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The role of interaction effect between renewable energy consumption and real income in carbon emissions: Evidence from low-income countries

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ABSTRACT

Even though the existing studies have extensively investigated the impacts of renewable energy and real income on carbon emissions, the literature overlooks the role of their interaction effect in the level of emissions. In addition, the studies have usually chosen high-income and middle-income countries as focused group. To fill these gaps in the existing body of energy-environment literature, this study investigates the impacts of real income, renewable energy consumption and their interaction effect on carbon emissions in low-income countries by employing empirical estimations that control different econometric and economic issues such as heterogeneity and cross-sectional dependence. The results reveal that renewable energy mitigates emissions; however, the interaction effect stays positive. The marginal effect of renewable energy on emissions varies with the levels of real income. Policymakers in these economies should implement policies and regulations to promote the adoption and use of renewable energy to mitigate carbon emissions. Besides, this study emphasizes that the levels of renewable energy and real income are not the only panacea to abating pollution, but the interaction effect should be considered in ensuring environmental sustainability.

1. Introduction

The impacts of real income and renewable energy consumption (REN) on carbon emissions have attracted the attention of several researchers in the last decades [1]. Besides, empirical evidences show that REN lessens environmental pollution whereas non-renewable energy increases it [2–4]. However, some issues remained unresolved regarding the nexus between economic activities and environmental sustainability. First, "Can low-income countries (LICs) actually grow-out of pollution?" While this question has been extensively investigated for middle-income countries (MICs) and high-income countries (HICs), the empirical evidence remains scanty in LICs [5]. Our study fills this research gaps and makes contribution to the extant literature by unveiling the non-linear relationship between real income and pollution in LICs, a group of countries that has been overlooked in the empirical literature. These countries are classified as LICs by the World Bank [6] based on real GDP per capita of USD1,025 or less. It is important to focus on this subject because Ehigiamusoe and Lean [7] argued that real income increases emissions in LICs whereas it diminishes emissions in HICs. Available statistics from the World Development Indicators [8] show that the average level and growth rate of real GDP per capita in LICs are USD628.7 and 0.89% during the 1990–2016 period. The corresponding data for MICs are USD3049.6 and 3.12% while the corresponding data for HICs are USD35529.4 and 1.48%. These differences in income level and growth rates among LICs, MICs and HICs could produce different impact on the environment. Therefore, a knowledge of the non-linear relationship between real income and pollution in LICs is important for policy formulations. This research aligns with the agenda of the United Nations' Sustainable Development Goals 2030; particularly, Goal 7: Affordable and Clean Energy, Goal 12: Responsible Consumption and Production, and Goal 13: Climate Action and Goal (Sustainable Development Goals— [9].

The second unresolved issue is "Does the increase in REN mitigates emissions in LICS?" Nguyen and Kakinaka [10] reported that the effects of REN on real income and pollution could differ among different income groups. Since most LICs are characterized by low economic, political, and technological development, it could be reasonable to assume that LICs possess low capacities to develop clean energy, energy efficiency and green real income. Contrariwise, the available statistics suggest that a large proportion of energy use in LICs are sourced from

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renewable resources compared to non-renewable resources. According to Sharif et al. [11]; though renewable energy resources occur on large ecological regions (which are focused on a minimum number of countries), the quick positioning of the resources produce economic benefits, energy security and mitigation of climate change. Data from the World Development Indicators [8] show that the average REN (percentage of total final energy consumption) in LICs was approximately 70% and the proportion rose from 58.5% in 1990 to 76.2% in 2016. Precisely, out of the 31 countries classified as LICs by the World Bank [6]; 24 countries obtained 60% (or above) of their total energy use from renewable resources. Comparatively, the average energy sourced from renewable resources were 25.3% and 8% in MICs and HICs respectively during the period. Despite the high percentage of REN in LICs, the level of pollution remains high albeit declining in recent years.[1] For instance, carbon dioxide emissions declined from 0.6 to 0.3 metric ton per capita in LICs during the 1990–2016 period. To the best of our knowledge, the nexus between REN and emissions has not been thoroughly explored in LICs. Hence, our study fills this gap and makes contribution to the extant literature by determining whether the variations in REN can explain the variations in carbon emissions using data from LICs. The empirical outcomes of this investigation could assist policy makers in formulating environmental and energy policies to address the intensity of pollution. This is a fundamental inference because the rising emissions constitute global environmental threat and aggravate global warming and climate change.

The third unresolved issue is “How does the interaction effect between REN and real income play a role in the level of emissions in LICs? Alternatively, “Does real income weaken the mitigating effect of REN on emissions?” This study represents a foremost endeavor to examine these issues (to the best of our knowledge). Unlike Ehigiamusoe et al. [5] who investigated the moderating role of total energy use on the nexus between pollution and real income in 64 MICs, we focus on the interplay between REN and real income in LICs. It is important to investigate this issue because climate change and global warming are primarily driven by anthropogenic greenhouse gas emissions, of which carbon emissions remain the largest contributor [12]. The effectiveness of the mechanisms to mitigate pollution should not only focus on reducing the reliance on fossil fuels energy (or increasing REN) but also on a clear knowledge of how the interaction between REN and real income affect the environment. LICs cannot afford to sacrifice economic expansion for environmental sustainability but could use rational management and technological innovation to expand their economies without compromising environmental sustainability. Otherwise, real income may be at odd with environmental conservation since economic expansion usually requires enormous use of energy and other resources.

In light of the above-mentioned discussions and the evaluation of existing studies, this study contributes to the literature in four ways: First, even though the existing studies have extensively investigated the non-linear impact of real income on carbon emissions (i.e., U-shaped or inverted U-shaped), the issue has not been thoroughly explored in LICs. Therefore, our study provides empirical insights on whether LICs can actually grow-out of pollution. The outcomes of the investigation could be fundamental for policy formulations on economic expansion and environmental sustainability. Second, the empirical literature on the link between REN and emissions in LICs is still scanty. Previous studies have usually chosen high-income and middle-income countries as focused group, while LICs are not focused as much as other group of economies. Hence, our study contributes to the extant literature on energy-environment nexus by unveiling how variations in REN influence variations in pollution in LICs. This is important since most LICs obtain their energy from renewable sources, and the finding will assist policy makers to formulate energy and environmental policies that can mitigate the intensity of pollution in LICs. Third, our study represents the first attempt (to the best of our knowledge) to unveil the role of the interaction between REN and income on the level of emissions. We employs the interaction model to show the marginal effect of REN on emissions at various levels of income. This enable us to show whether a simultaneous increase in both REN and income will increase or decrease emissions in LICs. Fourth, as apposite the majority of studies which focuses on either single country analysis or panel data analysis, this study provide country-specific analysis alongside panel data estimation results. This strategy is essential to know in which country renewable energy, real income, and their interactions influence pollution and in which they do not, therefore is critical to formulating reliable policies. To produce robust outcomes that can aid policy formulations, our that account for cross-sectional dependence and heterogeneity. To fill these four gaps, this study analyses the effects of real income, renewable energy consumption and their interaction on carbon emissions in LICs by employing modern estimation approaches that control the issues of heterogeneity and cross-sectional dependence.

Apart from this introduction, the remaining parts of the paper are structured as follows: Section 2 presents the review of related literature; Section 3 summarises the methods and data; Section 4 contains the empirical outcomes; Section 5 contains discussions and implications; and Section 6 concludes with some policy options.

2. Literature review

2.1. Environmental kuznet curve hypothesis

This study’s theoretical framework is rooted in the EKC which hypothesizes that economic expansion aggravates several indices of environmental degradation. But after a certain income level is achieved, a further rise in economic expansion will enhance environmental quality [13]. Empirically, several studies have tested the EKC hypothesis in different regions or countries using diverse data covering different periods. The empirical outcomes have produced two strands of literature. The first strand of literature provided robust evidence to support a valid EKC. They argued that countries can actually grow-out of pollution, and stressed the need to formulate policies to boost GDP with a view to lessening pollution [14]. For instance, Ehigiamusoe [13] investigated the EKC in ASEAN + China, and found robust evidence to support a valid EKC in ASEAN. But when China was added to the panel, the evidence of EKC became tenuous in ASEAN + China. Using data from 6 ASEAN, Anwar et al. [1] verified the existence of the EKC. Ehigiamusoe [15] also validated the EKC in 25 African nations. Similarly, Vural [14] confirmed the EKC in 8 African countries, while Al-mulali [16] provided similar empirical evidence in Ethiopia. Using a non-linear model, Liu et al. [17], validated the EKC in China, while Ridzuan, (2019) confirmed the EKC in 174 nations. Gokmenoglu and Taspinar [18] found a valid EKC in Pakistan, while Ozatac et al. [19] revealed that the EKC is supported in Turkey. Using data from the top renewable energy countries, Dogan and Seker [20] found evidence to validate the EKC in 23 countries.

Another strand of literature argued that countries cannot surmount the challenges of pollution through greater economic expansion, instead, countries should embrace the environmental and energy policies which are capable of reducing the adverse environmental impacts of economic activities [21,22]. In this regard, Ehigiamusoe et al. [5] investigated the EKC in 64 MICs, and found insignificant support for the EKC in the panel. However, the country-specific analysis found no evidence to support the EKC in 42 nations, albeit the EKC was conformed in 22 countries. Dogan et al. [23] tested the EKC in BRICST (Brazil, Russia, India, China, South Africa, Turkey), and found no evidence to verify the EKC in the panel. Acheampong [22] also revealed that the EKC is not valid in 46 African nations, while Arminen and Menegaki [21] could not substantiate the EKC in 67 HICs and MICs. Hove and Tursoy [24] could

[1] Carbon dioxide emissions rose from 2.71 to 3.75 metric ton per capita in MICs while carbon dioxide in HICs declined from 11.29 to 10.39 metric ton per capita during the period. All data were obtained from the World Development Indicators published by the World Bank.

not find any robust evidence to confirm the EKC in 24 emerging economies. Moreover, Antonakakis et al. [25] reported that the EKC is not supported in 106 nations. Using empirical strategies that control structural breaks, Dogan and Ozturk [26] revealed that the EKC is invalid in USA. Besides, Wang [27] could not find any robust evidence to validate the EKC in 109 nations, while Jaunky [28] could not validate the EKC in 36 countries. Using data of 43 developing nations (categorized into different groups based on regional location), Narayan and Narayan (2010) revealed invalid EKC in 28 nations, albeit the EKC was confirmed in 15 nations. The panel data estimation could not support the EKC in Africa, Latin America, and East Asia, albeit the EKC was validated in Middle East and South Asia.

2.2. Renewable energy consumption and carbon emissions

Some scholars have investigated the impacts of REN and non-renewable energy consumption (NREN) on emissions in different regions and countries, albeit the findings are inconclusive. For example, Ehigiamusoe [13] showed that REN mitigates environmental pollution while NREN aggravates it in ASEAN. Using data from 6 ASEAN, Anwar et al. [1] revealed that REN diminishes emissions while NREN increases emissions. Vural [14] reported that REN diminishes pollution while NREN exacerbates it in 8 African nations. Eyuboglu and Uzar [29] also showed that REN is a catalyst that reduces emissions in 7 countries. Using different indicators for environmental quality, Salahuddin et al. [30] showed that REN mitigates pollution and energy intensity, while NREN exacerbates pollution and energy intensity in 34 Sub-Sahara African countries. Al-mulali [16] also found that both REN and NREN have mitigating impacts on emissions. The study attributed the favourable effect of NREN on emissions to the low proportion of NREN in the overall energy mixture in Ethiopia. Hove and Tursoy [24] reported that REN lessens pollution while NREN aggravates pollution in 20 emerging countries. Inglesi-Lotz and Dogan [31] showed that REN has a mitigating impact on environmental degradation while NREN is detrimental to the environment in 10 African countries. Dogan and Ozturk [26] reported that REN decreases environmental degradation while NREN intensifies it. Dogan and Seker [20] also revealed that an increase in REN diminishes emissions while a rise in NREN intensifies the level of emissions in 23 nations.

2.3. Moderating effect

Some studies have employed the interaction model to determine the moderating role of energy consumption (EC) on the nexus between carbon emissions and income. For instance, Ehigiamusoe et al. [5] investigated the moderating role of EC on the impact of income on emissions in 64 MICs. They reported that EC has insignificant moderating role on the emissions-income nexus in the panel. However, the country-specific analysis showed that EC significantly moderates the emissions-income nexus in 20 MICs, but has insignificant moderating role in 44 MICs. Using a nonlinear panel smooth transition regression framework, Cheikh et al. [32] showed that the energy-pollution nexus follows an inverted U-shaped pattern of income per capita in 12 MENA nations. It further showed that pollution tends to increase as income rises, until it gets to the stabilization point, and thereafter declines. It concluded that the impact of EC on pollution depends on the level of economic development. Mesagan et al. [33] investigated the moderating role of capital investment on the energy-pollution nexus, and reported that capital investment has a significant moderating impact on the nexus between energy and pollution in SANEM (South Africa, Algeria, Nigeria, Egypt and Morocco). The country-specific estimations revealed that the interaction term lessens emissions in Morocco, Egypt, Nigeria, and South Africa (except in Algeria). Acheampong [22] also showed that the interaction between EC and financial development is a significant determinant of pollution in 46 Sub-Sahara African countries. Kwakwa and Alhassan [34] showed that the interaction between fossil EC and urbanization influences environmental degradation in Ghana, while York and McGee [12] reported that the interaction between renewable electricity production and GDP worsens pollution in 128 nations.

This review indicates that some scholars have investigated the direct influence of REN on emissions. Although other views exist, the consensus is that REN mitigates emissions. Besides, the review also showed that some researches have investigated the role of the interaction between EC and GDP (or other variables) on pollution. Nonetheless, the indirect impact of REN (via GDP) on pollution has not been thoroughly examined. In other words, real income could have a negative or positive moderating role on the nexus between REN and emissions. This subject matter has been overlooked in the empirical literature. Consequently, our study attempts to contribute to the literature by filling this gap using LICs data. This category of nations has not been thoroughly explored in the empirical literature.

3. Methodology and data

3.1. Model specification

Following the extant literature [1,35,36], we investigate the impacts of REN and GDP on emissions with the following model[2]:

$$CO2_{it} = \alpha_0 + \alpha_1 GDP_{it} + \alpha_2 GDP^2{}_{it} + \alpha_3 REN_{it} + \varepsilon_{it} \tag{1}$$

where CO2 denotes carbon emissions measured in metric ton per capita; GDP represents real GDP per capita (measured in dollars at 2010 constant price); GDP^2 denotes the squared of real GDP per capita; REN signifies renewable energy consumption measured as a percentage of total final energy consumption,ε represents error term; *i* denotes country index; and *t*represents time index; $\alpha_0, \alpha_1, \alpha_2, \alpha_3$ represent parameters to be estimated. For instance, a negative and significant parameter (e.g.α_3) indicates that an increase in REN will decrease CO2 emissions while an insignificant parameter (e.g.α_3) shows that REN has no impact on CO2 emissions. We take the natural logarithm of the variables before conducting the analysis.

Based on *a priori* expectation, the coefficient of GDP should be positive ($\alpha_1 > 0$) while the coefficient of GDP^2 should be negative ($\alpha_2 < 0$) to support the EKC hypothesis. The hypothesis posits that GDP has an inverted U-shaped non-linear impact on emissions, an indication that LICs can grow-out of emissions. Otherwise, the EKC is not supported. The coefficient of REN is expected to be negative ($\alpha_3 < 0$), implying that REN reduces carbon emissions.

Next, we investigate the effect of the interaction term between REN and GDP on emissions using the following model [5,12]:

$$CO2_{it} = \beta_0 + \beta_1 GDP_{it} + \beta_2 GDP^2{}_{it} + \beta_3 REN_{it} + \beta_4 (REN * GDP_{it}) + \varepsilon_{it} \tag{2}$$

where REN*GDP represents interaction term between renewable energy consumption and GDP. It is the multiplication of renewable energy consumption and GDP. Hence, REN favourably influences the adverse effect of GDP on emissions if the coefficient of GDP is positive ($\beta_1 > 0$) and the coefficient of interaction term is negative ($\beta_4 < 0$). Alternatively, GDP adversely affects the favourable impact of REN on emissions if $\beta_1 < 0$and $\beta_4 > 0$. Essentially, the interaction term allows us to calculate the marginal effect of REN on emissions at different levels of GDP through the partial derivative[3] of Model 2 with respect to REN as

[2] NREN was not included in the model due to unavailability of data in some countries. Similar model was used by some previous research (e. g. Iwata et al., 2011; [35].

[3] The essence of taking the partial derivatives of the interaction term model (with respect to REN) is to enable us to compute the marginal effect of REN on emissions at different levels of GDP. The marginal effect is important because it shows whether a simultaneous increase (decrease) in both REN and GDP can increase (decrease) carbon emissions.

follows:

$$\frac{\partial CO2_{it}}{\partial REN_{it}} = \beta_3 + \beta_4 GDP$$

A positive marginal effect implies that simultaneous rise in REN and GDP worsens emissions while a negative marginal effect suggests otherwise. Lastly, the interaction term between REN and GDP squared was included in the model to determine how the interplay between REN and higher level of GDP[4] affect emissions as follows:

$$CO2_{it} = \varphi_0 + \varphi_1 GDP_{it} + \varphi_2 GDP^2{}_{it} + \varphi_3 REN_{it} + \varphi_4 (REN * GDP^2_{it}) + \varepsilon_{it} \quad (3)$$

where REN*GDP[2] denotes the interaction term between REN and GDP squared. Thus, REN favourably influences the adverse impact of GDP squared on emissions if $\varphi_2 > 0$and $\varphi_4 < 0$. Nonetheless, GDP squared adversely affects the favourable impact of REN on emissions if $\varphi_3 < 0$and $\varphi_4 > 0$. The interaction term allows us to compute the marginal effect of REN on emissions at various levels of GDP squared via the partial derivative of Model 3 with respect to REN as follows:

$$\frac{\partial CO2_{it}}{\partial REN_{it}} = \varphi_3 + \varphi_4 GDP^2$$

A positive marginal effect implies that simultaneous rise in REN and GDP squared exacerbates emissions while the reverse is the case if the marginal effect is negative. Finally, we ascertain whether the marginal effects are statistically significance by computing the standard errors as well as t-statistic using the estimated coefficients and the covariance matrix at various levels of GDP [5].[5]

3.2. Data

This study uses the panel data of LICs[6] covering 1990–2016 and sourced from the World Development Indicators [8]. The LICs is chosen based on the World Bank [6] categorization of nations based on income levels. Out of the 31 countries categorized as LICs (with real GDP per capita of USD1,025 or less), 26 countries have complete data on REN. Therefore, our study focuses on these 26 LICs. Besides, the period of estimation is limited to 1990–2016 due to data unavailability in some nations before and after this period as of December 2020.

3.3. Estimation techniques

This study employs the following empirical strategies: First, it investigates the presence of cross-sectional dependence in the panel by using the Bias adjusted LM test developed by Pesaran et al. [37]; as well as the general CD and scaled CD_{LM} tests developed d by Pesaran [38]. This test is important because it enables us to choose the appropriate empirical strategies to conduct the unit root, cointegration estimation, as well as Granger causality. Second, it examines the integration properties of the variables using the tests developed by Pesaran [39]; Im et al. [40] and Levin et al. [41]. These diverse tests enable us to control for individual and common unit root processes, cross-sectional dependence, and heterogeneous coefficient. The integration properties of the variables also determine the appropriate cointegration and estimation techniques. Third, the study employs the Johansen-Fisher and Westerlund [42] panel cointegration techniques to determine the cointegration relationship. The latter cointegration technique is capable of accounting for cross-sectional dependence. If the variables are cointegrated, it would be necessary to employ the appropriate estimation technique. Fourth, the study uses the Fully Modified Ordinary Least Squares (FMOLS) developed by Pedroni [43]; Dynamic Ordinary Least Squares (DOLS) proposed by Stock and Watson [44]; Pooled Mean Group (PMG) developed by Pesaran et al. [45] and the Augmented Mean Group (AMG) proposed by Eberhardt and Bond (2009) to estimate the coefficients. We choose the DOLS and FMOLS because the conventional OLS is not suitable for cointegrated model because it will yield spurious outcomes. The DOLS offers reliable and consistent results for panels that have cointegration relationships, though is does not account for cross sectional heterogeneity [44]. Consequently, we use the FMOLS that account for heterogeneous long-run coefficients (cross sectional heterogeneity), serial correlation and endogeneity problems. It produces consistent estimates even in small sample [43]. The justification for using the PMG is to account for heterogeneity and reveal short-run, long-run and convergence coefficients. By distinguishing between long-run and short-run effects, the PMG provides options for policy formulations, Moreover, the AMG was employed to account for cross-sectional dependence and reveals the individual-country estimations. Finally, the study uses the Dumitrescu and Hurlin [46] panel Granger non-causality to determine the causal relations between the variables. This technique is chosen because it can control for cross-sectional dependence and heterogeneity.

4. Empirical results

4.1. Preliminary analysis

The descriptive statistics and correlations presented in Table 1 reveals large disparities between the variables. The standard deviations indicate that the variables are quite dispersed around their means. It shows that GDP is positively correlated with emissions whereas REN is negatively correlated with emissions.

Figs. 1–3 shows the trends of emissions, GDP and REN in LICs. The average emissions and GDP rose while the average REN declined during the period. These trends necessitate a rigorous econometric analysis to ascertain whether the changes in emissions can be explained by the changes in REN and GDP during the period.

From Table 2, we reject the null hypothesis at 1 percent significant level, suggesting the presence of cross-sectional dependence.

From Table 3, we reject the null hypothesis that there is no unit root

Table 1
Descriptive statistics and correlations.

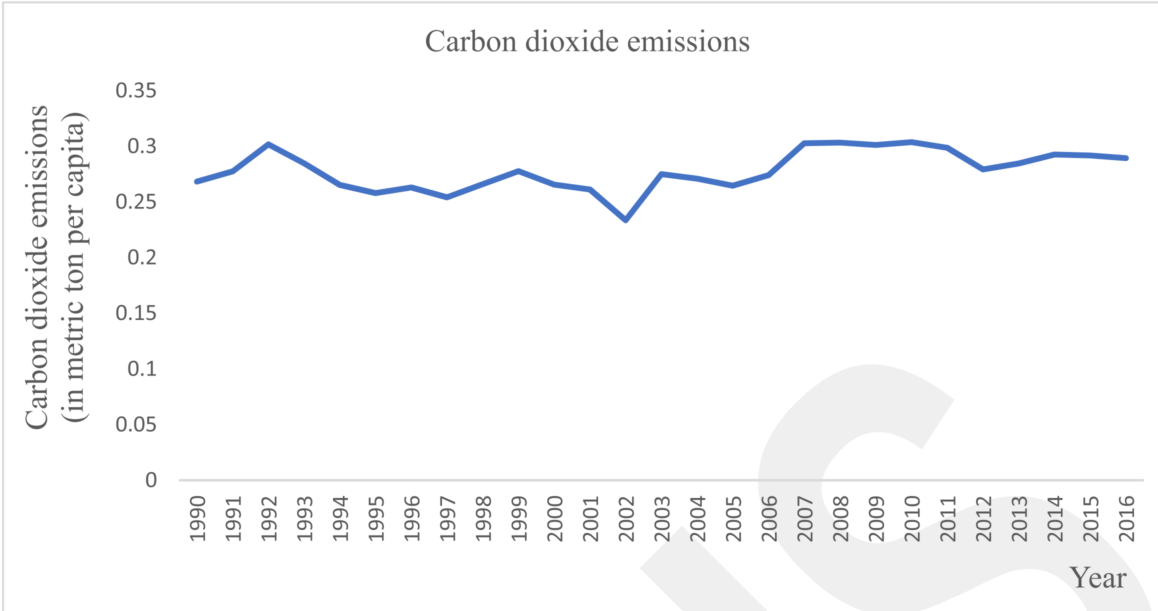
	CO2	GDP	REN
Mean	0.278	541.902	74.765
Maximum	3.366	1469.703	98.342
Minimum	0.017	164.336	0.521
Standard Dev.	0.550	227.420	26.130
CO2	–		
GDP	0.582***	–	
REN	−0.736***	−0.674***	–

Notes: *** indicate statistically significant at 1% level. CO2 = carbon emissions measured in metric ton per capita, GDP = real GDP per capita measured in dollars at 2010 constant price, REN = renewable energy consumption measured as a percentage of total energy consumption.

[4] This analysis also experiments with both interaction terms between REN and GDP as well as between REN and GDP squared in a separate model.

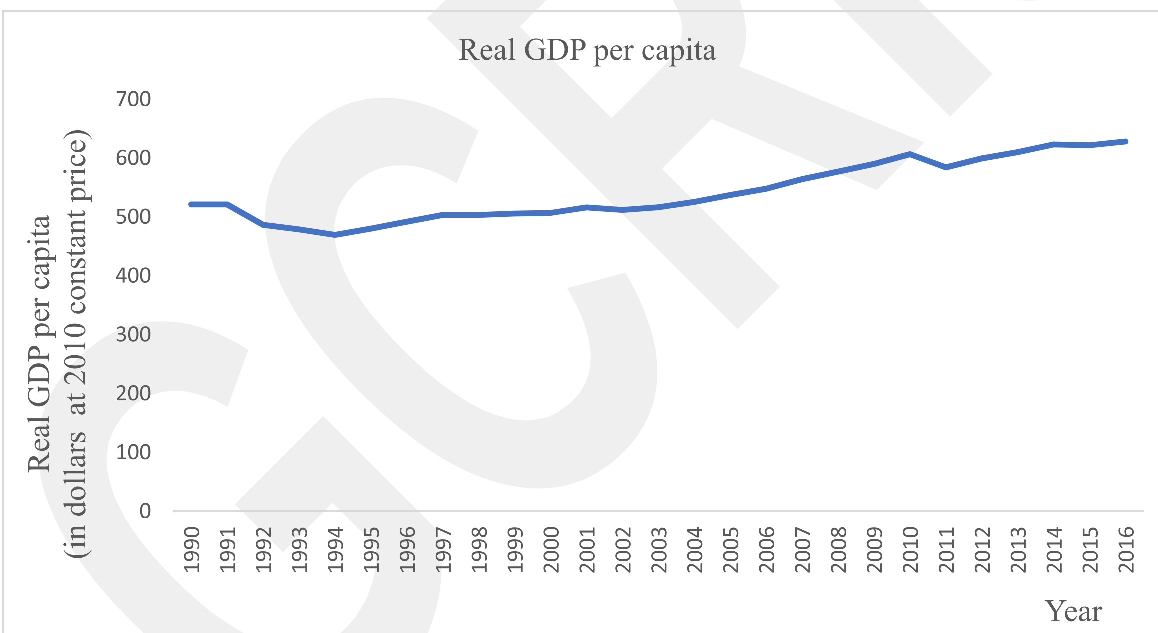
[5] The rationale for computing the t-statistics of the marginal effects is to determine whether the marginal effect are statistically significant. A significant and positive marginal effect implies that a simultaneous increase in both REN and GDP will increase carbon emissions, while an insignificant marginal effect suggests otherwise. The steps to compute the t-statistic are as follows: (i) Compute the variance using the estimated coefficients and the covariance matrix at various levels of GDP; (ii) Take the square root of the variance to obtain the standard errors. (iii) Divide the marginal effect by the standard error to obtain the t-statistic. A large t-statistic (>1.96) indicate that the marginal effect is statistically significant at 5% level (see Refs. [5,8,20,32].

[6] The countries include Afghanistan, Burkina Faso, Benin, Burundi, Congo Democratic Republic, Central African Republic, Ethiopia, Eritrea, Gambia, Guinea-Bissau, Guinea, Haiti, Malawi, Madagascar, Mozambique, Mali, Niger, Nepal, Rwanda, Syria, Sierra Leone, Tajikistan, Togo, Tanzania, Uganda, and Yemen.



Source: Drawn with data from World Development Indicators (2020)

Fig. 1. The trend of carbon dioxide emissions in low-income countries. Source: Drawn with data from World Development Indicators [8].



Source: Drawn with data from World Development Indicators (2020)

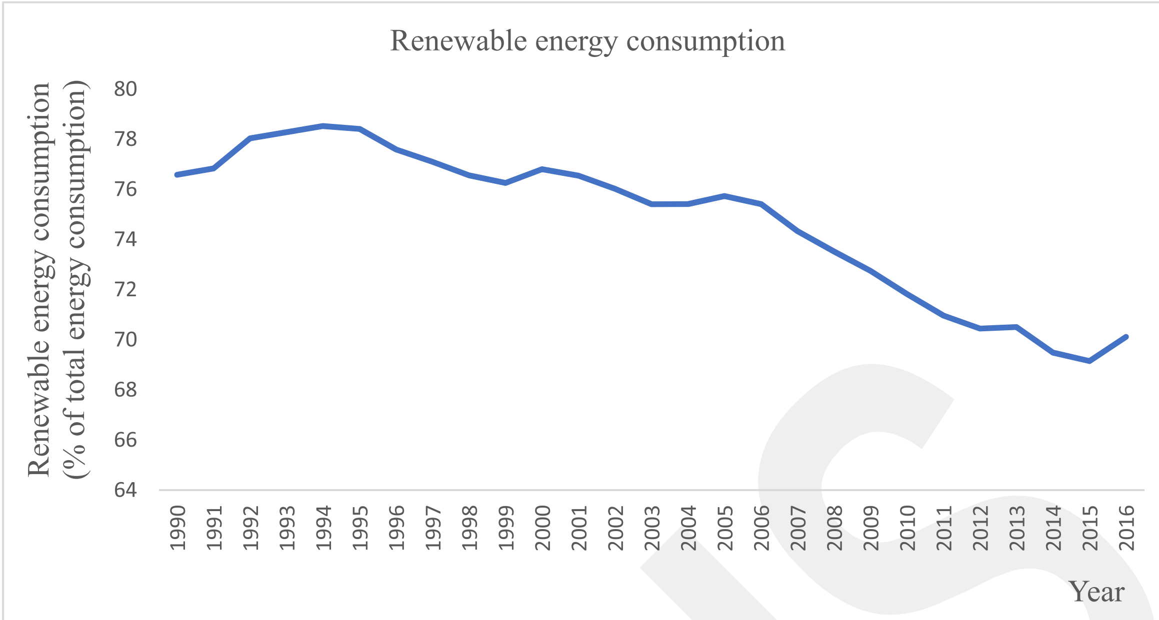
Fig. 2. The trend of real GDP per capita in low-income countries. Source: Drawn with data from World Development Indicators [8].

at 1 percent significant level for emissions, GDP and REN, indicating the existence of unit root. All the variables become stationary at first differenced.

Table 4 presents the cointegration tests results, and there is evidence to reject the null hypothesis at 1 percent significant level, an indication that the variables are cointegrated.

4.2. Estimation results

The FMOLS estimations presented in Table 5 (Column 1) show that GDP enters with a significantly positive coefficient while GDP squared enters with a significantly negative coefficient at 1 percent level. This suggests that emissions and GDP have an inverted U-shaped relationship in LICs. This empirical evidence implies that LICs can actually grow-out of pollution as hypothesized by the EKC. This empirical outcome agreed with Chen et al. [47] who confirmed the EKC in 188 countries; Ehigiamusoe [15] also validated the EKC in 25 African nations; Ridzuan [48] supported a valid EKC in 174 nations; Sarkodie and Ozturk [49] validated the EKC for Kenya; and Pandey et al. [50] also found evidence to confirm the EKC in Asian economies.



Source: Drawn with data from World Development Indicators (2020)

Fig. 3. The trend of renewable energy consumption in low-income countries. Source: Drawn with data from World Development Indicators [8].

Table 2
Results of cross-sectional dependence tests.

Test Statistic	CO2	GDP	REN
Pesaran scaled LM	95.119***	92.553***	85.561***
Pesaran CD	11.933***	17.141***	29.880***
Bias-Corrected Scaled LM	94.619***	92.053***	85.061***

Notes: *** indicate statistically significance at 1% level, and a rejection of the null hypothesis of no cross-section dependence.

Table 3
Results of panel unit root tests.

	LLC	IPS	CIPS
CO2	−0.335	1.260	2.493
GDP	0.760	1.936	−0.651
REN	−0.805	0.315	−1.232
ΔCO2	−11.498***	−12.348***	−4.159***
ΔGDP	−7.975***	−10.966***	−3.013***
ΔREN	−8.527***	−12.496***	−3.458***

Notes: *** and ** indicate statistically significant at 1% and 5% levels respectively, and a rejection of the null hypothesis of no unit root. Δ = first differenced notation, LLC = Levin, Lin and Chu, (2002) test, IPS= Im, Pesaran and Shin [40] test, CIPS= Pesaran [39] test.

Moreover, the results show that REN mitigates emissions in LICs. Precisely, a percentage increase in REN will reduce emissions by 0.157 percentage points in LICs. This empirical evidence agreed with Ito [51] who showed that REN mitigates pollution in 42 nations. Similar empirical evidence are documented by Dogan and Seker [20] in 23 countries; Eyuboglu and Uzar [29] in 7 countries; and Vural [14] in 8 African countries.

The model estimated in Column 2 (of Table 5) comprises of the interaction term between REN and GDP. We reveal that the coefficient of the interaction term is significantly positive whereas REN enters with a significantly negative coefficient at 1 percent level. This indicates that the interplay between REN and GDP aggravates pollution. Moreover, the marginal effects of REN on emissions calculated at the maximum, mean and minimum levels of GDP are 3.145, 2.613 and 2.065 respectively. Since the marginal effect increases as GDP increases, we conclude that GDP undermines the mitigating impact of REN on pollution in LICs. Fig. 4 shows the graphical representation of the marginal effects of REN on carbon emissions at various levels of GDP. The upward sloping graph clearly indicates that the marginal effects increase as GDP rises. This empirical outcome partly agreed with York and McGee [12] who showed that the interaction between renewable electricity production and GDP worsens pollution in 128 nations. In Column 4 (of Table 5), we include the interaction term between REN and GDP squared in the model. The outcome reveal that the interaction term enters with a significantly positive coefficient whereas REN enters with a significantly negative coefficient at 1 percent level. This indicates that the effect of REN on pollution varies with the levels of GDP squared in LICs. Furthermore, the marginal effects of REN on emissions calculated at the maximum, mean and minimum levels of GDP squared are −0.869, −1.374 and −1.819 respectively. Since the marginal effect increases as GDP squared increases, we conclude that GDP squared weakens the impact of REN on pollution in LICs. Fig. 5 shows the graphical representation of the marginal effects of REN on carbon emissions at various levels of GDP squared. Although, the marginal effects are negative, the upward sloping graph is an indication that the marginal effects rise with an increase in GDP squared. Ehigiamusoe et al. [5] showed that the interaction between energy consumption and GDP squared intensifies pollution in 7 MICs.

4.3. Robustness checks

To ascertain the veracity of the estimations, this study conducts robustness checks. First, we use the DOLS estimation technique, and the empirical outcome[7] are similar (regarding the significance and sign of the coefficients). Second, we use the PMG estimator that permits us to reveal both short-run and long-run coefficients as well as account for heterogeneity in the panel. It also shows the convergence coefficient that shows the speed that the system adjusts to long-run equilibrium when

[7] The estimations are not reported because of lack of space, albeit available on request.

Table 4
Results of panel cointegration tests.

	Model 1		Model 2		Model 3	
Johansen Fisher tests						
Hypothesized No. of CE(s)	Trace test	Max-eigen test	Trace test	Max-eigen test	Trace test	Max-eigen test
None	388.1***	291.0***	672.1***	464.2***	673.0***	464.3***
At most 1	158.6***	123.0***	315.1***	192.2***	316.5***	192.5***
At most 2	79.18***	69.38**	164.8***	119.0***	165.7***	118.3***
At most 3	70.00**	70.00**	92.29***	72.77**	93.30***	73.57**
At most 4	–	–	89.98***	89.98***	90.36***	90.36***
Westerlund tests						
Tests	Value	Bootstrap p-value	Value	Bootstrap p-value	Value	Bootstrap p-value
Group-τ	−2.628	0.010***	−2.401	0.110	−2.347	0.110
Group-α	−7.245	0.480	−5.317	1.000	−5.284	0.940
Panel-τ	−10.586	0.060*	−9.536	0.050**	−9.498	0.070*
Panel-α	−4.942	0.580	−3.669	0.990	−3.628	0.920

Notes: ***, ** and * indicates statistically significant at 1%, 5% and 10% levels respectively, and a rejection of the null hypothesis of no cointegration.

Table 5
Results of FMOLS estimations.

Linked variables	Model 1: α terms	Model 2:β terms	Model 3: φ terms
GDP	4.258***	−2.673***	−0.338
	(0.588)	(0.773)	(0.663)
GDP^2	−0.298***	0.098**	−0.069
	(0.048)	(0.055)	(0.048)
REN	−0.157***	−0.449***	−2.731***
	(0.050)	(0.261)	(0.133)
REN*GDP		0.493***	
		(0.038)	
REN* GDP^2			0.035***
			(0.010)
R^2	0.947	0.954	0.954
Adj. R^2	0.945	0.952	0.951
Marginal effects			
Minimum		2.065**	−1.819**
Mean		2.613**	−1.374**
Maximum		3.145**	−0.869**

Notes: ***, ** and * indicates statistically significant at 1%, 5% and 10% levels, respectively. Standard errors in parenthesis. Dependent variable is carbon emissions.

the system encounters short-run deviations. The PMG estimations presented in Table 6 are consistent with the FMOLS estimations. In summary, the EKC is supported in the long-run, while REN mitigates pollution in both short-run and long-run. The coefficients of the interaction terms are significantly positive. The marginal effects of REN on pollution increases as GDP (and its squared) increases, indicating that GDP (and its squared) undermines the impact of REN on emissions in LICs.

Third, to provide the country-specific estimations in a framework that controls for cross-sectional dependence, we use the AMG estimator. The results reported in Table 7 shows that REN diminishes pollution in the panel, while the country-specific estimations show the mitigating impact of REN in 19 countries. Nevertheless, REN has no mitigating effect on pollution in 7 countries. Low level of REN in the energy mixture could be a possible explanation of why REN does not reduce pollution in some LICs. For instance, the proportion of REN in the energy mixture in Syria and Yemen were 1.8% and 1.2% respectively, compared to the LICs average of 74.7% during the period. So, it is not surprising why REN cannot lessen pollution in these countries. Besides, Ehigiamusoe et al. [5] argued that energy consumption can influence the impact of GDP on pollution in countries with effective energy policies and tighter environmental regulations.

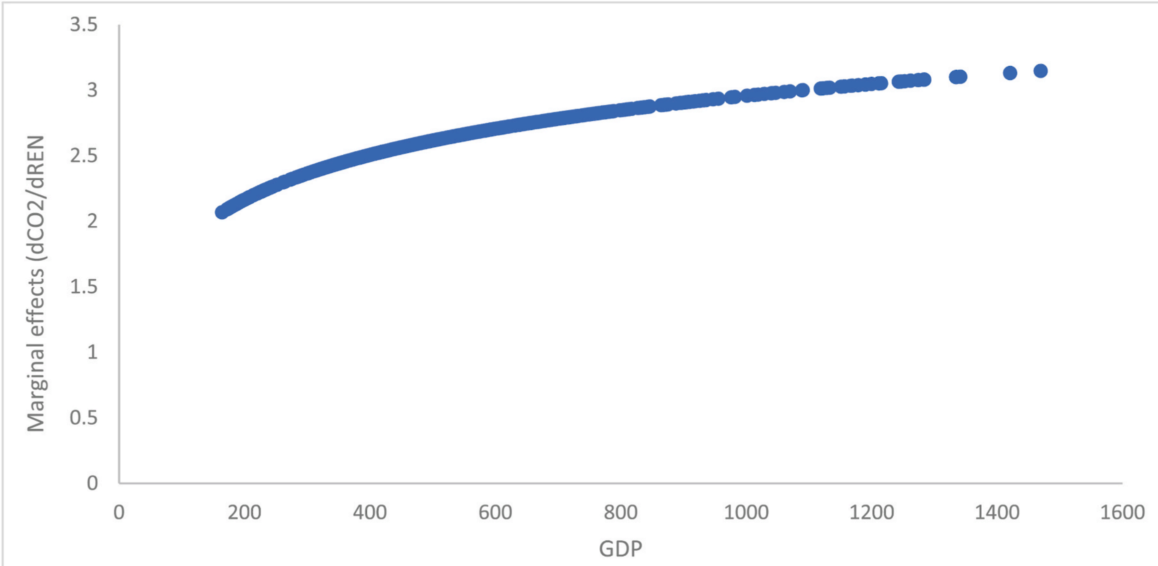
4.4. Dumitrescu and Hurlin Granger non-causality

The Dumitrescu and Hurlin Granger non-causality results reported in Table 8 show a unidirectional causal relation from GDP to emissions. This evidence agreed with Jaunky [28] for 36 countries. Hence, environmental policies should be designed with a clear knowledge of the link between the two variables. It may be necessary to apply a carbon conservation policy (e. g. lower fossil fuel consumption) to mitigate pollution. Second, we reveal a bidirectional causality between REN and pollution, suggesting that the two variables reinforce each other. This finding is consistent with Mirza and Kanwal [52] for Pakistan. Third, we find a bidirectional causal relation between GDP and REN. The feedback effect implies that policies to increase GDP may also influence REN. This outcome agreed with Apergis and Payne [53] who reported a feedback effect between REN and GDP in 20 OECD countries. Finally, we show a unidirectional causal relation from the interaction terms to pollution in LICs. This finding reiterates that the interplay between REN and GDP is a significant determinant of pollution in LICs.

5. Discussion and policy implications

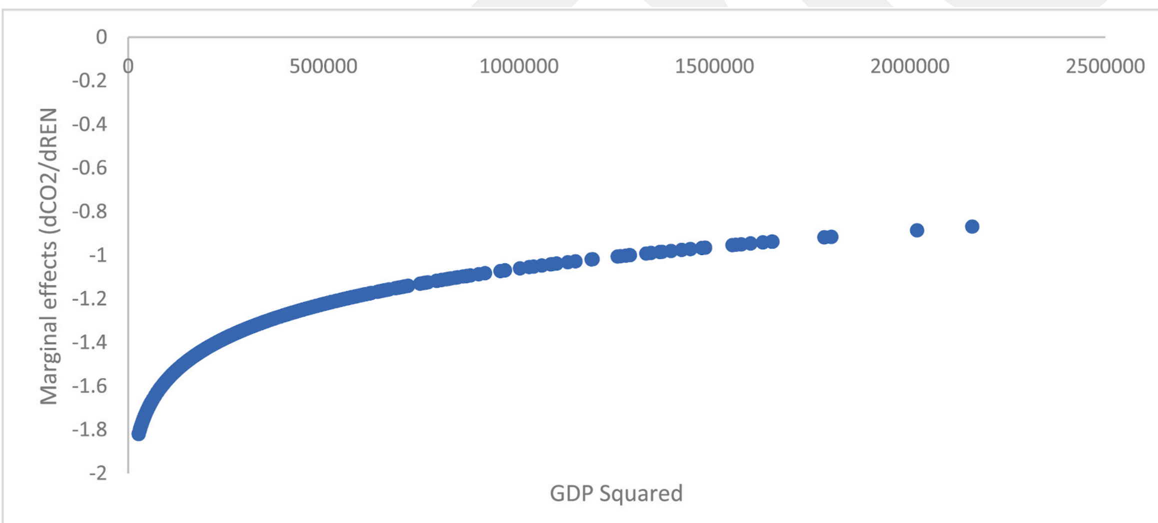
We summarize the findings of this study as follows: First, the study shows that LICs can actually grow-out of pollution as hypothesized by the EKC. This is evident in the inverted U-shaped link between GDP and pollution. This suggests that as countries move from a low level of GDP to a higher level of GDP, the environmental effect of real income improves. In other words, after a certain threshold level of GDP, a further rise in GDP will cause improvement in environmental quality. This finding agreed with some studies (e. g. Refs. [1,13,14,20]. Specifically, Anwar et al. [1] provided evidence to validate the EKC in 6 ASEAN; Dogan and Seker [20] confirmed the EKC in 23 countries. Ehigiamusoe [13] validated the EKC in ASEAN; and Vural [14] verified the EKC in 8 African nations. The policy implication is that efforts to accelerate the real income should be vigorously pursued in LICs. Hence, LICs should give priority to the programs or policies that can boost the real income in their development agenda.

The second finding of this study is that REN has a mitigating impact on pollution in LICs. This is evident from the negative coefficient of REN. Hence, a rise in REN will lessen pollution in LICs. This outcome agreed with some research (e.g., Refs. [11,24,30,31]. More precisely, Salahuddin et al. [30] showed that REN mitigates pollution in 34 African nations; Hove and Tursoy [24] reported that REN lessens pollution in 20 emerging countries; Inglesi-Lotz and Dogan [31] showed that REN diminishes pollution in 10 African nations; and Sharif et al. [11] showed that REN reduces pollution in 74 nations. Besides, Hanif et al. [54] argued that the transition from NREN to REN is fundamental to abating



Source: Drawn by authors using the estimated coefficients of REN and interaction term as well as GDP data

Fig. 4. The marginal effects of REN on CO2 at various levels of GDP in low-income countries. Source: Drawn by authors using the estimated coefficients of REN and interaction term as well as GDP data.



Source: Drawn by authors using the estimated coefficients of REN and interaction term as well as GDP squared data

Fig. 5. The marginal effects of REN on CO2 at various levels of GDP squared in low-income countries. Source: Drawn by authors using the estimated coefficients of REN and interaction term as well as GDP squared data.

pollution in 25 Asian economies. The policy implication of this finding is that LICs should formulate the policies that can reduce pollution, and encourage the use of greater proportion of REN in the energy consumption mixture.

The third finding of this study is that the interplay between REN and GDP aggravates pollution This is evident as the coefficient of the interaction term is significantly positive while the coefficient of REN is significantly negative. Besides, the marginal effect of REN on pollution increases as GDP increases. Hence, it can be concluded that GDP undermines the impact of REN on pollution in LICs. The positive coefficient of the interaction term unveiled in this study agreed with some research. For instance, York and McGee [12] reported that the interaction between renewable electricity production and GDP worsens pollution in 128 nations. Ehigiamusoe et al. [5] also showed that energy consumption adversely influences the effect of GDP on pollution in 7 MICs. This finding implies that a simultaneous increase in both REN and GDP aggravates pollution at higher level of real income than at lower level. One possible explanation for the outcome is that the attainment of higher GDP requires greater energy consumption and higher economic activities (e.g., transportation, industrial activities, tourism) which possibly increase pollution. The policy implication of this finding is that LICs should encourage the use of clean or green technologies in the production process (including the use of low-carbon technologies in conducting economic activities) to accelerate economic growth and ensure environmental sustainability.

We discuss the implications of the above findings by analyzing the political, economic, social, technological, legal and environmental (PESTLE) implications and policy options. Politically, governments of high-carbon LICs should expand their national and international strategies to deal with environmental degradation, reduce fossils fuels

Table 6
Robustness checks using PMG estimations.

Linked variables	Model 1: α terms	Model 2:β terms	Model 3:φ terms
Long-run coefficients			
GDP	6.152*** (2.080)	−6.230** (3.185)c	2.448 (2.198)
GDP^2	−0.459*** (0.168)	−0.150 (0.185)	−0.815*** (0.143)
REN	−0.667*** (0.117)	−14.357*** (1.864)	−7.899*** (0.927)
REN*GDP		0.991*** (0.288)	
REN* GDP^2			0.152*** (0.021)
Convergence coefficient	−0.230*** (0.040)	−0.249*** (0.047)	−0.250*** (0.047)
Short-run coefficients			
ΔGDP	−14.886* (7.920)	−14.660 (18.067)	−3.909 (9.125)
ΔGDP^2	1.190* (0.652)	0.316 (0.728)	−0.508 (0.667)
ΔREN	−2.729*** (0.627)	−17.349 (15.652)	−9.929 (7.911)
ΔREN* GDP		2.316 (2.411)	
ΔREN* GDP^2			0.179 (0.189)
Constant	−4.527*** (0.793)	12.806*** (2.437)	5.826*** (1.128)
Marginal effects			
Minimum		−9.301**	−3.942**
Mean		−8.210**	−2.008**
Maximum		−7.130**	−0.185**

Notes: ***, ** and * indicates statistically significant at 1%, 5% and 10% levels, respectively. Standard errors in parenthesis. Dependent variable is carbon emissions.

Table 7
Results of Augmented Mean Group (AMG) estimations.

S/N	Country	GDP	GDP^2	REN	Constant
1	Afghanistan	−0.083	0.122	−1.403***	2.022
2	Benin	−62.161	4.746	−1.684***	209.35
3	Burkina Faso	−7.208	0.683	−0.127	16.637
4	Burundi	38.357	−3.383	−13.249***	−51.585
5	CAR	−27.769	2.284	1.221***	76.210
6	Congo DR	25.108***	−1.959***	−11.381***	−31.052**
7	Eritrea	−19.027	1.483	1.072	54.946
8	Ethiopia	4.199	−0.370	−9.676***	29.486
9	Gambia	140.94	−11.259	−0.946***	−43.881
10	Guinea	35.991***	−2.726***	−1.312***	−114.49***
11	Guinea-Bissau	5.785	−0.413	−8.759***	17.384
12	Haiti	−63.914	4.775	−5.825***	23.741
13	Madagascar	90.992***	−7.467***	−2.929***	−26.659***
14	Malawi	−0.349	−0.022	−3.400***	15.336
15	Mali	72.327***	−5.578***	0.607	−23.971***
16	Mozambique	−3.511	0.347	−1.396	12.573
17	Nepal	31.925***	−2.558***	−10.525***	−54.336
18	Niger	71.570	−5.876	−2.180**	−21.044
19	Rwanda	0.921	−0.117	−0.702**	−0.861
20	Sierra Leone	−6.448	0.588	−2.513***	26.606*
21	Syria	−11.428**	0.829**	−0.064	40.464**
22	Tajikistan	24.617***	−1.991***	−2.674***	−65.919***
23	Tanzania	16.417	−1.241	−5.254***	−32.588
24	Togo	−35.903*	2.837*	−2.472***	12.291*
25	Uganda	−4.574	0.462	−5.320**	32.121*
26	Yemen	−44.369***	3.233***	−0.100	15.192***
	Panel	10.477	−0.872	−3.500***	−17.731

*Notes: ***, ** and * indicate statistically significant at 1%, 5% and 10% levels respectively. Dependent variable is carbon emissions. Standard errors are not reported for want of space but available upon request.*

Table 8
Dumitrescu-Hurlin panel causality tests.

Null Hypothesis:	W-Stat.	Zbar-Stat.	Prob.	Conclusion
GDP does not homogeneously cause CO2	5.749	7.238	0.000	GDP → CO2
CO2 does not homogeneously cause GDP	2.354	0.270	0.786	
GDP^2 does not homogeneously cause CO2	5.797	7.336	0.000	GDP^2 → CO2
CO2 does not homogeneously cause GDP^2	2.384	0.333	0.738	
REN does not homogeneously cause CO2	4.294	4.252	0.000	REN ↔ CO2
CO2 does not homogeneously cause REN	3.630	2.890	0.003	
GDP*REN does not homogeneously cause CO2	5.077	5.859	0.000	GDP*REN → CO2
CO2 does not homogeneously cause GDP*REN	1.857	−0.749	0.453	
GDP^2*REN does not homogeneously cause CO2	5.424	6.571	0.000	GDP^2*REN → CO2
CO2 does not homogeneously cause GDP^2*REN	2.000	−0.455	0.648	
REN does not homogeneously cause GDP	3.178	1.962	0.049	GDP ↔ REN
GDP does not homogeneously cause REN	4.069	3.792	0.000	

Notes: → unidirectional causality, ↔ = bidirectional causality.

consumption, encourage renewable energy consumption in all sectors, promote greater investment in the generation of energy from renewable resources. Government policies, taxes laws and tariff, stability of government and entry mode regulations are fundamental in combating environmental issues. Hence, the government should use policies and incentives to encourage the sectors (e.g., agricultural. Industrial, financial, service) to support environmental-friendly projects. LICs should also embrace international renewable energy cooperation in the areas of investment, innovation, and technology to gradually phase-out (or reduce) fossil fuels energy. These financial and technological assistances (e.g., development assistance projects) are fundamental, given that the mitigation of pollution at global level can be achieved through international collaboration among countries. Economically, since LICS can grow-out of pollution, the governments of LICs should vigorously pursue the requisite monetary, fiscal, and external policies that can stimulate real income. They should adopt policies that can accelerate capital accumulation and productivity real income (e.g., human capita development, financial development, microeconomic stability) that represents the key sources of real income. In the production process, LICs should consider sustainable real income via the use of advanced or low-carbon production techniques (e.g., reduction in fossil fuels utilization). Since REN mitigates emissions in LICs, the adoption and utilization of renewable energy technologies should be embraced in the production process. Additional measures such as tax reduction, production or consumption subsidies for renewable energy should be adopted in LICs. Socially, the governments of LICs should address the social behaviours or activities that are detrimental to the environment. It may be necessary to embark on campaigns relating to the social lifestyles, cultural beliefs or values, domestic structures and demographics issues that constitute environmental problems. The implementation of the necessary regulatory policies that will increase public awareness on renewable energy and environmental sustainability should be vigorously pursued. LICs should increase environmental education, public awareness and knowledge about environmental protection, incentives for carbon emissions reduction since a knowledge of the environmental consequences of social activities will provide insights for the people to strike a balance between social imperatives and environmental sustainability.

Technologically, the governments of LICs should identify the rate of technological obsolescence in their countries, and increase investment in new discoveries, enhance the rate of technological advances and innovative technological platforms in the areas of renewable energy resources. It may be necessary to increase investment (in Research & Development) on how to produce renewable energy at a lower cost relative to non-renewable energy. Legally, the governments of LICs should revisit all kinds of product regulations, employment regulations, competitive regulations, patent infringements, health and safety regulations that inhibit the adoption and use of green technologies in the countries. It should implement stringent environmental laws and regulations to mitigate environmental degradation. Environmentally, the governments of LICs should employs effective environmental regulations, conservation and decarbonization management, as well as punishment and supervision of polluting firms or industries to ensure environmental sustainability. Issues relating to geographical location, the climate and weather, waste disposal laws, energy consumption regulation, and people's attitude towards the environment should be prioritized in their environmental agenda.[8]

6. Conclusion

This study employs panel and disaggregated data of 26 LICs to examine the effects of REN, GDP and their interaction on pollution. Our diverse empirical strategies allow us to control diverse econometric and economic issues. We reveal that LICs can actually grow-out of pollution as hypothesized by the EKC. We also show that though REN alleviates pollution, but the interplay between REN and GDP does not. Specifically, the marginal effects of REN on pollution increases as GDP increases, suggesting that real income undermines the effect of REN on pollution in LICs.

This study has some policy implications. First, since LICs can actually grow-out of pollution, priority should be given to the acceleration of GDP in the development agenda of LICs. Second, since REN mitigates pollution, LICs should raise the percentage of energy sourced from renewable resources in the total energy consumption mixture. It may be necessary to encourage the development and utilization of renewable energy technologies to enhance the maximization of renewable energy resources. Finally, since real income undermines the impact of REN on pollution, LICs should adopt production techniques (e. g. green real income and technologies) that do not worsen pollution. They should optimize their industrial structure through a reduction the amount of high-energy, high-pollution, and resource-intensive firms or industries. This industrial transformation can accelerate real income without aggravating emissions.

This research succeeds in revealing how the interplay between REN and GDP affect pollution in LICs. Since renewable energy is obtained from different sources (e.g., hydro, solar, wind, biomass), it is recommended that future study should investigate the moderating roles of these sources on the nexus between real income and environmental pollution in LICs. Since GDP and REN differ among diverse income groups, it is recommended that future studies should explore this subject matter in HICs and MICs. Besides, we employ carbon emissions as our dependent variable, it is recommended that future research should employ another indicator of environmental pollution (e.g., greenhouse gases, ecological footprint, etc) for the purpose of inferences.

[8] Despite the recommendations that high-carbon intensity LICs should switch to green technologies and renewable energy production, we acknowledge that many LICs have struggling political, economic, and social situations that may lower their priority for renewable energy production and consumption. Apart from low per capita income, most LIC are characterized by high poverty and unemployment rates; poor health care and education systems; high income inequality; rapid population growth rates; heavy reliance on primary sectors (e. g., agriculture) and dependence on exports of primary commodities; low infrastructural and technological development; security challenges and undeveloped legal system; inadequate access to housing, safe water, food security and sanitation; low opportunities for global trade and partnership. These issues may be top in the development agenda of LICs rather than environmental sustainability.

Credit author statement

Eyup Dogan: Supervision, Model; Kizito Uyi Ehigiamusoe: Writings, Data, Analysis: The role of interaction effect between renewable energy consumption and real income in carbon emissions: Evidence from low-income countries.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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