evident from this non-exhaustive review of the literature that most of these studies do not highlight the impact that interactions between renewable energy and CO_2 emissions may have on economic performance. Furthermore, it is noted that there is a lack of research in the literature on the renewable energy Kuznets curve (REKC) and the indirect impact of renewable energy on economic performance via climate change. It is against this backdrop that this study aims to make a contribution to the literature.

2. Data and model specification

2.1. Data

The study covers 84 developing countries from 1990 to 2018. Data are limited due to the absence of certain data for certain countries and at certain dates. All data used are secondary data from the World Development Indicator (WDI).

The main variables used in this study are gross domestic product per capita in current US dollars as a proxy for economic performance, renewable energy consumption as a percentage of total energy consumption, and carbon dioxide emissions (in metric tons) per capita. Variables such as foreign direct investment (FDI), trade openness, and traditional factors of production (capital and labor) are then deployed to control for omitted variable bias. All variables are expressed in natural logarithms.

2.2. Model specification

Based on the KLEM (Capital, Labor, Energy, and Material) production function model of Stern and Cleveland (2004) and Lee & Chang (2008), we write the equation:

$$Y = F(K, L, E) = L^{\alpha} K^{\beta} RE^{\gamma} \quad (1)$$

Where α is the elasticity of output with respect to labor, β the elasticity of output with respect to capital, and γ is the externality related to the use of renewable energy.

Writing equation (1) in terms of growth rates, we obtain equation (2):

$$\frac{\Delta Y}{Y} = \alpha \frac{\Delta L}{L} + \beta \frac{\Delta K}{K} + \gamma \frac{\Delta RE}{RE} \quad (2)$$

Equation (1) did not incorporate the effects of CO2 emissions on economic growth. And if we agree with the International Panel on Climate Change (IPCC, 2016), climate change will affect countries regardless of their CO2 emission levels. Indeed, the economic performance of developing countries relies on climate-dependent sectors (agriculture, forestry, fishing, and tourism, etc.).

To incorporate this hypothesis of the impact of climate change and CO2 emissions on economic performance, we agree with Dell et al. (2008), who argue that climate change directly and negatively affects factor productivity but also indirectly and negatively impacts agriculture. Economic theory therefore accepts that climate change (rising temperatures, irregular rainfall, insufficient rainfall) reduces the yield of the agricultural sector due to the decline in water availability caused by rising temperatures, the uncertain or shortened length of the growing season, the reduction in arable land, etc. (see Bsais & Mokaddem, 2019). It can therefore be expected that climate change (CO2) will have a negative impact on the yield of the agricultural sector and, consequently, on economic performance.

To incorporate the hypothesis that climate change affects the economic growth of a developing country, the following equation is used:

$$Y = F(K, L, E) = e^{\varphi CO2} L^{\alpha} K^{\beta} RE^{\gamma} \quad (3)$$

With $\gamma = \rho_1 + \rho_2 CO2$ (4)

Where φ measures the direct effect of CO2 on economic performance. φ <0 means that CO2 emissions by negatively affecting total factor productivity have a negative effect on economic performance (Dell et al. 2008).

ρ1 represents the contribution of renewable energy to economic growth in the absence of climate change. This is the hypothetical ideal world, the zero-carbon world.

ρ1 > 0, ρ1 < 0, all other things being equal, the use of renewable energy can have positive or negative effects on economic activity.

ρ2 represents the share of CO2 emissions interacting with renewable energy. By hypothesis, ρ2 > 0. This means that in the presence of renewable energy, the negative effect of CO2 is absorbed and induces a positive effect on overall output.

By introducing (4) into (3), then converting the resulting equation into a growth rate, we obtain:

$$\frac{\Delta Y}{Y} = \alpha \frac{\Delta L}{L} + \beta \frac{\Delta K}{K} + \varphi CO2 + \rho_1 \frac{\Delta RE}{RE} + \rho_2 \frac{\Delta RE}{RE} * CO2 \quad (5)$$

This theoretical perspective allows us to account for the importance of renewable energy in the energy mix. Indeed, fossil fuel use cannot be stopped abruptly for fear of plunging the global economy into an energy crisis. However, it is possible to gradually move towards clean energy, hence the central issue of the energy transition is of particular interest in current debates.

The direct effect of renewable energy consumption on economic performance can be expressed, allowing for the nature of the relationship, as equation 6:

$$\text{LogGDP}_{it} = \varphi_0 + \theta_i + \delta_t + \varphi_1 \text{LogREC}_{it} + \varphi_2 \text{LogREC}^2{}_{it} + \beta_k Z_{itk} + \mu_{it} \quad (6)$$

Where $LogGDP_{it}$ represents the logarithm of GDP per capita of countries i in period t, $LogREC_{it}$ *et* $LogREC^2{}_{it}$ represent the renewable energies consumption and the renewable energies consumption squared taken in logarithm, respectively; $\beta_k Z_{itk}$ the vector of other explanatory variables.

The Total effect of renewable energy consumption on economic performance, which is the direct effect plus the indirect effect via climate change can be expressed as equation 7.

$$\text{LogGDP}_{it} = \alpha_0 + \theta_i + \delta_t + \alpha_1 \text{LogREC}_{it} + \alpha_2 \text{LogREC}^2{}_{it} + \alpha_3 \text{LogCO2}_{it} + \alpha_4 \text{REC} * \text{CO2}_{it} + \alpha_5 \text{REC}^2 * \text{CO2}_{it} + \beta_1 \text{LogGFCF}_{it} + \beta_2 \text{LogEmpl}_{it} + \beta_3 \text{LogTrade}_{it} + \beta_4 \text{LogFDI}_{it} + \mu_{it} \quad (7)$$

Where i= 1, 2, 3,….,84 and t= 1, 2, 3, …, 29 , $LogCO2_{it}$ is the logarithm of CO2 emissions, and GFCF_{it} , Empl_{it}, Trade_{it} and FDI_{it} are respectively gross fixed capital formation (investment), employment, trade openness and foreign direct investment in logarithm. α_0, α_o, … α_5 and $\beta_1, \ldots, \beta_4$ and are parameters to be estimated; θ, the country-specific effect; δ, the time-specific effect and μ_{it} the error term.

3. Result and discussion

Table 1: Descriptive statistics

Variable	Obs	Mean	Std. Dev.	Min	Max
lnGDP	2,421	7.152973	1.047291	3.126556	9.491422
lnREC	2,435	3.296695	1.518262	-6.33991	4.58846
lnREC_SQ	2,435	13.17237	6.626137	2.51E-05	40.19445
lnCO2	2,435	-0.25585	1.39623	-4.11581	2.585536
lnEMPLOY	2,352	4.039765	0.229784	3.421327	4.505239
lnINVEST	2,392	3.06643	0.438942	-1.22803	4.374512
lnFDI	2,206	0.494844	1.556437	-13.1213	4.008611
lnTRADE	2,403	4.12017	0.553338	-3.86327	5.339011
lnREC_CO2	2,435	-2.31393	5.12242	-18.8852	6.582564
lnREC²_CO2	2,435	-10.5116	22.20152	-86.6542	81.92755

Source : Computed by the authors

Table 1 shows that the logarithm of renewable energy consumption (REC) as a percentage of total energy consumption reached a peak of 4.58. This corresponds to the consumption of the Democratic Republic of the Congo in 2001, and the minimum value of almost zero, -6.15 (0.002), was recorded in 1997 by Turkmenistan, whilst the average REC over the study period was 3.32. This indicates a fairly significant disparity in the consumption of this type of energy in developing countries. Indeed, some countries make only limited use of this energy for

several reasons, notably the difficulty of access in terms of technology, but also a lack of political will in certain countries, as noted by the United Nations Environment Programme (UNEP, 2013)..

To avoid the possibility of multicollinearity, a correlation test (correlation matrix) is performed. The importance of the correlation matrix is that it allows us to assess the strength of the relationship between the variables in the model. The observation of the correlation matrix in Table A1 in the appendix shows significant correlations between the endogenous variable and the explanatory variables, whether they are positive or negative. We also note a weak (or absent) correlation between the explanatory variables, which allows us to suspect the absence of a possible multi-collinearity problem.

The Pesaran test of cross-sectional independence in Appendix Table A2 indicates the existence of cross-sectional dependence. The results of the Wald test for GroupWise heteroscedasticity in the fixed-effects regression model indicate that the model suffers from heteroscedasticity.

The results of the Wooldridge autocorrelation test on panel data indicate the existence of serial autocorrelation of errors. Finally, based on the tests performed, regression with Driscoll-Kraay standard errors should be performed. Indeed, Driscoll and Kraay (1998) propose "a nonparametric covariance matrix estimator that produces heteroscedasticity-consistent standard errors that are robust to very general forms of spatial and temporal dependence" (Hoechle, 2007). Although the estimation procedure is initially based on a large T assumption, Driscoll & Kraay (1998) demonstrate that the estimator is consistent even for very short time dimensions. Furthermore, it has been shown that for models in which the cross-sectional dimension is relatively larger than the time dimension, this approach is more appropriate than alternative approaches (Zhang and Lin, 2012). Therefore, the following section presents the results of the estimates using Driscoll-Kraay standard errors, and estimates using two-stage GMMs will be carried out to test robustness.

We present the empirical results of the analysis of the direct effects of renewable energy consumption on economic performance in Table 2 and the direct + indirect effects in Table 3.

Table 2. Estimates of the effect of REC on economic performance in Developing countries

Dep var Log GDP	2SGMM Model 1	Fixed Effect Model 2	Driscoll-Kraay Modèle 3
Log GDP per capita (-1)	0.699***		
	(0.0425)		
Log REC	-0.156**	-0.174***	-0.174***
	(0.00783)	(0.0427)	(0.0358)
REC^2	0.0793**	0.0894***	0.0894***
	(0.00361)	(0.00713)	(0.00622)
Log Invest	0.0509*	0.265***	0.265***
	(0.0260)	(0.0389)	(0.0705)
Log Employment	0.0242	2.306***	2.306***
	(0.0395)	(0.271)	(0.140)
Log FDI	0.00192	0.0904***	0.0904***
	(0.0172)	(0.00939)	(0.0200)
Log Trade	0.0561**	0.251***	0.251***
	(0.0239)	(0.0453)	(0.0645)
Constant	-0.0857	16.37***	16.37***
	(0.416)	(1.142)	(0.635)
Observations	1,942	2,094	2,094
Threshold	0.983	0.973	0.973

Source : Computed by the authors

Note : Standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1 pour 1%, 5% et 10% levels of signifiance, respectively.

$\frac{dGDP}{dREC}$= -0.174+2(0.0894)REC=0

$\Longrightarrow$ 0.1788REC=0.174 thus REC=**0.973** for Driscoll-Kraay and Fixed Effect estimates.

$\frac{dGDP}{dREC}$= -0.156+2(0.0783)REC=0

$\Longrightarrow$ 0.1586REC=0.156 thus REC=**0.983** for two step system GMM.

Table 2 initially shows that all the estimation techniques used, renewable energy consumption (REC) negatively and significantly affects economic performance in developing countries. However, as the REC increases, its impact becomes positive and significant so that there is a U-shaped relationship between these two variables. Indeed, this indicates that the relationship between these two variables is non-linear in developing countries constituting this panel. Here we show the renewable energy Kuznets curve (REKC), in line with the pioneering work of Yao et al. (2024) and Pata et al. (2025).

Table 3: Estimates of the influence of climate change on the nexus between REC and economic performance in Developing countries

Dep var : Log PIB/hbt VARIABLES	Model 1	Model 2	Interaction 1 Model 3	Interaction 2 Model 4	Model 5 Driscoll-Kraay	Model 6 FE	Model 7 POLS
Log REC	-0.234***	-0.159***	-0.0871	-0.533***	-0.524***	-0.524***	-0.286*
	(0.0650)	(0.0501)	(0.102)	(0.101)	(0.120)	(0.130)	(0.0922)
Log REC^2	0.205***	0.321***	0.0304***	0.118***	0.0802***	0.0802***	0.0580*
	(0.0195)	(0.0102)	(0.0105)	(0.0161)	(0.0205)	(0.0230)	(0.0160)
Log CO2 per capita		-1.021***	-0.809**	-0.989***	-1.219***	-1.219***	-0.0971
		(0.132)	(0.335)	(0.306)	(0.114)	(0.135)	(0.0900)
Log (REC * CO2)			0.0506**	0.215*	0.183**	0.183**	0.0956*
			(0.0507)	(0.0540)	(0.0748)	(0.0762)	(0.0510)
Log (REC^2 * CO2)				0.0478***	0.0484***	0.0484***	0.0189**
				(0.00656)	(0.0103)	(0.0132)	(0.00856)
Log Invest					0.156**	0.156***	0.161***
					(0.0571)	(0.0355)	(0.0416)
Log Employment					1.209**	1.209***	-0.277
					(0.491)	(0.253)	(0.0786)
Log Trade					0.169***	0.169***	-0.0416
					(0.209)	(0.0409)	(0.0691)
Log FDI					0.0675***	0.0675***	0.0643***
					(0.0148)	(0.00857)	(0.0106)
Constant	9.309***	7.322***	7.598***	7.213***	10.30***	10.30***	8.120***
	(0.360)	(0.166)	(0.309)	(0.253)	(1.252)	(1.072)	(0.523)
Observations	2,420	2,420	2,420	2,420	2,094	2,094	2,094
R-squared						0.402	0.620
Number of groups	84	84	84	84	83	83	83
Threshold	0.570	0.247	0.11	0.49	0.741	0.741	0.760

Source: Computed by the authors

Notes : Standard errors in parentheses *** p<0.01, ** p<0.05, * p<0.1 for 1%, 5% and 10% levels of significance, respectively.

$\frac{dGDP}{dREC}$= -0.524+2(0.0802)REC+0.183$\overline{CO_2}$+2(0.0484)REC*$\overline{CO_2}$ =0

$\Longrightarrow$-0.524+0.1604REC+0.29097+0.1539REC=0

$\Longrightarrow$ 0.3143REC=(0.533-0.291) et REC=**0.741**

Table 3 highlights the various interactions between the effects of renewable energy use and carbon dioxide emissions on the economic performance of developing countries across five (5) models using the Driscoll-Kraay approach and Pooled Least Squares (POLS) to test the robustness of the overall results.

The POLS estimation shows a satisfactory R2 of 0.62, meaning that 62% of the variability in the dependent variable is explained by the variables included in this model.

Regarding the individual significance of the variables, the variable of interest (renewable energy consumption) is statistically significant across all three (3) models estimated at the 1% and 5% level of significance. The coefficients associated with REC across the different models are initially negative and then positive when REC is squared, suggesting that high levels of renewable energy consumption significantly improve economic performance. However, the effect is not immediate; there is a threshold beyond which any increase in REC induces an upward variation in economic performance. This result suggests a U-shaped relationship. Thus, a 1% increase in REC leads, all other things being equal, to a 0.52% decrease in economic performance at the 1% threshold (Model 5). Then, as the level of renewable energy use increases (REC squared), a 1% increase in REC induces a 0.08% increase in economic performance. The relationship is therefore non-linear; a U-shaped curve is obtained. Such a result can be explained in the sense that the cost of access to renewable energy technologies is high, as highlighted by AfDB (2016), particularly for developing countries in sub-Saharan Africa. Similarly, it is noted that this energy is not intensively used in industries that remain dependent on fossil fuels in most developing countries. Furthermore, this relationship can be explained by the low level of REC in some countries of the group, but also by the importance of the industrial sector which has been driven for a long time by fossil fuels (hence the relatively high average level of carbon dioxide emissions). However, this trend is reversed in the subsequently as more renewable energy is used. It seems that in the short term the average level of REC as a percentage of total energy consumption is not sufficient to increase GDP per capita in this group of developing countries which include some African countries.

In recent years, there has been a certain popularization and reduction in the costs of using renewable energies. If these trends continue, the positive impact on the economic

performance of developing countries seems certain, as implied by these results. Regarding climate change, its effect on performance remains negative and significant at the 1% level. However, the significance is not robust. Although the effect is negative, when changing the estimation technique, it is not significant. However, this suggests that the use of fossil fuels is not always good for economic performance at all times and in all places.

We also note that the interaction between renewable energy and CO2 emissions (REC*CO2) has a positive and significant effect at the 5% level of significance on the economic performance of developing countries. A 1% increase in this interaction leads to a 0.05% improvement in economic performance (Model 6), and this trend is robust (Model 7). Continuing the analysis of the effects of the interactions between renewable energy and REC, we observe that a higher level of renewable energy use leads to carbon dioxide emissions (REC2*CO2), all other things being equal; this interaction has a positive and significant impact on economic performance. This highlights the critical importance of the use of renewable energy as an important factor in mitigating the negative impact of carbon emissions, but also as a lever that decision-makers can use to improve economic performance and pursue sustainable development.

The indirect effect of renewable energy consumption on economic performance is transmitted through carbon dioxide emissions. From Model 5, we can calculate the overall threshold (direct + indirect) of renewable energy consumption beyond which additional units are associated with improvements in economic performance (Model 5 or Model 6 of Table 3).

Furthermore, using either the fixed effects or Driscoll-Kraay residual adjustment technique, we find a U-shaped relationship between renewable energy consumption and economic performance—an indication that levels below 97% of total energy consumption are associated with lower economic performance, while levels above this threshold are associated with improved economic performance (see Table 2). More importantly, we observe that the overall (direct + indirect) threshold of renewable energy consumption beyond which additional units are associated with improved economic performance is 74% of total energy consumption. This is evidence that accounting for both renewable energy consumption and climate change in a growth-generating function reduces the threshold above which renewable energy consumption leads to improvements in economic performance (Table 3).

The estimated thresholds of 97% and 74% may appear high given the level of development in African and Asian countries. However, the WDI total renewable energy consumption

indicator used in this paper includes biomass, which accounts for between 60% and 85% of energy consumption in most low-income African and Asian countries (IEA, 2022).

Consequently, these figures can be interpreted as a structural transformation point rather than merely an observed average level. Indeed, during the initial phases of the energy transition, developing countries incur significant costs related to infrastructure investment, technology, energy storage, and grid reinforcement. From this perspective, these costs may initially outweigh economic benefits, explaining the negative impact of renewable energy on economic performance below the threshold. Conversely, once renewable energy becomes the dominant force in the energy mix, economies of scale, efficiency gains, and reduced reliance on fossil fuels offset initial costs and generate positive effects on economic performance. Thus, the 97% threshold reflects a tipping point where the net benefits of the energy transition surpass implementation costs, this finding consistent with the work of Wang et al. (2023) and Nabaweesi et al. (2024).

In a nutshell, these results suggest that the use of renewable energy (hydroelectricity, solar, wind, biomass, etc.) leads to positive effects on economic activity depending on the threshold level in the total energy consumption spectrum. In other words, the consumption of renewable energy above a certain level contributes to increasing the wealth of developing countries. This result is consistent with the work of Inglesi-Lotz (2016) and Lekena (2019), and Armeanu et al. (2017) on Europe and Kahia et al. (2017) on the MENA region. It is also consistent with the findings of the work of Muhammad et al. (2015) in Pakistan, Rafindadi & Ozturk (2017) in Germany, as well as Amri (2017a), Armeanu et al. (2017), Raihan and Tuspekova (2022) in Peru, and more recently the work of Pata et al. (2025) in the United States.

Regarding the control variables, we note that overall, their signs on economic performance are generally satisfactory and in line with theoretical expectations. Indeed, traditional production factors (capital and labor) are expected to have a positive and significant impact on economic performance. Similarly, trade openness and foreign direct investment have a positive and significant impact on economic performance at the 1% level of significance. This implies that openness to international trade and investment attraction policies should be promoted in development strategies. The employment variable, for its part, is statistically insignificant during the period and in this group of countries.

Robustness check

To test the robustness of the empirical results presented below, we estimate the models for three regional groups of developing countries: Africa, Central and Latin America, and Asia-

Pacific. Tables 4 and 5 below show, respectively, the direct effect (the non-linear relationship between renewable energy and economic performance) and the indirect effect of renewable energy on performance via climate change.

Table 4: Estimates of the effect of REC on economic performance of three regions

Dep variable : log GDP	Africa		Asia-Pacific		Central and latin America	
VARIABLES	GMM	Driscoll/Kraay	GMM	Driscoll/Kraay	GMM	Driscoll/Kraay
Log GDP per capita (-1)	0.649***		0.516***		0.549***	
	(0.0255)		(0.0296)		(0.0613)	
Log REC	-0.2115**	-0.2542***	-0.0221**	-0.094**	0.519*	0.531**
	(0.0138)	(0.0963)	(0.0883)	(0.117)	(0.308)	(0.518)
$LogREC^2$	0.1126**	0.1378***	0.0452**	0.0914***	-0.282*	-0.291***
	(0.00315)	(0.0192)	(0.00340)	(0.0226)	(0.0469)	(0.0893)
Log Invest	-0.0400	0.141*	-0.0754*	0.037***	0.147	0.365***
	(0.0264)	(0.0740)	(0.0399)	(0.0638)	(0.129)	(0.122)
Log Employment	0.0165	0.218**	0.112	0.043***	0.0458	0.822***
	(0.0632)	(0.263)	(0.0871)	(0.813)	(0.330)	(0.616)
Log FDI	0.0550	-0.0398	0.0986	0.025***	0.0990	-0.204
	(0.0552)	(0.147)	(0.0686)	(0.186)	(0.0701)	(0.174)
Log Trade	0.0686**	0.0828***	-0.107***	0.103***	-0.154**	0.110**
	(0.0265)	(0.0201)	(0.0374)	(0.0167)	(0.0594)	(0.0525)
Constant	0.458	12.45***	-1.360**	11.17***	-2.100	-6.838***
	(0.472)	(1.504)	(0.536)	(4.236)	(1.654)	(2.467)
Observations	960	993	572	593	343	356
Number of id	39		24		15	
Number of groups		39		24		15
Number of instru.	14		6		4	
Prob Fisher	0.000					
Prob Hansen	0.59					
Prob AR (1)	0.015					
Prob AR (2)	0.582					
Threshold	0.94	0.92	0.244	0.514	0.92	0.91

Source: Computed by the authors

Note: Standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1 pour 1%, 5% et 10% levels of signifiance, respectively.

Note : Six (6) countries not belonging to the three groups are excluded from the sample.

Table 5: Estimates of the influence of climate change on the nexus between REC and economic performance in Developing countries

Dep. Variable : log GDP	Africa		Asia-Pacific		Central and latin America	
VARIABLES	Driscoll/Kraay	PLS	Driscoll/Kraay	PLS	Driscoll/Kraay	PLS
Log REC	-0.598***	-0.660**	-0.572***	-0.368	0.0608	0.085
	(0.251)	(0.132)	(0.154)	(0.133)	(0.864)	(0.922)
Log REC^2	0.105***	0.135***	0.0884**	0.0590**	-0.114	-0.790
	(0.0318)	(0.0219)	(0.0393)	(0.0267)	(0.118)	(0.130)
Log CO2 per capita	-0.324***	-0.166***	0.482***	0.252***	-0.111***	-0.343***
	(0.413)	(0.217)	(0.175)	(0.0931)	(1.017)	(1.221)
Log (REC * CO2)	0.0981***	0.0984***	0.282***	0.280**	0.013***	0.257
	(0.175)	(0.112)	(0.100)	(0.0684)	(0.474)	(0.700)
Log (REC^2 * CO2)	0.156***	0.1624***	0.0379**	0.0197	0.037***	0.585
	(0.0218)	(0.0145)	(0.0176)	(0.0134)	(0.0660)	(0.0995)
Log Invest	0.0706	0.147*	0.440**	0.566***	0.214	0.154
	(0.0599)	(0.0384)	(0.0576)	(0.108)	(0.174)	(0.127)
Log Employment	0.091***	0.518***	0.581***	0.430**	0.631***	0.272
	(0.256)	(0.102)	(0.546)	(0.179)	(0.403)	(0.352)
Log Trade	-0.221*	-0.136**	0.454**	0.290***	0.423***	0.291**
	(0.119)	(0.0519)	(0.178)	(0.103)	(0.0882)	(0.0500)
Log FDI	0.0556***	0.0435***	0.0592**	0.00846	0.0886**	0.0558**
	(0.0118)	(0.00821)	(0.0224)	(0.0303)	(0.0377)	(0.0281)
Constant	1.05***	6.629***	5.07*	5.907***	4.952**	5.10***
	(1.362)	(0.492)	(2.249)	(0.887)	(2.016)	(2.501)
Observations	993	993	593	593	356	356
R-squared		0.786		0.403		0.586
Number of id						
Number of groups	39		24		15	
Threshold	0.63	0.637	0.415	0.428	0.738	0.757

Source: Computed by the authors

Notes : Standard errors in parentheses *** p<0.01, ** p<0.05, * p<0.1 for 1%, 5% and 10% levels of significance, respectively.

An examination of the direct effect in Table 4 reveals a U-shaped relationship between renewable energy and economic performance, primarily in Africa and, to a lesser extent, in the Asia-Pacific region; this confirms the overall trend observed in Table 2. However, an inverted U-shaped relationship is observed for the Latin America and Central America group, highlighting the potential heterogeneity among country groupings. We also note that Africa exhibits the highest threshold (92%), largely due to the significant share of biomass in its renewable energy mix. The inverted U-shaped pattern in Central and Latin America with a threshold of 91% may indicate a point beyond which increased renewable energy consumption leads to a decline in economic performance; this could result from the crowding out of other productive investments and a reliance on imported renewable energy equipment. Furthermore, this non-linear relationship may be attributable to diminishing returns.

In Table 5, incorporating CO2 emissions into the model reveals a trend similar to that observed in the global model. The transition threshold drops to 63% for Africa and 41% for Asia and the Pacific. However, the threshold is not statistically significant for Latin America and the Pacific. This suggests that, for the first two country groups, an energy mix comprising an optimal combination of renewable and non-renewable sources lowers the threshold beyond which renewable energy yields positive effects on economic performance. These results also indicate that large-scale adoption of renewable energy can reduce CO2 emissions while simultaneously boosting the economic performance of these countries.

Overall, when the sample is divided into three regional groups (Africa, Asia-Pacific, and Latin and Central America), the first two groups confirm the initial finding regarding the direct and indirect effects of renewable energy on economic performance (a U-shaped relationship). However, the third group exhibits a non-linear relationship opposite to that of the first two (an inverted U-shape), thereby highlighting the heterogeneity that persists among the groups.

From a policy perspective, these findings suggest that both government authorities and private-sector stakeholders should prioritize strategies that promote an optimal balance of renewable energy within the overall energy mix. Achieving such a balance can enhance economic performance while safeguarding environmental quality, thereby supporting the broader goal of sustainable development pursued worldwide. It can also facilitate the transition toward cleaner and more sustainable energy systems, helping countries meet sustainable development objectives and expand access to reliable, affordable, and

environmentally friendly energy services in accordance with the commitments of the United Nations Framework Convention on Climate Change (UNFCCC).

To realize these objectives, policymakers can introduce measures aimed at lowering the cost of renewable energy technologies, including solar photovoltaic systems, hydropower facilities, wind energy installations, and advanced biomass technologies. In addition, governments and financial institutions can provide incentives and funding mechanisms to support renewable energy projects, particularly the deployment of solar energy infrastructure in both rural and urban communities. Furthermore, international cooperation should be strengthened to encourage the transfer of clean-energy technologies and technical expertise across countries. Such efforts are especially important for developing economies, particularly those in sub-Saharan Africa, where the acquisition and implementation costs of renewable energy technologies remain relatively high. By reducing these barriers, countries can accelerate the adoption of clean energy and achieve more inclusive and sustainable economic growth.

Conclusion

This study examined the extent to which climate change affects the relationship between renewable energy consumption and economic growth across 84 developing economies over the period 1990–2018. In particular, the research investigated the direct impact of renewable energy use on economic performance and its indirect influence through climate change dynamics. To achieve this objective, the analysis employed the Driscoll–Kraay fixed-effects estimator with robust standard errors, the System Generalized Method of Moments (System GMM), and the Pooled Ordinary Least Squares (Pooled OLS) approach.

The empirical findings revealed a statistically significant U-shaped association between renewable energy consumption and economic performance. Specifically, results from the Driscoll–Kraay estimator showed that when renewable energy accounts for less than 97% of total energy consumption, an increase in its use is linked to a decline in economic performance. However, once this threshold is exceeded, additional renewable energy consumption contributes positively to economic performance. Furthermore, incorporating climate change as an interaction factor with renewable energy consumption lowered the turning point to approximately 74% of total energy use. This suggests that a balanced combination of renewable and conventional energy sources can reduce the minimum level of renewable energy required to generate positive economic outcomes. The consistency of these

results across different estimation techniques underscores their robustness and supports policy frameworks that promote a diversified energy portfolio. Such policies can harness the environmental benefits of renewable energy, enhance climate change mitigation and adaptation efforts, curb global warming, and foster sustainable economic growth in developing countries.

ANNEXES

Table A1: Correlation matrix

	GDP	REC	REC Sq	CO2	Empl	Invest	FDI	Trade	REC*CO2	REC^2*CC
GDP	1.00									
REC	-0.371193	1.000000								
REC Sq	0.524763	0.836409	1.000000							
CO2	-0.734545	-0.701542	-0.794102	1.000000						
Empl	0.391647	0.441778	0.498275	-0.500760	1.000000					
Invest	0.324334	-0.221646	-0.232030	0.352169	-0.079346	1.000000				
FDI	0.281439	-0.059003	-0.135562	0.230229	-0.012443	0.232230	1.000000			
Trade	0.290826	-0.184901	-0.236192	0.341296	-0.153034	0.264815	0.387628	1.000000		
REC*CO2	0.763627	-0.422309	-0.562333	0.322477	-0.470183	0.337388	0.257752	0.350087	1.000000	
REC^2*CC	0.742487	-0.524215	-0.517894	0.437065	-0.481737	0.361900	0.257770	0.356399	0.357503	1.000000

Source : Computed by the authors

Table A2: Pesaran test of cross-sectional independence

Value	Probability
122.722	0.0000

Source : Computed by the authors

Table A3: Wald test for GroupWise heteroscedasticity

Value	Probability
15296.30	0.0000

Source : Computed by the authors

Table A4: Wooldridge test of serial autocorrelation on panel data

Value	Probability
137055.66	0.0000

Source : Computed by the authors

Table A5: VIF test

Variables	VIF	1/VIF
Log REC	3.62	0.28
Log CO2 per capita	3.21	0.31
Log Invest	2.29	0.44
Log Employment	2.67	0.37
Log Trade	2.18	0.46
Log FDI	1.92	0.52

Source : Computed by the authors

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