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Renewable Energy Consumption and Carbon Emissions—Testing Nonlinearity for Highly Carbon Emitting Countries

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Abstract: An increase in energy consumption indicates increased economic activity; whether it leads to prosperity depends on the sustainability and stability of the energy source. This study has selected the top ten highly carbon emitting countries to assess renewable energy consumption dynamics for 1991 to 2018. The development of renewable energy ventures is not an overnight transformation. Further, it also entails an infrastructure development gestation which may increase CO_2 emissions for the short term. To assess this non-linear pattern with CO_2 and its heterogeneities, renewable energy consumption and its three types (Wind, Solar and Hydropower) are used. The empirical results estimated with a pooled mean group (PMG) method indicate that renewable energy consumption and hydropower follows inverted U-shaped behavior, with wind and solar energy consumption behavior also U-shaped. Forest area and patents are responsible for carbon remissions, while economic growth is responsible for increasing carbon emissions in sampled countries.

Keywords: environmental quality; energy sustainability; Panel ARDL

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1. Introduction

Over time, energy consumption in economic activities has increased rapidly worldwide [1]. According to British Petroleum statistics, the world total energy consumption in 1991 was 8168 Mtoe (million tones oil equivalent) which rose to 13,865 Mtoe in 2018 (BP-Statistics, 2019). The leading form of energy is based on fossil-fuels [2], which fulfil almost 85% of the global total energy requirements [3]. Fossil-fuel-based energy use is a major cause of carbon emission and global warming [4]. It also causes numerous types of environmental issues, which reduce the earth's carrying capacity, hampering sustainable development.

The major originator of carbon emissions in the world is from the large economies of the world. The top ten polluted countries contribute almost 62% of the total world GDP [5]. On the other hand, these ten countries consume almost 65% of the total world energy and are responsible for 67% of global carbon emissions [3]. The pie chart in Figure 1 contains the summarized information about carbon dioxide emissions by these top 10 countries, here China, USA and India had a major share in the CO_2 emissions.

These countries are now focusing on transitioning their energy portfolio. One report summarized the strategies and challenges faced by these countries [6]. Brazil is focusing on increasing the biofuels and reducing deforestation. Canada has committed to the Kyoto Protocol of reducing emission 6%. China has aimed to only use 20% of its energy from fossil fuel in order to cut down the imports of coal. For this they are limiting the power grid companies to prioritise renewable energy.

Europe has committed to reducing emissions by 20%, for this they have use the strategy of carbon credits. India is participating in Clean Development Protocol and ambitiously set a goal to extract 20 gigawatts of energy from solar source. Indonesia has pledged to reduce emissions by 26% by moving away from using wood as energy. After the Fukushima incident, Japan is looking to explore renewable energy alternatives to nuclear energy to reduce emissions by 25%. Russia has declared their energy-efficiency goals but environmentalists are skeptical of it. Lastly, the USA pledges a 17% reduction in emissions; several states are capping greenhouse gas emissions to achieve this target.

In recent years, countries have recognized such problems. Therefore, the pursuit of alternative energy sources has started [7,8]. Energy consumption from hydrocarbon-based sources is the primary source of CO_2 emissions [9]. The policymakers and scientists have considered green or renewable energy to combat environmental problems [10,11].

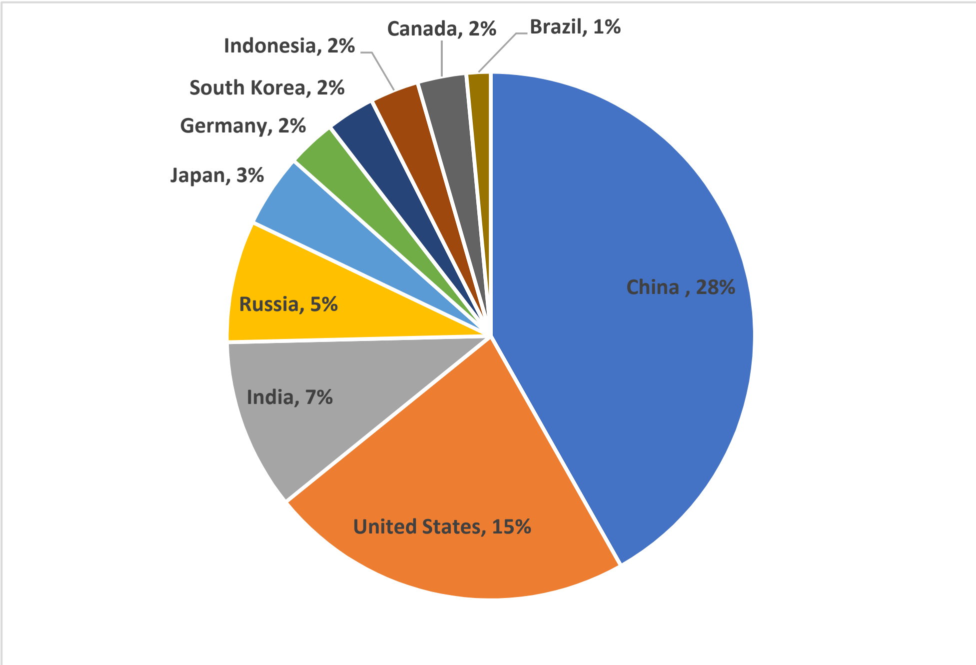

Figure 1. CO_2 Emissions (% Share by Country). Source: British Petroleum Statistics and Union of Concerned Scientists [3,12].

The aspiration to increase economic growth has caused an upsurge in the demand for energy [13], due to which an increased energy consumption directly affects carbon emission [14] economic growth in the short run [15]. The impact of renewable energy consumption on the environment is favorable rather than non-renewable [16,17]. So, in the long run, green economic growth, renewable energy consumption can be a better choice [18,19].

Other factors are also openly related to carbon emissions, including innovations [20]. Innovations help improve existing technology and make them energy-efficient and eco-friendly [21,22]. On the other hand, forests benefit the environment by becoming a carbon sink [23,24]. Economic growth has a profound impact on the environment, as confirmed by studies of STIRPAT [25].

The impact of renewable energy is not as straightforward as it seems. The infrastructure of renewable energy is yet to be developed. So when a nation transitions energy composition to renewable energy, they have to plan to develop the appropriate infrastructure, which will entail pollution from construction and logistics [26]. So, studying a longer horizon, the renewable energy projects start from net positive CO_2 positive emissions, which will be offset in due time when it starts reducing CO_2 emissions [27]. Keeping in view the significance of energy in the environment, this study aims to test the non-linear impact of renewable energy consumption and its three types (wind, solar and hydro) on carbon emissions. For this purpose, the sample of the top ten highly carbon-emitting countries are taken. Other factors like forests area, innovations and economic growth are also taken to control carbon emissions. It is also included in this study's objective to propose a suitable policy, keeping in view the importance of renewable energy consumption.

After a comprehensive introduction regarding energy consumption and carbon emissions, the study reviewed some existing literature to strengthen the subject matter and identify the literature gap. After that, a procedural outline to discuss the econometrics techniques and later the results and discussion. As environmental protection is related to sustainable development goals, this study also interlinked the findings with these Sustainable Development Goals (SDGs). In the end, there is the conclusion of this study.

2. Literature Review

Environmental pollution is a worldwide challenge. There is a need for a consented struggle to alleviate carbon emanation hazards. The relevant literature on carbon emissions, forest area, renewable energy consumption, and innovation is revisited. One study selected nine developed nations. Their findings revealed that carbon emission lessens due to renewable energy consumption [28]. Similarly, a study has selected the top renewable energy countries [29] and another selected five emerging market economies [30]; both of these studies found that renewable energy consumption is responsible for reducing carbon emissions, and it is a better alternative than nuclear energy [31]. A similar outcome was shown for Denmark and Finland [32] and for 74 carbon emitting countries [33]. Several other recent studies are in line with this notion that renewable energy is good for the environment [34–37], but one study found mixed results for the African countries [38].

The present literature gives plentiful studies exploring the association between carbon emissions and technological innovations, but empirical results are contradictory. A study in China found that carbon emissions decline due to innovations in technology [39]. Another study explored technological progress and technical efficiency in carbon emanations for China. They reported that, for reducing carbon emanations, low carbon investments and technological innovations are momentous [40].

Correspondingly, one study has reported an insignificant linkage between innovations and carbon in Malaysia [41]. The investment in technological innovations is futile in lessening the carbon emanation in the production sector for BRICS countries [42].

Researchers have reported innovations, and carbon releases and technology innovations are related negatively for China [43]. Likewise, technological innovations have a negative and momentous influence on carbon releases for global 30 countries [44]. Similarly, some authors have noted that an increase in energy innovations reduces carbon emissions for France [45]. The findings for OECD countries [46] and for a panel of 80 countries [25] indicate that innovations can protect the environment.

Literature suggests that forests are still the most efficient carbon absorbers [23,24,47]. One study pointed out that if there is a consistent decrease in forest area, planting more trees might not reduce CO_2 emissions as new trees are not an efficient carbon sink [48].

There is extensive literature about economic growth leading to carbon emissions [49–57]. According to them, economic growth is responsible for damaging the environment. Beyond the specific level, economic growth starts to reduce CO_2, confirming an inverted U-shaped relationship, also known as the Environmental Kuznets curve (EKC). The antecedents of these inverted U-shaped effects are an excessive use of fossil energy at the start, for positive effects, and innovation at the end for negative effects. This study linearizes the quadratic effect of economic activity by using variables such as renewable energy and innovation in the model. Hence, now economic activity will represent human behaviors, resource scarcity and their compliance to carbon literacy.

Therefore, our study's contribution to the existing literature is twofold. First, this study explores the influence of renewable energy consumption overall and disaggregated energy like Hydro, Solar and Wind on carbon emission, by considering the role of technological innovation, economic growth and forest area. There is a dearth of studies exploring the quadratic impact of sub-indices of renewable energy consumption (Hydro, Wind and Solar) on carbon emission for top 10 polluted countries to the best of our knowledge. Few studies have explored the quadratic function in studying energy and development; this study extends it to different types of renewable energy on CO_2 emissions [58,59]. Secondly, this study has incorporated renewable energy and its three types of non-linearity in the expectation that green energy transition via these energy sources will have different effects on CO_2 emissions. So, these were the missing aspects which this study is going to fulfil.

3. Empirical Model

3.1. Theoretical Background

The framework to explore the non-linear relationships to develop the environmental Kuznets curve is discussed in the literature [25,60]. This study is adopting this model in explaining the role of renewable energy on environmental quality. The hypothesis of this study is the inverted U-shaped effect of energy source with CO_2 emissions in Figure 2. Here, Figure 2a depicts the depreciation in the environment when the country is developing the required infrastructure for renewable energy generation. This includes the developing and manufacturing of components, logistics and effort to build the energy plant and use of non-recyclable equipment.

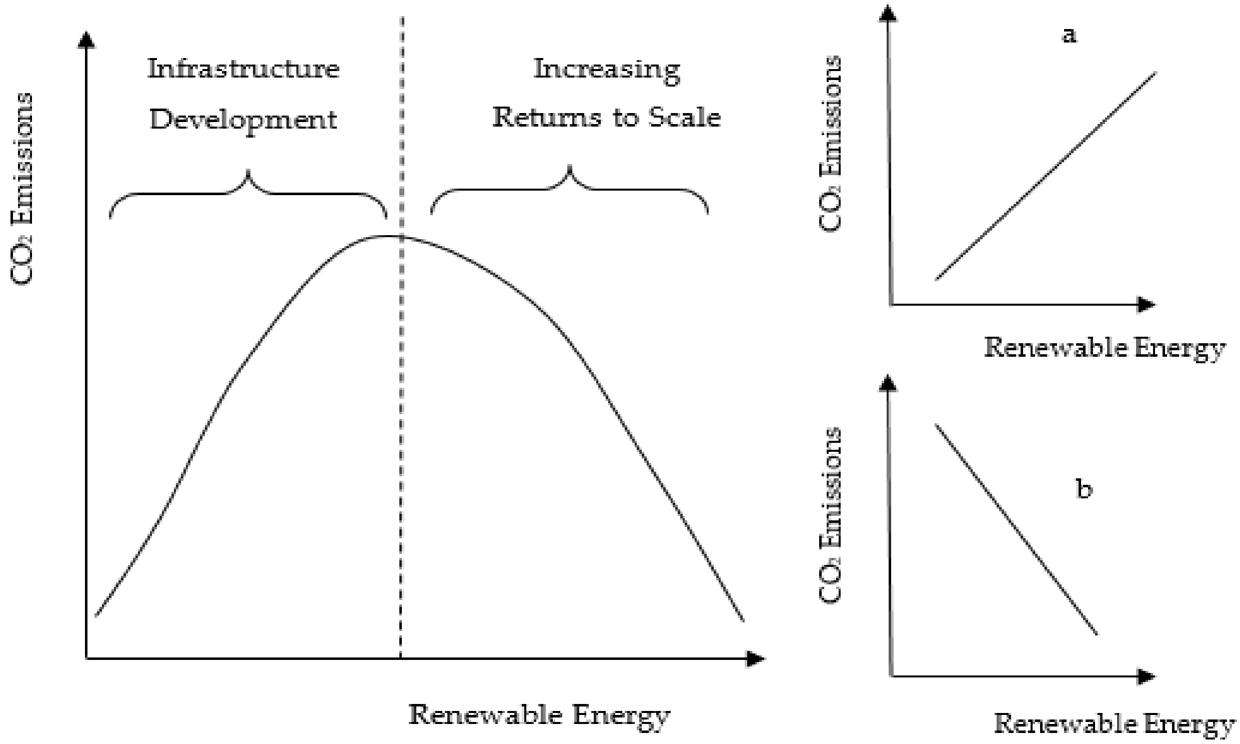

Figure 2. Theoretical Model of Inverted U-EKC. (**a**) Positive Renewable Energy Effect, (**b**) Negative Renewable Energy Effect.

Further, when the infrastructure is developed, Figure 2b shows the decrease in CO_2 emissions with the increase in renewable energy production, as confirmed by many studies in the literature.

Lastly, when several renewable energy production ventures are being developed in the country and are in different stages of development or energy production, then an increase in energy production from renewable sources at the national level will follow the inverted U-shaped pattern as shown in Figure 2, because this opposite effect of increasing and decreasing CO_2 requires optimization to produce renewable energy to at least reach a level where it offsets the CO_2 emitted from the projects which are under development. In order to estimate the U shaped pattern, this study had used the quadratic transformation of renewable energy indicators. This quadratic transformation will provide the average linear and curvilinear effect [60]. However, the exact shape of the curve also depends on the incidence (mean and standard deviation) of the independent variable [61].

3.2. Modeling and Data

In this study, the association between renewable energy consumption and its three types like Wind, Solar, Hydro and carbon dioxide emissions is done by incorporating some controlling factors such as technological innovations, forest area and economic growth. Since these energy indicators are presented in the form of % of total, it also explains the transition from fossil energy to renewable energy. The sampled countries are USA, India, South Korea, China, Japan, Russia, Germany, Canada, Brazil, and Indonesia, which were the 10 most polluted economies during 1991–2018. For this purpose, the unbalanced panel data of renewable energy consumption and its further types are obtained from British Petroleum [3]. Additionally, forest area data, technological innovation, carbon dioxide emissions and economic growth are taken from world development indicators [5]. The analysis is conducted in STATA. So, the proposed models of the study are as follows.

$$\text{ENV} = \text{f (REC, REC2, INN, FAS, ECG)} \tag{1}$$

$$\text{ENV} = \text{f (WEC, WEC2, INN, FAS, ECG)} \tag{2}$$

$$\text{ENV} = \text{f (SEC, SEC2, INN, FAS, ECG)} \tag{3}$$

$$\text{ENV} = \text{f (HEC, HEC2, INN, FAS, ECG)} \tag{4}$$

The Equations (1) to (4) are the four functional forms that this study has proposed to estimate environmental quality. Since this study intends to explore the quadratic role of transition towards sustainable energy, four proxies are used to expect a heterogeneous transition pattern. There are four equations leading to four models. Here, ENV is the carbon dioxide emissions (Metric tons per capita). REC is the renewable energy consumption (% of total energy consumption), and REC2 is its squared form. WEC is the wind energy consumption (% of total energy consumption), and WEC2 is its squared form. SEC is the solar energy consumption (% of total energy consumption), and SEC2 is its squared form. HEC is the hydro energy consumption (% of total energy consumption), and HEC2 is its square form. Among the controlling factors, INN is the per capita technological innovations (Patents non-residential plus residential applications per capita). FAS is the forest area (Square kilometers per capita). ECG is the gross domestic per capita (constant US Dollar). The control variables, especially ECG are assumed to have constant returns to scale in terms of elasticity as the non-linear channel of ECG is discussed via transition of renewable energy consumption indicators. ECG controls for the effects of recession in the development plans of renewable infrastructure and its effect on CO_2. All these variables are in the natural log form to linearize the model. The proposed stochastic equations are as follows.

$$\text{ENV}_{it} = \beta_{0i} + \beta_1\,\text{REC}_{it} + \beta_2\,\text{REC2}_{it} + \beta_3\,\text{INN}_{it} + \beta_4\,\text{FAS}_{it} + \beta_5\,\text{ECG}_{it} + \xi_t \tag{5}$$

$$\text{ENV}_{it} = \beta_{0i} + \beta_1\,\text{WEC}_{it} + \beta_2\,\text{WEC2}_{it} + \beta_3\,\text{INN}_{it} + \beta_4\,\text{FAS}_{it} + \beta_5\,\text{ECG}_{it} + \xi_t \tag{6}$$

$$\text{ENV}_{it} = \beta_{0i} + \beta_1\,\text{SEC}_{it} + \beta_2\,\text{SEC2}_{it} + \beta_3\,\text{INN}_{it} + \beta_4\,\text{FAS}_{it} + \beta_5\,\text{ECG}_{it} + \xi_t \tag{7}$$

$$\text{ENV}_{it} = \beta_{0i} + \beta_1\,\text{HEC}_{it} + \beta_2\,\text{HEC2}_{it} + \beta_3\,\text{INN}_{it} + \beta_4\,\text{FAS}_{it} + \beta_5\,\text{ECG}_{it} + \xi_t \tag{8}$$

Four regression lines are being estimated (against four functional forms Equations (1) to (4) in this study. Different forms of energy are assessed in different equations to avoid collinearity, shown in Equations (5) to (8). Here i represents cross section and t represents time, β_0 is the intercept term, β_1 to β_5 are the elasticities of respective variables, and ξ_t is the white noise error term. The estimated model adapted by the study will ensure that the ξ_t term is independently and identically distributed.

4. Procedural Outline

4.1. Panel Unit Root Test

Long panel data models tend to depict the properties of non-stationarity. To check the stationarity/unit root trend in the variables across all countries jointly, this study has been applied Levin Lin and Chu (LLC) test proposed by [62]. LLC is a specified panel unit root test, and this test incorporated lags of the dependent variable and follows the below presented Equation (5).

$$\Delta Y_{it} = \varphi\, Y_{i,\, t-1} + Z_{it}'\gamma_i + \sum_{j=1}^{p} \theta_{ij}\Delta Y_{i,\, t-1} + \mu_{it} \quad (9)$$

4.2. Panel Cointegration Test

If any of the variables is non-stationary, then the set of variables must be cointegrated jointly across all countries to have reliable long run estimates. Two panel cointegration tests are applied in this study. First is the Kao Test [63] and second is the Pedroni test [64]. Few studies have used similar unit root and cointegration tests for the validation of environmental quality models [65].

4.3. Panel ARDL/Pooled Mean Group

Since the sample has more than 20 years per cross section the model is expected to be dynamic and non-stationary. The model is estimated using a panel Autoregressive Distributive Lag (ARDL) or pooled mean group (PMG) method. This PMG method assumes homogeneity of long-term parameters while permitting the short-term coefficients to differ among economic groups [66]. The Panel ARDL model has been used widely [67–71]. This Panel ARDL-PMG has three aspects: long run coefficients, short run coefficients and the error correction model, where the short run coefficients vary across cross sections while the long run assumes homogenous across cross sections. Equations (10) to (13) are representing the ECM equation form which is the estimate-able version of Equation (5) to (8) in time series perspective [72], PMG model selects the lag order for all variables selected using AIC method. Because of limited data, the model is simplified to a maximum lag of 1. In these equations, the β_2 to β_6 when divided with β_1 provide long run coefficients, and αs are short run coefficients, respectively. ε_{it} is the normally distributed error term different for each equation and is assumed to have zero mean and constant variance.

$$\begin{aligned}\Delta ENV_{it} = \alpha_{0i} &+ \sum\nolimits_{j=1}^{k}\alpha_{1ji}\,\Delta ENV_{it-j} + \sum\nolimits_{j=0}^{k}\alpha_{2ji}\,\Delta REC_{it-j} + \sum\nolimits_{j=0}^{k}\alpha_{3ji}\,\Delta REC^2_{it-j} \\ &+ \sum\nolimits_{j=0}^{k}\alpha_{4ji}\,\Delta INN_{it-j} + \sum\nolimits_{j=0}^{k}\alpha_{5ji}\,\Delta FAS_{it-j} + \sum\nolimits_{j=0}^{k}\alpha_{6ji}\,\Delta ECG_{it-j} \\ &- \beta_1\, ENV_{it-1} + \beta_2\, REC_{it-1} + \beta_3\, REC^2_{it-1} + \beta_4\, INN_{it-1} + \beta_5\, FAS_{it-1} + \beta_6\, ECG_{it-1} + \varepsilon t\end{aligned} \quad (10)$$

$$\begin{aligned}\Delta ENV_{it} = \alpha_{0i} &+ \sum\nolimits_{j=1}^{k}\alpha_{1ji}\,\Delta ENV_{it-j} + \sum\nolimits_{j=0}^{k}\alpha_{2ji}\,\Delta WEC_{it-j} + \sum\nolimits_{j=0}^{k}\alpha_{3ji}\,\Delta WEC^2_{it-j} \\ &+ \sum\nolimits_{j=0}^{k}\alpha_{4ji}\,\Delta INN_{it-j} + \sum\nolimits_{j=0}^{k}\alpha_{5ji}\,\Delta FAS_{it-j} + \sum\nolimits_{j=0}^{k}\alpha_{6ji}\,\Delta ECG_{it-j} \\ &- \beta_1\, ENV_{it-1} + \beta_2\, WEC_{it-1} + \beta_3\, WEC^2_{it-1} + \beta_4\, INN_{it-1} + \beta_5\, FAS_{it-1} + \beta_6\, ECG_{it-1} + \varepsilon t\end{aligned} \quad (11)$$

$$\begin{aligned}\Delta ENV_{it} = \alpha_{0i} &+ \sum\nolimits_{j=1}^{k}\alpha_{1ji}\,\Delta ENV_{it-j} + \sum\nolimits_{j=0}^{k}\alpha_{2ji}\,\Delta SEC_{it-j} + \sum\nolimits_{j=0}^{k}\alpha_{3ji}\,\Delta SEC^2_{it-j} \\ &+ \sum\nolimits_{j=0}^{k}\alpha_{4ji}\,\Delta INN_{it-j} + \sum\nolimits_{j=0}^{k}\alpha_{5ji}\,\Delta FAS_{it-j} + \sum\nolimits_{j=0}^{k}\alpha_{6ji}\,\Delta ECG_{it-j} \\ &- \beta_1\, ENV_{it-1} + \beta_2\, SEC_{it-1} + \beta_3\, SEC^2_{it-1} + \beta_4\, INN_{it-1} + \beta_5\, FAS_{it-1} + \beta_6\, ECG_{it-1} + \varepsilon t\end{aligned} \quad (12)$$

$$\begin{aligned}\Delta ENV_{it} = \alpha_{0i} &+ \sum\nolimits_{j=1}^{k}\alpha_{1ji}\,\Delta ENV_{it-j} + \sum\nolimits_{j=0}^{k}\alpha_{2ji}\,\Delta HEC_{it-j} + \sum\nolimits_{j=0}^{k}\alpha_{3ji}\,\Delta HEC^2_{it-j} \\ &+ \sum\nolimits_{j=0}^{k}\alpha_{4ji}\,\Delta INN_{it-j} + \sum\nolimits_{j=0}^{k}\alpha_{5ji}\,\Delta FAS_{it-j} + \sum\nolimits_{j=0}^{k}\alpha_{6ji}\,\Delta ECG_{it-j} \\ &- \beta_1\, ENV_{it-1} + \beta_2\, HEC_{it-1} + \beta_3\, HEC^2_{it-1} + \beta_4\, INN_{it-1} + \beta_5\, FAS_{it-1} + \beta_6\, ECG_{it-1} + \varepsilon t\end{aligned} \quad (13)$$

Panel ARDL or PMG includes the error correction model (ECM), which is the speed of convergence of the model or correction speed. This coefficient expresses how much time the economy must come again in the equilibrium after any random shock. In Equations (10) to (13), the β_1 term represents the convergence coefficient whose negative value between −1, 0 represents that the model is converging.

The Panel ARDL/PMG models are designed to incorporate the cross sectional heteroscedasticity, serial autocorrelation and cross sectional dependence. Further miss-specification is addressed using the quadratic function [73,74].

5. Analysis and Discussion of Results

Descriptive Statistics

The empirical analysis started from Table 1, which is about the combined descriptive analysis for all countries in the panel data. Here we can see that all the variables have a mean value higher than the standard deviation, which means these variables are under dispersed and closely scattered in the sample. Here the mean value of the data is a better representation for all the countries in the sample.

Table 1. Descriptive Statistics.

Variables	Mean	S.D	Minimum	Maximum	Observations
ENV	1.739	1.014	−0.33	3.01	280
REC	2.365	1.306	−0.817	4.057	250
WEC	−3.17	3.156	−11.5	2.09	241
SEC	−4.86	2.985	−10.8	1.289	217
HEC	1.403	1.26	−1.76	3.641	280
INN	0.094	0.116	0.000	0.420	280
FAS	2.054	3.445	0.009	12.420	260
ECG	9.335	1.348	6.355	10.907	280

Table 2 provides the recent incidence of renewable energy consumption as percentage of total energy consumption for the selected countries. Here we can see that countries like Brazil, Canada, China, India, and Indonesia had relied on hydro energy. Countries like Germany had relied on wind energy. Meanwhile, countries like Japan, South Korea and USA are relying on more than one source.

Table 2. Renewable Energy Consumption in 2018.

Country	Renewable Energy Consumption	Wind Energy	Solar Energy	Hydro Energy
Brazil	34.80181	3.84059	0.24852	30.7127
Canada	22.80599	1.73458	0.19121	20.8802
China	12.14472	2.5459	1.23469	8.36413
Germany	12.65646	8.08647	3.34532	1.22467
India	6.50715	1.70106	0.8668	3.93929
Indonesia	2.06452	0.02458	0.00228	2.03766
Japan	8.08133	0.34406	3.63278	4.10449
Russia	5.99758	0.00715	0.01793	5.9725
South Korea	1.11153	0.18208	0.70824	0.22121
USA	5.10868	2.13823	0.74771	2.22274

Table 3 provides the panel unit root test estimates to check whether the selected variables are stationary or non-stationary. Here the unadjusted *t*-test and adjusted *t*-tests are provided with the null hypothesis that the series are stationary. The test values with an asterisk show the significance of test and acceptance of alternative hypothesis. Here, only hydro energy consumption is stationary at a level while others are stationary at first difference. This mixed order of integrated has merited the use of Panel ARDL model. Further, Table 4 provides the estimates of the panel cointegration test. The null hypothesis is no cointegration among the selected variables shown in Equations (1) to (4) which denote as model 1 to 4, respectively. Here, the test values which have an asterisk sign shows that the alternative hypothesis is accepted for that case. It denotes that most tests indicate the presence of cointegration for the regression models, which are to be estimated. According to these significant test statistics, the Equations (10) to (13) can estimate long run and short run effects. The significant results mean the rejection of null hypothesis which refuse the existence of cointegration.

Table 3. Levin Lin and Chu Unit Root Test.

	At Level		At First Difference	
Variables	**Unadjusted *T*-Test**	**Adjusted *T*-Test**	**Unadjusted *T*-Test**	**Adjusted *T*-Test**
ENV	−1.932	−0.417	−7.869	−1.944 **
REC	−2.199	−0.589	−8.473	−2.015 **
WEC	5.691	11.313	−8.828	−1.517 *
SEC	−0.719	9.299	−4.393	−4.268 ***
HEC	−5.577	−2.019 *	−14.603	−7.989 ***
INN	−1.875	0.595	−9.988	−3.107 ***
FAS	−4.674	−2.654 ***	−3.448	−1.685 **
ECG	−1.223	−0.652	−7.915	−2.570 ***

***, **, * Demonstrate significance level at 1%, 5% and 10%, respectively.

Table 4. Pedroni and Westerlund Cointegration Test.

	Model 1	**Model 2**	**Model 3**	**Model 4**
Pedroni Test	**Test Statistic**	**Test Statistic**	**Test Statistic**	**Test Statistic**
Modified Phillips-Perron *t*-test	1.510 *	1.133	2.483 ***	1.989 **
Phillips-Perron *t*-test	−3.150 ***	−1.573 *	−3.285 ***	−2.037 **
Augmented Dicky-Fuller *t*-test	−3.664 ***	−2.551 ***	−2.716 ***	−2.432 **
Westerlund Test				
Variance Ratio	−1.485 *	−1.953 **	0.215	−0.876

***, **, * Demonstrate significance level at 1%, 5% and 10%, respectively.

Table 5 presents the long run results of all the models; as the study is based on panel data and these results are estimated using PMG these long run coefficients are homogenous for all country groups. Regarding model 1, the results demonstrate that renewable energy consumption has an Inverted-U shaped association with CO_2 emission. A 1% increase in renewable energy consumption increases carbon emission by 0.109%, whereas a 1% increase in a square of renewable energy consumption impedes carbon emanation by 0.0.82%, ceteris paribus. Based on the coefficients, the inverted U shape will have a peak value at 3.86% of renewable energy. Hence, if the selected countries increase their renewable energy consumption beyond 3.86% of total energy, their CO_2 emissions will fall for each unit of renewable energy consumed, accounting for the CO_2 produced during the power plant installation only. These results are supporting the hypothesis proposed by this study.

The coefficient of technology innovations was insignificant. The result of the forest area shows an influence on carbon emanations. A 1% rise in forest area leads to an increase in carbon emission by 0.139%, ceteris paribus. The outcome of economic growth demonstrates a progressive impression on carbon emission. A 1% increase in economic growth causes an upsurge in the carbon emission by 0.568%, ceteris paribus.

Regarding the long run results of model 2, wind energy consumption coefficient shows that a negative and its square also negatively impact carbon emission. It means it has an exponentially decreasing function. So, the 1% increase in wind energy consumption decreases the carbon emission by 0.087%. Further, a 1% rise in squared wind energy consumption causes a fall in carbon emission by 0.008%, ceteris paribus. This shows that the increase in share of energy consumption from wind will exponentially reduce CO_2. Since the signs are not changing in the equation, there is no cut off value.

Table 5. Long-run Coefficients.

Variables	Dependent Variable: ENV							
	Model 1		Model 2		Model 3		Model 4	
	Coeff.	S.E	Coeff.	S.E	Coeff.	S.E	Coeff.	S.E
REC	0.109 *	0.061						
REC2	−0.082 ***	0.016						
WEC			−0.087 ***	0.031				
WEC2			−0.008 ***	0.003				
SEC					−0.069 ***	0.022		
SEC2					−0.007 **	0.003		
HEC							−0.497 **	0.248
HEC2							0.095	0.086
INN	0.183	0.177	−0.923	0.698	−0.942 **	0.458	−3.206 ***	1.188
FAS	0.139 ***	0.031	0.103	0.093	0.178 **	0.075	0.174	0.122
ECG	0.568 **	0.039	0.890 ***	0.117	0.727 ***	0.092	0.656 ***	0.109
obs	240		240		240		240	
Cut off values	0.66		–		–		–	
Antilog.	3.86%							

***, **, * Demonstrate significance level at 1%, 5% and 10%, respectively.

Technological innovation and forest area has an insignificant effect. Economic growth leads to the rise of carbon emanation because the coefficient of economic growth shows that a 1% increase in economic growth increases carbon emanation by 0.89%, ceteris paribus.

Table 5 also contains long run results of model 3. Solar energy consumption is negative, and its square reduces carbon emission. It is indicating an exponential negative relationship. So, the 1% increase in solar energy consumption reduces the carbon emission by 0.069%. Additionally, a further 1% surge in solar energy consumption decreases the carbon release by 0.007%, ceteris paribus. The results are similar to the wind energy where an increase in energy consumption from solar energy will exponentially reduce CO_2 emissions. Since the signs are not changing in the equation so there is no cut off value.

The role of technology is statistically significant in this model; a 1% increase in innovation per capita will reduce CO_2 emissions by 0.942% on average, ceteris paribus. Further, 1% change in forest area increases the carbon discharge by 0.178%, ceteris paribus. Economic growth is positively connected with carbon emission, as a 1% increase in economic growth enhances carbon emission by 0.717%, ceteris paribus.

Table 5 also contains long run results of model 4. Hydro energy consumption is negative while the square of hydro energy consumption is insignificant. It has a linear negative relationship with carbon emissions. Thus, a 1% increase in hydro energy consumption causes a decrease in the carbon emission by 0.497%, ceteris paribus. Since the signs are not changing in the equation there is no cut off value.

Carbon emanation and technological innovation are negatively related. A 1% improvement in technological innovation declines the carbon emission by 3.206%, ceteris paribus. Forest area has an insignificant effect. Economic growth encourages carbon emanation. So, the 1% improvement in economic growth raises the carbon emission by 0.656%, ceteris paribus.

Table 6 is showing the finding of short run of all the models. In this table, the most important thing is the error correction model (ECM). In any external shock, if disequilibrium prevails in the proposed model, this coefficient tells the required number of years to attain the equilibrium again. For models 1 to 4, the time to coverage back to the equilibrium is 2.94, 10.31, 7.09 and 13.51 years, respectively. Here, from energy types, only hydro energy has a negative effect on CO_2 emissions in short run. Meanwhile, economic growth has a CO_2 promoting effect in all models in the short run.

Table 6. Short-run Coefficients with ECM.

Variables	Dependent Variable: ENV							
	Model 1		Model 2		Model 3		Model 4	
	Coeff.	S.E	Coeff.	S.E	Coeff.	S.E	Coeff.	S.E
ECM_{t-1}	−0.340 ***	0.102	−0.097 ***	0.001	−0.141 ***	0.032	−0.074 **	0.019
ΔREC	7.113	6.234						
ΔREC2	−1.119	0.979						
ΔWEC			−0.018	0.127				
ΔWEC2			−0.001	0.001				
ΔSEC					−0.027	0.187		
ΔSEC2					−0.002	0.001		
ΔHEC							−0.017	0.017
ΔHEC2							−0.023 **	0.007
ΔINN	0.502 ***	0.165	0.403	0.271	0.097	0.253	0.933 ***	0.245
ΔFAS	−1.601	12.837	0.202	0.351	0.079	0.886	0.042	0.318
ΔECG	0.552 ***	0.160	0.892 ***	0.095	1.027 ***	0.120	0.447 ***	0.073
Cons.	−1.215 ***	0.336	−0.676 ***	0.198	−0.762 ***	0.213	−0.306 ***	0.112
Conv. Speed	2.94		10.31		7.09		13.51	

***, **, * Demonstrate significance level at 1%, 5% and 10%, respectively.

Figures 3–6 show the post regression quadratic fit of overall renewable energy against the marginal effects, wind energy, hydro energy and solar energy, respectively. Their plots are based on the long run coefficients, mean and standard deviation [75]. Here we can see that overall renewable energy (in Figure 3) follows the negative portion of the inverted U shape relationship, the wind energy (in Figure 4) shows a decrease in CO_2 emissions and hydro energy (in Figure 5) is showing an inverse relationship. This is because of the incidence of the data [60,75].

While comparing Figures 3 and 4 the difference is accounted for by the low values of wind energy compared to the total renewable energy by definition. Solar energy (in Figure 6) shows the increasing effect at diminishing rate relationship making inverted U shape effect. Here the coefficients were not showing alternative slope directions, but still the curvature in Figures 4 and 6 pointed to an initial positive effect. The reason behind it is that the data is in logarithemic form whereby if the incidence is less than 1% of total energy, its log transformation will have negative value. So at low values (<1% of renewable energy) the marginal effect becomes positive. Hence, because of transformation there is a threshold in this renewable energy type, i.e., 1% of total energy consumption.

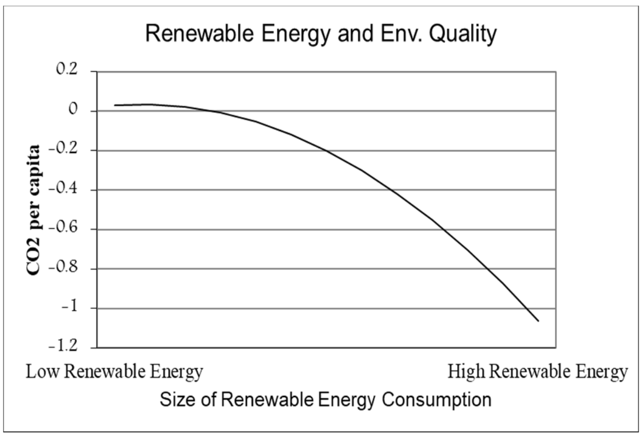

Figure 3. Renewable energy fit.

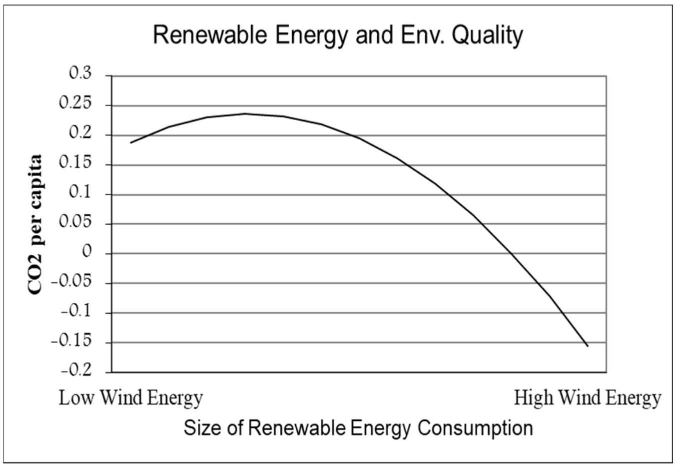

Figure 4. Wind energy fit.

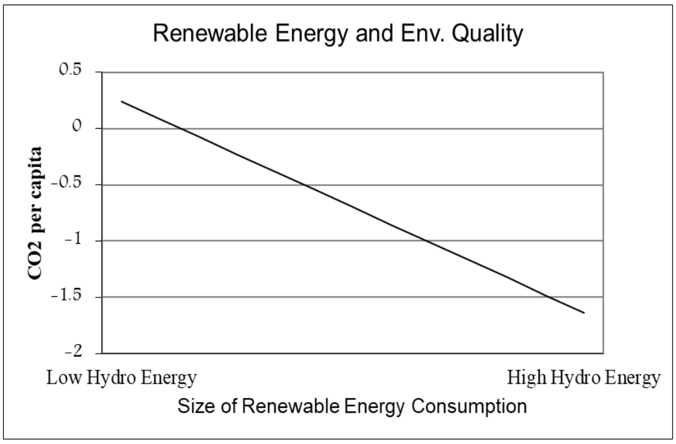

Figure 5. Hydro energy fit.

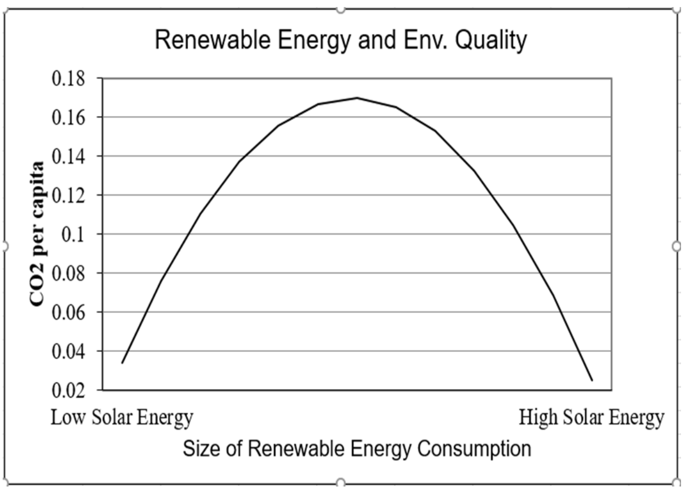

Figure 6. Solar energy fit.

All these graphs are showing different patterns as compared to the overall case (Figure 3), this confirms the proposed theory that all renewable energy development projects are not at same stage, some are currently constructed, causing CO_2 emission because of logistics while others are producing energy leading to reducing CO_2 emissions.

Since the PMG model is robust to most of the panel post regression issues, this study has assessed the common diagnostics which showed that the model is valid.

While comparing the y axis values in the Figures 3–6, it is noted that the Figures 4 and 5 have shown the lowest estimated CO_2 values for each unit increase in the respective renewable energy. This means that wind and hydro energy has the highest potential in mitigating CO_2 emissions from the energy sector. Table 2 shows that countries like Indonesia and Russia must adapt the Germany model of higher wind energy consumption. And South Korea must adapt hydro energy learning from the hydro energy consumption dominant countries.

Lastly, Table 5 presents the country wise linearized marginal effects estimated at the 2018 value of relevant energy consumption. Since each country has different incidence of renewable energy in 2018, they exhibit different effects on emissions while staying within the estimated quadratic effects.

Here the asterisked terms represent the positive marginal effect of the particular energy consumption of that country in 2018. The estimates indicate that the incidence of renewable energy is not high enough to offset the CO_2 produced during the transition process. These countries include Indonesia and South Korea for renewable energy total, Indonesia, Russia and South Korea for wind energy, Brazil, Canada, India, Indonesia, Russia, South Korea and USA for solar energy and South Korea for hydro energy. Here the positive effect (for South Korea) generated from the linear negative model of hydro energy consumption is because of negative values from log transformation of values less than 1%. So the transformation-based threshold for South Korea is to cross 1% of overall energy consumption

The model directs these countries with positive marginal effects to allocate resources to increase the respective level of renewable energy consumption to increase net CO_2 reduction from their economies.

6. Implications for Cleaner Production Based Development

According to the estimated results, the proposed indicators including incidence of renewable energy are playing their role in the production process to impact carbon emission in the long run. Renewable energy and its different types have heterogeneous country-wise impacts on carbon emissions defined by non-linear specification. These heterogeneous effects are because of differences in the average renewable energy consumption and its differences in the incidence across all countries [75]. These estimations are vital, keeping in view the sustainable economic growth proposed by United Nations [1]. To achieve the desirable targets of sustainable development with respect to environment, this study plays its role in optimizing the renewable energy consumption in these sampled countries with high CO_2 emissions.

So, to protect the environment, renewable energy consumption and its subtypes can reduce carbon emission as discussed in literature [16,34,52,76–78]. Moreover, few studies have proved the inverted U-shaped impact of renewable energy consumption on carbon emissions, which are also confirmed from this study for individual renewable energy types too [79]. It means that in the production processes of renewable energy power plants, there is a cost of developing new infrastructure for a transition toward cleaner energy production. When businesses or governments wish to install a new renewable energy plant, it requires equipment, logistics and construction mobilization, which cause CO_2 emissions. However, later on, when the production process transitions to using renewable energy, it becomes cleaner and greener.

Similar is the case for solar energy. Studies also established that solar energy can reduce carbon emissions [80,81]. According to the long estimated results of this study, hydro energy type of energy consumption will decrease carbon emissions; it also has other benefits like water storage for agriculture purposes. The model has kept the insignificant variable because of model comparability, theoretical importance and allowing for a potential non-linear effect for future extensions.

At the second step, this study has incorporated the role of wind energy with carbon emissions. According to the long run findings of this study, wind energy consumption also has a significant impact on carbon emissions [82–84]. Wind energy has the potential to reduce carbon emissions. However, according to the estimated results of this study, wind energy has a U-shaped relationship. This is because the materials used in the production of wind propellers are not recyclable and their production includes CO_2 emissions [85].

So, keeping in view the sustainable development goals, this study can play its role; this study focuses on the portfolio management of renewable energy and its types for reducing carbon emissions. Renewable energy consumption itself is initially damaging the environment because of using non-recyclable materials, logistics and construction related emissions. This requires the further development of adapting green production processes. Hence, it takes a higher share of renewable energy to reduce CO_2 beyond what it produced during transition. So, this type of energy consumption is ideal rather than non-renewable energy consumption in the long run, but it is imperative to know which type and how much of renewable energy consumption is suitable for sustainability depending on the gestation time periods. This initial increase and later decrease in emissions were evident for wind and solar energy consumption.

The linearization of renewable energy effects (Table 7) showed that countries with high environment deterioration effects across all energy like Indonesia and South Korea need to devour measures in increasing the renewable energy consumption so that the net effect on CO_2 could be reduced.

Table 7. Marginal Effects at Consumption of 2018 level.

Country	Effect of Renewable Energy	Effect of Wind Energy	Effect of Solar Energy	Effect of Hydro Energy
Brazil	−0.65	−0.13	0.08 *	−1.70
Canada	−0.46	−0.05	0.09 *	−1.51
China	−0.24	−0.09	−0.01	−1.06
Germany	−0.25	−0.22	−0.09	−0.10
India	−0.08	−0.05	0.01 *	−0.68
Indonesia	0.04 *	0.21 *	0.16 *	−0.35
Japan	−0.13	0.08	−0.10	−0.70
Russia	−0.07	0.23 *	0.16 *	−0.89
South Korea	0.01 *	0.12 *	0.02 *	0.75 *
USA	−0.04	−0.07	0.02 *	−0.40

* positive effect on CO_2 at 2018 energy consumption level.

Keeping in view some controlling factors such as innovations has a significant impact on the reduction in carbon emissions as they make things better; in this way carbon emissions can also be reduced [25,46]. Forest are always found valuable for environmental protection [23,24,47,86], but few studies have pointed out that currently, the forest cover is decreasing (the selected data also showed that forests area per capita is reducing at 1.5% annually), which is releasing the carbon in the environment, which is showing a positive effect of increasing forest area on CO_2 as the new trees have less ability to absorb CO_2 as compared to old [48]. Economic growth always impacts the environment, but basically, the more the economic activity, the more the carbon emissions. The long run estimated results of this study are indicating that economic growth is harming the environment [51,56,87–89]. This study has added the channels of economic growth-based EKC by adding renewable energy and innovation. Hence, the linear effect is assumed to avoid multicollinearity.

For sustainable development, other factors like forests and innovations reduce carbon emissions so these countries should consider these two things completely. The sampled countries should grow more forests to move on sustainable economic growth besides innovative technologies. Economic growth at the cost of the environment is not an ideal choice, this study is indicating that economic growth in these countries is damaging the environment by releasing carbon. They should formulate some policies, rules and regulations regarding carbon friendly economic activity and speed up the transition to renewable energy. Basically, these countries should follow innovative and eco-friendly production techniques technology.

7. Conclusions

This study found the significant impact of overall renewable energy consumption along with its different types. Generally, renewable energy consumption follows the inverted U-shaped relationship with carbon emissions, which means initially renewable energy is responsible for increasing carbon emissions but is later responsible for reducing it. In its subtypes, only solar energy consumption is following this relationship. However, wind and solar energy consumption follow an inverted U-shaped relationship with carbon emissions, which means these energy consumptions initially reduce carbon emissions but later increase it. That is why this study indicates that if they favor renewable energy consumption, they should consider solar energy to depend on.

Innovations make the existing things better; these countries should spend a proper budget in the perspective of research and development, which leads to an increase in innovations. Through this channel, these countries can improve their technologies which consequently will improve the environment. Secondly, forests are very beneficial for human health; forests should not be cut down, rather they should be growing more to overcome the environmental issues. In fact, there should be a proper prohibition on forests being cut down. Firstly, to increase development, there is a need to increase economic growth but not at the cost of environmental deterioration. Economic growth can be useful for the environment if some innovative technology starts to occur during production. Environmental rules and regulations should be followed during the production process. Moreover, advertisements should also start to increase the consumption of healthy goods.

This study has some limitations as well, which can be covered by other researchers, these are also the directions for future research work. This study has focused only on highly carbon emitting countries and exploring the net CO_2 effect of renewable only excluding the CO_2 produced from fossil. This analysis can also be split into income or region wise categorize country groups and the role of non-renewable consumption can also be tested.

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