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Renewable energy, economic freedom and economic policy uncertainty: New evidence from a dynamic panel threshold analysis for the G-7 and BRIC countries

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Abstract

This study aims to demonstrate the impact of renewable energy consumption (REC) on environmental degradation using the EKC hypothesis testing for the BRIC and G-7 countries. Two EKC models were created and tested, with Model 2 including REC and other independent variables such as economic freedom (EF) and economic policy uncertainty (EPU), which affect the level of renewable energy consumption and CO_2 emissions. Empirical findings indicate that the EKC hypothesis is verified faster in the REC-EF-EPU-based EKC model (Model 2) than in the EF-EPU-based EKC model (Model 1) for G-7 countries since the turning point takes place earlier in Model 2 than in Model 1 with REC. This suggests that renewable energy consumption accelerates the reduction of CO_2 emissions. Moreover, this earlier turning point results in lower environmental cleaning costs, less time vesting, and saving resources and money for G-7 countries. However, the study found no evidence supporting the EKC hypothesis for the BRIC countries.

Keywords EKC hypothesis · Renewable energy consumption · EPU · BRIC and G-7 countries

JEL Classification P18 · Q4 · Q43

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1 Introduction

The relationship between economic growth and the environment is a critical issue for achieving sustainable development goals since high levels of economic activity can lead to significant environmental problems that negatively impact sustainable development (Bongers 2020). To combat environmental issues without compromising economic prosperity and well-being, it is essential to analyze and understand the impact of economic growth on environmental degradation. Grossman and Krueger (1991) proposed a non-linear relationship between economic growth and environmental degradation, illustrated by the inverted U-shaped curve of the Environmental Kuznets Curve (EKC) in Fig. 1.

According to the EKC hypothesis, a rise in real GDP per capita initially leads to an increase in CO_2 emissions in the first stages of economic growth due to the consumption of fossil fuels. Eventually, this leads to a decrease in CO_2 emissions after a certain turning point due to the adoption of eco-friendly technologies, policies, and cleaner energy demand (Dinda 2004; Soytas and Sari 2009; Aslan et al. 2018; Destek and Sarkodie, 2019a; Dogru et al. 2019; Erdogan and Acaravci 2019; Kisswani et al. 2019; Isik et al. 2019a, b; Destek et al., 2020a; Destek and Sinha, 2020b; Ongan et al. 2020; Ongan et al. 2022, 2023; Ahmad et al., 2023, 2022, 2021a, b, c; Alvarado et al. 2021a, b, c, 2022a; Işık et al. 2020a, 2021a, b, 2022; Çetin et al., 2023; Jabeen et el., 2023). Therefore, the critical question is how countries can reach this turning point with a lower real GDP per capita and earlier. Delaying the turning point will increase the cost of environmental cleaning and time investments for countries. On the other hand, an earlier turning point means that economic growth policies based on real GDP per capita and energy policies based on environmental degradation (i.e., CO_2 emissions) converge quickly and sustainably at a lower cost. Therefore, increasing renewable energy consumption is one of the factors that can accelerate the reduction of CO_2 emissions. As studies have provided solid
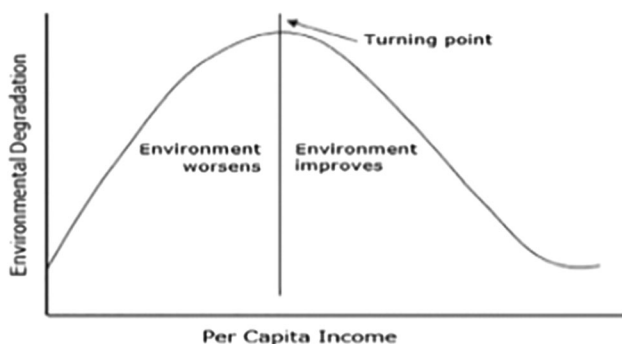

Fig. 1 Environmental Kuznets Curve (EKC)

evidence for the positive relationship between fossil energy consumption and environmental degradation, the focus has shifted toward renewable energy consumption. Therefore, recent studies have examined the nexus between renewable energy consumption, economic growth, and CO_2 emissions (Amoah et al. 2020; Ali et al. 2021; Alsanusi et al. 2022; Alvarado et al. 2022a, 2022b, c; Assi et al. 2021; Avci and Sarigul 2022; Baig et al., 2022; Deng et al. 2022; Fatima et al. 2022; Hussain et al. 2022; Jiang et al. 2022; Irfan et al. 2021; Pata and Işık, 2021; Kartal 2022; Rehman et al. 2022a, b, c; 2021a, 2021b, 2021c; Serttas et al., 2022; Yasir et al. 2022; Shahzad et al. 2021; Dogan et al. 2020; Dogru et al. 2020; Işık 2013; Işık et al. 2020a; Ongan et al. 2017, 2018a, b; Işık and Radulescu, 2017; Işık 2010; Bölük and Mert 2015; López-Menéndez et al. 2014).

Through EKC hypothesis testing, this study focuses on the importance of renewable energy consumption (REC) on environmental degradation. The study aims to determine if the EKC model with REC reaches the turning point earlier than the EKC model without this variable for the BRIC and G-7 countries. The study assumes that more economic freedom (EF) enables innovation and adopting eco-friendly technologies for more renewable energy consumption, but there is little research and mixed results on the EF-environmental degradation link. The study also considers changing economic policy uncertainty, measured by Baker et al. (2016) with the EPU index, which is significant for the renewable energy consumption- CO_2 emissions link and influences investments in renewable energy (Romano and Fumagalli (2018); Jiang et al. (2019); Adedoyin and Zakari, (2020); Işık et al. 2020b, Wang et al. (2020); Adams et al. (2020); Aimer, (2021). However, investments in renewable energy have decreased globally in recent years, and the International Energy Agency (IEA) is concerned that this development may negatively impact on achieving established climate objectives (IEA., 2018).

In this context, for testing the EKC hypothesis in the presence of independent variable renewable energy consumption (REC), we have built a REC-EF-EPU-based EKC model (Model 2). This model will be compared to Model 1 without REC as an EF-EPU-based EKC model. Furthermore, when we do this, we will examine all these relationships comparatively for the BRICS and G-7 countries, which have different EF, EPU, GDP, and CO_2 emissions levels. Our sample countries groups are the BRIC (Brazil, Russia, India, and China) and G7 (Germany, France, the UK, Italy, Canada, the USA, and Japan) (see averages of the CO_2 and GDP in Figs. 2, 3). In this context, this investigation will be between developed and developing economies.

Given these observations, the novelty of this research lies in the comparative analysis between the G7 and BRIC countries and the gaps in the literature. Firstly, G7 countries were selected for investigation because their leaders
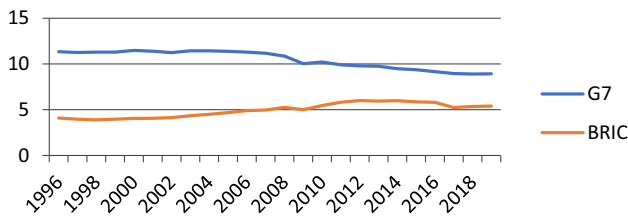
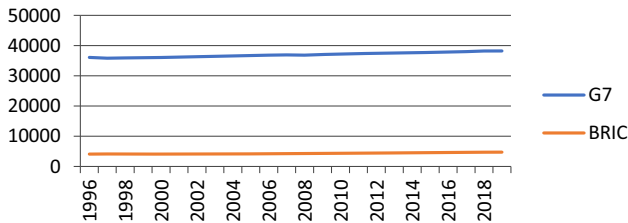Fig. 2 Average CO_2 in G7 and BRIC countries

Fig. 3 Average GDP in G7 and BRIC countries

significantly increased funding for nature by 2025 and mobilized substantial private finance to ensure faster net-zero emissions. On the other hand, BRIC states are among the world's largest polluters, with an aggregated population of over 3 billion people, significantly contributing to global emissions. Recent studies have also indicated that energy consumption has the most significant long-term effect on the environment, making it the primary cause of pollution for BRIC states (Yilanci et al., 2020). The comparative analysis focuses on these two groups of countries since they share the long-term target of reducing pollution, despite having different patterns regarding pollution levels (BRIC countries contribute more to global pollution than G7 countries). Thus, the novelty of this research lies in demonstrating how renewable energy consumption can be a solution to decreasing pollution for both groups of countries. While many studies confirm the role of renewable energy in reducing environmental degradation (Khattak et al. 2020), none of them analyze this topic comparatively for G7 and BRIC states, clustering of countries with different pollution trends but with the same objective of mitigating climate change.

The rest of this study is structured as follows: Sect. 2 summarizes the literature review. Section 3 explains the empirical model, while Sect. 4 presents the estimation methodology. In Sect. 5, the findings are discussed, and finally, Sect. 6 presents the conclusion with the study's policy implications.

2 Literature review

Many studies focused on the EKC hypothesis, including the independent variables of renewable energy consumption, economic policy uncertainty, and economic freedom,

with very mixed results regarding the shape of EKC. For instance, Jebli et al. (2013) applied the Fully Modified Ordinary Least Squares (FMOLS) and Dynamic Ordinary Least Squares (DOLS) models. They found evidence for the EKC hypothesis in the presence of renewable energy consumption. Bölük and Mert (2015) applied the autoregressive distributed lag (ARDL) approach and found no evidence for the EKC hypothesis, but found an association between REC and CO_2 emissions in Turkey. Bento and Moutinho (2016) applied the ARDL bounds testing approach to cointegration and verified the EKC hypothesis with the contribution of REC in CO_2 emissions for Italy. Bilgili et al. (2016) applied the FMOLS and DOLS models and verified the EKC hypothesis with the support of REC in reducing CO_2 emissions for the OECD countries. Jebli et al. (2016) applied the same methodology supporting the EKC hypothesis and found the same contribution of REC in reducing CO_2 emissions for the OECD countries. Dong et al. (2017) used the panel unit root, cointegration, and causality tests, and validated EKC hypothesis for the BRICS[1] countries. They also found a significant negative relation between REC and CO_2 emissions. López-Menéndez et al. (2014) examined 27 EU countries using panel data and proved the existence of the EKC hypothesis in the presence of REC. Danish et al. (2019) applied panel data estimation techniques to verify this hypothesis and found the REC's contribution to the BRIC countries' ecological footprint. Destek (2019b) applied the second-generation panel data methodologies and verified the EKC and REC's contribution to CO2 emissions in Central and Eastern European countries. Işık et al. (2019a, b) used the common correlated effects estimator and validated the EKC hypothesis for 5 out of 10 US states. They also found a significant contribution of REC to CO_2 emissions. Sharif et al. (2019) applied the heterogeneous panel estimations and verified the EKC. They also revealed the contribution of REC in 74 countries. Zhang et al. (2020) used the ARDL model and supported this hypothesis for developing Asian economies. They also found that renewable energy enhanced the trajectory rate of EKC. Erdogan et al. (2020) used the FMOLS and DOLS models and found evidence supporting the EKC hypothesis with REC for the OECD countries. Sun et al. (2020) used the Malmquist-Luenberger productivity index and verified the EKC with REC. Khattak et al. (2020) applied the common correlated effect mean group (CCEMG) technique. They found evidence supporting the EKC hypothesis in all BRICS countries and found the contribution of REC in CO_2 emissions only in Russia, India, and China. The following papers found mixed results regarding the relationship between economic freedom and environmental degradation. Carlsson and

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[1] BRICS countries are Brazil, Russia, India, China, and South Africa.

Lundström ([2001]) used the pooled estimation method and found that increases in economic freedom led to decreases in CO_2 emissions in low-income and high-income countries. Dasgupta et. al. ([2006]) applied the Hausman test for low-middle-upper-middle income countries. They found mixed results on the impact of economic freedom on CO_2 emissions Wood and Herzog ([2014]) applied the two-staged model and found that increased economic freedom led to decreasing CO_2 emissions. Hartwell and Coursey ([2015]) used a pooled OLS and a fixed-effects specification and found that economic freedom supports CO_2 emissions in 292 countries. Bae et. al. ([2016]) used the GMM approach for 15 post-Soviet Union independent (PSI) countries and found that high economic freedom increases CO_2 emissions. Joshi and Beck ([2018]) applied the Arellano-Bover/Blundell-Bond Generalized Method of Moments (GMM) estimator for 22 OECD countries. They could not find evidence supporting the positive contribution of economic freedom to environment. Adesina and Mwamba ([2019]) applied the GMM estimator for 24 African countries. They found that high economic freedom (proxied by the trade freedom index, business freedom index, freedom from corruption, and fiscal freedom index) increases environmental quality. Adesina and Mwamba ([2019]) applied the two-step system GMM methodology for 12 African countries. They found that increases in economic freedom improve environmental quality lowering CO_2 emissions. Shahnazi and Shabani ([2021]) applied cross-sectional dependence and found evidence supporting the positive contribution of economic freedom to CO_2 emissions in the EU area. The following papers found mixed results regarding the relationships between environmental degradation and the economic policy uncertainty (EPU) index. Jiang et al. ([2019]) applied a novel parametric test of Granger causality in quantiles for the USA. They found that CO_2 emissions would rise, if EPU index increases. Ulucak and Khan ([2020]) applied the dynamic ARDL estimation and found that EPU determines the increase of CO_2 emissions through the energy intensity effect in the USA. Abbasi and Adedoyin ([2021]) used the novel dynamic ARDL simulation model and could not find a significant relationship between CO_2 emissions and EPU index in China. Adams et al. ([2020]) applied the Panel Pooled Mean Group Autoregressive Distributed lag model (PMG-ARDL) and found that policy uncertainty degrades the environment. Wang et al. ([2020]) applied the ARDL model and found that high economic policy uncertainty (measured by the World Uncertainty Index—WUI) leads to high CO_2 emissions. Adedoyin and Zakari ([2020]) applied ARDL-bound testing and found no relationship between CO_2 emissions and economic policy uncertainty for the UK. Ulucak and Khan ([2020]) used the dynamic ARDL approach and found that rises in the EPU index policy

uncertainty adversely affect environmental quality. Anser et al. ([2021]), using a PMG (pooled mean group)-ARDL approach, found that EPU increases the world's CO_2 emission. Considering the relationship between population and CO_2 emission, many scholars found that population growth increases CO_2 emission. For instance, Zhang and Lin ([2012]) applied the STIRPAT model and found that population growth leads to high CO_2 emission in China. Wang et al. ([2013]) used the STIRPAT (stochastic impacts by regression on population, affluence, and technology) for Guangdong Province, China, and found that population negatively impacts on CO_2 emission. Wang and Zhao ([2015]) applied the same methodology and found the same results for China. Dong et al. ([2018]) applied the cross-sectional dependence and slope homogeneity tests for 128 countries and found that population negatively impacts on CO_2 emission. Kim et al. ([2020]) applied the FMOLS model for South Korea, and proved that population aging reduces CO_2 emissions. Regarding verification of the EKC hypothesis for the BRIC and G-7 countries, the following scholars found mixed results. For instance, Mohsen and Ali Rezaei ([2013]) applied the unit root tests and Kao panel cointegration test and found evidence supporting the EKC hypothesis for the BRICS countries. Chang ([2015]) applied the non-oriented DDF model and found that the EKC hypothesis is not verified for the BRICS and G-7 countries. Sinha and Sen ([2016]) used GMM methodology for BRICS and verified the EKC hypothesis only for Brazil and India. Zhou et al. ([2019]) applied the panel quantile regression model and studied the EKC hypothesis in G7 and BRICS countries. They found that the EKC hypothesis is validated only for G-7 countries. Sinha et al. ([2019]) used the unit root and cointegrations tests and could not find evidence supporting this hypothesis for the BRICS countries.

3 Empirical model

This study's empirical approach is based on the following models (Models 1 and 2) without and with the independent variable REC. Model variables are in natural logarithmic forms:

$$\ln CO_{2it} = \alpha_0 + \alpha_1 \ln GDP_{it} + \alpha_2 \ln GDP_{it}^2 + \alpha_3 \ln X_{it} + e_{it} \tag{1}$$

where $\alpha_2 < 0$, maximum (optimal) real GDP per capita level for Model 1 is calculated by $GDP_1 = \exp(-\alpha_1/2\ \alpha_2)$. In Model 1, CO_2 represents carbon emissions (metric million tons); GDP and GDP^2 are real GDP per capita and the squared of real GDP per capita, respectively (in USD); X is control variables: economic freedom (EF) index, economic policy uncertainty (EPU) index, and population (POP); e

Table 1 Notations of relevant variables and their definitions

Acronyms	full name
GDP	Per capita gross domestic product (World Bank-https://databank.worldbank.org)
EKC	Environment Kuznets Curve (World Bank-https://databank.worldbank.org)
R-EKC	The renewable energy Kuznets Curve (World Bank-https://databank.worldbank.org)
REC	Renewable energy consumption (World Bank-https://databank.worldbank.org)
CO_2	Carbon dioxide emissions (World Bank-https://databank.worldbank.org) & IEA-www.iea.org/data-and-statistics)
EPU	Economic policy index (https://PolicyUncertainty.com)
ECFR	Economic freedom index (https://heritage.org/index)
POP	Population growth (World Bank)

represents white noise error terms. The expected signs for α_1 and α_2 are to be positive and negative, respectively since rises in real GDP per capita will initially increase CO_2 emissions and, eventually, decrease them after a certain (maximum) point implying the EKC hypothesis verification. Data were obtained from the World Development Indicators (2021), the World Bank Database, World Energy Agency, EPU[2] index, and EF[3] index. The empirical models are estimated with STATA 16. The sample period is 1996–2019 (See notations of relevant variables and their definitions in Table 1).

Following Eq. 1, we re-write our second model (Model 2) with the independent variable renewable energy consumption (REC) in the following form:

$$\ln CO_{2it} = \beta_0 + \beta_1 \ln GDP_{it} + \beta_2 \ln GDP_{it}^2 + \beta_3 \ln REC_{it} + \beta_4 \ln X_{it} + \varepsilon_{it} \quad (2)$$

where $\beta_2 < 0$,

The maximum (optimal) real GDP per capita level for Model 2 is calculated by $GDP_2 = \exp(-\beta_1/2\ \beta_2)$. The expected signs for β_1, β_2 and β_4 are the same as in Eq. 1, and for β_3, it is expected to be negative since an increase in renewable energy consumption (REC) leads to a decrease in CO_2 emissions. When comparing both models, it is expected that renewable energy consumption will accelerate the reduction of CO_2 emissions, resulting in an earlier turning point in Model 2 compared to Model 1. This implies that it will take less time to reach this point in Model 2 than in Model 1, assuming that real GDP per capita increases over time since the turning point occurs at a lower real GDP per capita level. Furthermore, the EKC trajectory of Model 2 is expected to be shorter than that of Model 1. It is also expected that the maximum real GDP per capita level (in dollars) for Model 2 (GDP_2) to be lower than its level achieved for Model 1 (GDP_1).

4 Estimation methodology

In the estimation methodology of the study, we will proceed with the analyses under the following sub-titles.

4.1 Preliminary tests for cross-section dependence, unit root and cointegration

Cross-sectional dependence is checked because the CO_2 emissions in one country might be correlated with those in another. CD Pesaran's (2004) test is used in this case because it is not affected by the small size of the sample, null hypothesis stating cross-sectional independence:

$$H_0 : \rho_{ij} = \rho_{ji} = cor(e_{it}, e_{jt}) = 0, i \neq j \quad (3)$$

$$H_1 : \rho_{ij} = \rho_{ji} \neq 0, for some i \neq j \quad (4)$$

ρ_{ij}- pair-wise correlation coefficient of the errors

$$\rho_{ij} = \rho_{ji} = \frac{\sum_{t=1}^{T} e_{it} \cdot e_{jt}}{\sqrt{\sum_{t=1}^{T} e_{it}^2} \cdot \sqrt{\sum_{t=1}^{T} e_{jt}^2}} \quad (5)$$

In the case of balanced panels, the statistic of CD Pesaran's (2004) test is determined as:

$$CD = \sqrt{\frac{2}{N(N-1)}} \cdot \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \hat{\rho}_{ij} \quad (6)$$

T_{ij}- number of common observations for countries i and j

$$\hat{\rho}_{ij} = \hat{\rho}_{ji} = \frac{\sum_{t \in T_i \cap T_j}(\hat{e}_{it} - \overline{e}_i)(\hat{e}_{jt} - \overline{e}_j)}{\sqrt{\sum_{t \in T_i \cap T_j}(\hat{e}_{it} - \overline{e}_i)^2} \cdot \sqrt{\sum_{t \in T_i \cap T_j}(\hat{e}_{jt} - \overline{e}_j)^2}} \quad (7)$$

$$\overline{e}_i = \frac{\sum_{t \in T_i \cap T_j}(\hat{e}_{it})}{\#(T_i \cap T_j)} \quad (8)$$

Under the hypothesis of cross-section dependence, the Breitung test is used to check for unit roots. For non-

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stationary data, the cointegration is tested based on Kao, Pedroni, and Westerlund tests.

4.2 Panel autoregressive distributed lag

The panel Autoregressive Distributed Lag model (panel ARDL) might also be used in case of no clear cointegration relationship. For Model 1 and Model 2, the ARDL model is represented as:

$$CO_{2it} = \alpha_{1i} + \sum_{l=1}^{p} \alpha_{10} CO_{2it-l} + \sum_{l=0}^{q} \alpha_{11} GDP_{it-l} + \sum_{l=0}^{q} \alpha_{12} GDP_{it-l}^2 + e_{1it} \tag{9}$$

$$CO_{2it} = \beta_{2i} + \sum_{l=1}^{p} \beta_{20} CO_{2it-l} + \sum_{l=0}^{q} \beta_{21} GDP_{it-l} + \sum_{l=0}^{q} \beta_{22} GDP_{it-l}^2 + \sum_{l=0}^{q} \beta_{23} REC_{it-l} + e_{2it} \tag{10}$$

After parameterization, the previous equations are represented as:

$$\Delta \ln CO_{2it} = \alpha_{1i} + \Phi_{1i}(\ln CO_{2it-l} - \theta_{11} \ln GDP_{it-l} \\ - \theta_{12} \ln^2 GDP_{it-l}) + \sum_{l=1}^{p-1} \lambda_{1il} \Delta \ln CO_{2it-l} \\ + \sum_{l=0}^{q-1} \lambda'_{1il} \Delta \ln GDP_{it-l} + \sum_{l=0}^{q-1} \lambda''_{1il} \Delta ln^2 GDP_{it-l} \\ + e_{1it} \tag{11}$$

$$\Delta \ln CO_{2it} = \alpha_{2i} + \Phi_{2i}(\ln CO_{2it-l} - \theta_{21} \ln GDP_{it-l} \\ - \theta_{22} \ln^2 GDP_{it-l} + \theta_{23} \ln REC_{it-l}) \\ + \sum_{l=1}^{p-1} \lambda_{2il} \Delta \ln CO_{2it-l} + \sum_{l=0}^{q-1} \lambda'_{2il} \Delta \ln GDP_{it-l} \\ + \sum_{l=0}^{q-1} \lambda''_{2il} \Delta \ln^2 GDP_{it-l} + \sum_{l=0}^{q-1} \lambda'''_{3il} \Delta \ln REC_{it-l} \\ + e_{2it} \tag{12}$$

where λ, λ', λ'', λ''' are short-run coefficients associated to lagged endogenous variable and explanatory variables. θ type coefficients refer to long-run coefficients for explanatory variables. The speeds of adjustment are given by Φ_{1i} and Φ_{2i}. The pool mean group (PMG) estimator supposes homogenous long-run equilibrium across countries and heterogeneous short-run relationships. Countries' gaps explain the heterogeneous short-run behaviour.

5 Empirical findings

5.1 Pesaran's CD test

According to CD Pesaran's test, the cross-section dependence is checked for almost all the variables in the BRIC and G-7 countries, excepting population growth and economic freedom index at a 5% level of significance (see Table 2).

5.2 Unit root and cointegration tests and coefficients of cointegration

According to the Breitung test that allows for cross-dependence, the panel data for all variables are stationary in the first differences in the BRIC and G-7 countries, which implies that the data in level are integrated of order 1(I(1)) (see Table 3).

Given the fact that the data for all variables are integrated in the same order, the cointegration relationship is checked using Kao, Pedroni, and Westerlund tests. According to Table 4, there is no cointegration relationship between variables at a 5% level of significance.

According to Table 4, there is mixed evidence related to the cointegration relationship in G-7 countries. The Westerlund test indicated no cointegration, while Kao and Pedroni's tests suggest a possible cointegration. Hence, we can estimate the coefficients of the models (see also Table 5).

Table 2 The Results of CD Pesaran's Test

Variable	BRIC countries	G-7 countries
CO_2	9.36*	17.80*
Real GDP per capita (GDP)	10.86*	15.52*
Population growth (POP)	1.67	−1.04
Economic freedom index (EF)	0.76	4.75*
Economic policy index (EPU)	2.68*	13.58*
Renewable energy consumption (REC)	2.48 *	17.30*

*p-value less than 5%

Table 3 The results of Breitung Test for Unit Root for G-7 and BRIC Countries

Group	Variable	Statistic (constant & trend) (no lag) data in level	Statistic (constant & trend) (one lag) data in level	Statistic (constant & trend) (no lag) data in the first difference	Statistic (constant & trend) (one lag) data in the first difference
BRIC	$\ln(CO_2)$	2.0454 0.9796	1.0396 0.8507	− 2.0810 0.0187	− 2.8556 0.0020
	$\ln(GDP)$	1.2841 0.9004	0.2194 0.5868	− 2.8981 0.0019	− 2.9005 0.0018
	$\ln(POP)$	− 0.3617 0.3588	− 0.4299 0.3336	− 2.0923 0.0108	− 2.1002 0.0104
	$\ln(EPU)$	0.0364 0.5145	− 0.5455 0.2927	− 3.5773 0.0002	− 2.8473 0.0022
	$\ln(EF)$	0.5288 0.7015	0.4827 0.6854	− 3.3907 0.0003	− 2.6618 0.0039
	$\ln(REC)$	1.1450 0.8739	− 0.7980 0.2124	− 4.3075 0.0000	− 2.7155 0.0033
G-7	$\ln(CO_2)$	− 0.1244 0.4505	− 0.7312 0.2323	− 3.2367 0.0006	− 3.0854 0.0010
	$\ln(GDP)$	0.4787 0.6839	0.9656 0.8329	− 4.5344 0.0000	− 2.8670 0.0021
	$\ln(POP)$	− 1.5680 0.0584	− 1.9643 0.0247	− 5.7549 0.0000	− 2.6565 0.0039
	$\ln(EPU)$	− 1.6196 0.0527	− 1.8055 0.0355	− 4.6838 0.0000	− 2.8798 0.0020
	$\ln(EF)$	− 0.7073 0.2397	− 1.2771 0.1008	− 1.8444 0.0326	− 2.7403 0.0031
	$\ln(REC)$	0.8727 0.8086	0.3699 0.6443	− 5.0013 0.0000	− 2.6454 0.0041

p-values are in brackets

Table 4 The Results of Cointegration Tests for BRIC Countries Source: Coefficients were Calculated by Stata 16

Kao test	Statistics	*p*-values
Modified Dickey	1.0675	0.1429
Dickey	0.7333	0.2317
Augmented Dickey	0.2259	0.4106
Unadjusted modified Dickey	1.3413	0.0899
Unadjusted Dickey	0.8644	0.1937
Pedroni test	Statistics	*p*-values
Modified phillips	1.6600	0.0485
Phillips	0.0819	0.4674
Augmented Dickey	0.2454	0.4031
Westerlund test	Statistics	*p*-values
Variance ratio	0.9621	0.1680

Table 5 The Results of Cointegration Tests for G-7 Countries Source: Coefficients were Calculated by Stata 16

Kao test	Statistics	*p*-values
Modified Dickey	− 3.0855	0.0010
Dickey	− 2.3668	0.0090
Augmented Dickey	− 1.0628	0.1439
Unadjusted modified Dickey	− 4.1081	0.0000
Unadjusted Dickey	− 2.7040	0.0034
Pedroni test	Statistics	*p*-values
Modified Phillips	1.6900	0.0455
Phillips	− 4.0325	0.0000
Augmented Dickey	− 4.6569	0.0000
Westerlund test	Statistics	*p*-values
Variance ratio	0.6794	0.2484

5.3 The pool mean group (PMG) and common correlated effects (CCE) estimator

To estimate the coefficients of Model 1 without REC and Model 2 with REC, we apply the pooled mean group (PMG) and common correlated effects (CCE) estimators developed by Pesaran et al. (1999) and Pesaran (2006), respectively. The PMG and CCE estimation results are reported in Table 6 and Tables 7 and 8, respectively.

Test results of Models 1 and 2 presented in Tables 6, 7 and 8, based on both the PMG and CCE estimators, indicate that the EKC hypothesis is verified only for G-7 countries since the BRIC countries' coefficients are insignificant. Furthermore, we confirm that renewable energy consumption (REC) in Model 2 accelerates the reduction of CO_2 emissions in the long run. This means the EKC hypothesis is verified faster in Model 2 (with a shorter EKC trajectory) than in Model 1, which didn't include REC. It can be quickly reached to the maximum (optimal)

Table 6 Pool Mean Groups (PMG) Regressions for G-7 and BRIC Countries Source: Coefficients were Calculated by Stata 16

	Variable	Model 2 with REC GDP$_2$ = $10,823		Model 1 without REC GDP$_1$ = $32,561	
		BRIC countries	G-7 countries	BRIC countries	G-7 countries
Long-run relationship	ln(GDP)	− 2.554 (0.000)	2.890 (0.000)	− 2.112 (0.000)	2.898 (0.000)
	ln^2(GDP)	0.240 (0.000)	− 1.335 (0.000)	1.57 (0.000)	− 0.445 (0.000)
	ln(REC)	− 0.258 (0.000)	− 0.788 (0.000)	–	–
	ln(POP)	0.149 (0.000)	0.336 (0.000)	0.632 (0.075)	0.198 (0.087)
	ln(EF)	− 0.527 (0.000)	− 0.447 (0.000)	− 0.620 (0.045)	− 0.337 (0.040)
	ln(EPU)	− 0.046 (0.000)	− 0.223 (0.000)	− 0.539 (0.047)	− 0.112 (0.043)
EC term		− 0.438 (0.043)	− 0.556 (0.023)	− 0.017 (0.075)	− 0.438 (0.030)
Short-run relationship	ln(GDP)	− 1.065 (0.180)	3.987 (0.225)	− 1.192 (0.381)	2.889 (0.334)
	ln^2(GDP)	1.030 (0.162)	− 3.456 (0.000)	1.534 (0.393)	− 1.567 (0.446)
	ln(REC)	− 0.159 (0.740)	− 0.203 (0.456)	–	–
	ln(POP)	0.152 (00,803)	0.129 (0.788)	0.955 (0.051)	0.337 (0.662)
	ln(EF)	− 0.016 (0.940)	0.033 (0.989)	− 0.043 (0.866)	0.054 (0.678)
	ln(EPU)	0.017 (0.359)	0.043 (0.778)	0.0144 (0.521)	0.053 (0.780)
	Constant	8.96 (0.434)	9.020 (0.556)	− 17.688 (0.754)	10.223 (0.600)
Residuals	I(0)	I(0)	I(0)	I(0)	I(0)

real GDP per capita level with a lower real GDP per capita level since GDP in Model 1 is higher than GDP in Model 2. Additionally, while a rise in economic freedom (EF) mitigates CO_2 emissions, a fall in EPU increases carbon emissions for both BRIC and G-7 countries in the long run. Higher policy uncertainty (EPU) reduces economic activity, which implies less pollution, but only in the long-run, not in the short-run. The population growth (POP) increases CO_2 emissions in all countries. It should also be noted that the positive impacts of economic freedom (EF) on the environment in stronger for the BRIC countries than in G-7 countries, according to the PGM model. This can be interpreted that the G-7 countries already have more freedom than the BRIC countries (see rest of the analysis in Appendix).

6 Conclusion with policy implications

This study aimed to empirically prove the accelerating impact of renewable energy consumption (REC) on environmental degradation. In this regard, the EKC hypothesis testing was used for the BRIC and G-7 countries. It was expected that the EKC model with REC would accelerate the reduction of CO_2 emissions. Therefore, two different EKC models were created and tested separately: Model 1 without REC and Model 2 with REC. Empirical findings of both the PMG and CCE estimators revealed that reaching the maximum (optimal) real GDP per capita level, took a shorter time (with lower real GDP per capita level) in Model 2 than in Model 1 for G-7 countries. This means that the EKC trajectory of Model 2 is shorter than in Model 1's.

Table 7 Pesaran's (2006) CCE Estimator (Model 1) *Source*: Coefficients were Calculated by Stata 16

GDP_1 = $76,665	Pesaran's (2006) CCE estimator	
	BRIC Countries	G-7 Countries
$Ln(CO_{2t-1})$	–	–
$ln(GDP_t)$	− 3.971	2.334
	(0.056)	(0.09)
$ln^2(GDP_t)$	2.617	− 1.522
	(0.063)	(0.004)
$ln(POP_r)$	0.0732	0.039
	(0.023)	(0.084)
$ln(EF)$	− 0.432	0.119
	(0.022)	(0.041)
$ln(EPU)$	− 0.063	− 0.045
	(0.058)	(0.097)
Constant	432.869	3.641
	(0.558)	(0.923)

Table 8 Pesaran's (2006) CCE Estimator (Model 2) *Source*: Coefficients were Calculated by Stata 16

GDP_2 = $53,769	Pesaran's (2006) CCE Estimator	
	BRIC Countries	G-7 Countries
$ln(CO_{2t-1})$	–	–
$ln(GDP_t)$	− 1.380	2.853
	(0.099)	(0.024)
$ln^2(GDP_t)$	1.004	− 2.603
	(0.014)	(0.028)
$ln(REC_r)$	− 0.584	− 0.149
	(0.079)	(0.000)
$ln(POP_r)$	0.264	0.07
	(0.041)	(0.064)
$ln(EF)$	− 0.343	0.059
	(0.012)	(0.087)
$ln(EPU)$	− 0.066	− 0.024
	(0.012)	(0.047)
Constant	2.259	50.389
	(0.935)	(0.796)

The economic inferences of this shorter period (early turning point) for the governments mean lower environmental cleaning costs, less time vesting, and saving the resources and money. This also means that the economic growth policies based on real GDP per capita and energy policies based on environmental degradation (i.e., CO_2 emissions) converge with each other quickly and

sustainably at a lower cost. At this point, we should remind something one more time. To be able to use the terms "early or quick turning point" in the EKC models, we assumed that real GDP per capita rises over time. This must be a mathematically necessary assumption in the EKC models since it brings a time dimension to the EKC models.

Overall, the study found that renewable energy consumption plays an essential role in accelerating the reduction of CO_2 emissions and it positively contributes to the environment. However, the EKC hypothesis could not be verified for the BRIC countries, indicating that their economic and energy policies may not be sustainable. This could be due to various reasons, such as the incorrect implementation of economic and energy policies and the low share of renewable energy consumption in their total energy consumption.

The study found that GDP growth, renewable energy consumption, and population significantly impact CO_2 emissions in the long run in G7 countries, especially when renewable energy consumption is included in the model. On the other hand, the impacts of economic policy uncertainty (EPU) and economic freedom (EF) on CO_2 emissions are weaker in G7 countries than in BRIC countries when renewable energy consumption is considered. However, when renewable energy consumption is excluded, all exogenous factors substantially impact BRIC countries more than G7 countries. Thus, it can be concluded that renewable energy consumption plays a crucial role in reducing CO2 emissions, particularly in G7 countries, and can contribute to improving economic freedom.

The main policy implication of this research is to show policymakers the importance and the accelerating impact of the renewable energy consumption for a cleaner environment. Moreover, the COVID-19 pandemic may force governments to invest more in renewable energy since it may strengthen resilience to protect people's health Dogru et al. (2023), Karagöz et al. (2021, 2023). Promoting renewable energy sources should be done by supporting public–private partnerships in the RE area for investing in these RE sources and acknowledging the benefits of RE use for the population (Işık et al. 2017, 2018). In this regard, G7 countries, as developed economies, can allocate significant financial funds and design adequate regulations for supporting these public–private partnerships and research in the RE area. All the regulations elaborated by the authorities should promote economic freedom by not deterring investments in the RE area or not generating large disinvestments in the RE consumption area because of the worsening of the macroeconomic and regulatory context. This is especially true for BRICS countries that are developing economies. They don't benefit from significant financial funds such as G7 countries, and the investments

are more sensitive to the macroeconomic framework in the developing countries than in the developed economies. However, BRICS represent top emerging economies, and they made significant progress and strengthened their cooperation for joint projects in the renewable energy area. Russia and China have access to wind energy. South Africa, India, and Brazil use solar energy primarily, and Brazil also uses biomass, so all BRICS have significant resource advantages in the RE sector. Economic freedom should improve in BRICS countries to support economic progress and investments in the RE area. Environmental policy should consider policy uncertainty and economic freedom to achieve the CO_2 reduction target. Our results suggested that a rise of policy uncertainty determines a decrease in CO_2 emissions, causing the economic activity to shrink so that the pollution can decrease, but will not attract investors in the RE area either, which is detrimental to the environment in the long run.

This study can be followed by future empirical works that will use different methodologies for different countries. However, we believe that the further studies will support the motto of this current study "more renewable energy consumption, a cleaner environment, lower cost, and more time-saving." From the empirical and methodological perspective, this will represent an "earlier turning point on the EKC or a faster EKC hypothesis verification."

Appendix 1

See Table 9.

All the GDP terms in polynomial specifications are significant, and output growth strongly impacts CO_2 emissions in G7 and BRIC countries, as we can see in Table 6, too. However, there are different patterns in the case of RKC. A U-shaped relationship was obtained for BRIC countries. This result is similar to the finding of Yao et al. (2020) for six large regions and for 17 developed and developing countries from 1990 to 2014. On the other hand, an inverse U relationship was observed in the case of G7 countries.

See Table 10.

GDP terms are not significant for the quadratic model. There are two different patterns in the two groups of countries, confirmed by Table 7, too. The positive sign for the linear and cubic specification and the negative one for squared GDP indicate an N-shaped relationship between CO_2 emissions and GDP in the case of G7 countries. On the other hand, BRIC countries present an inversely-N-shaped relationship. Since the GDP values for which the first derivative is null are not local extrema, there is an increasing relationship between GDP and pollution.

See Table 11.

In all the models for EKC, population growth has a positive but low impact on CO_2 emissions. The same positive influence of population on pollution was observed by Liddle (2015) in the case of 80 countries in the period 1971–2011.

Robusness: other control variables

The robustness of the results is checked by adding other control variables. For example, in the case of EKC, we

Table 9 Pool mean groups (PMG) regressions to explain the CO2 emissions in G7 and BRIC countries *Source*: own calculations in Stata 16

	Variable	Coefficients (RKC)		Coefficients (EKC)	
		BRIC countries	G7 countries	BRIC countries	G7 countries
Long-run relationship	ln(GDP)	− 1.796 (0.001)	2.586 (0.027)	− 2.723 (0.010)	2.428 (0.006)
	$\ln^2$(GDP)	0.123 (0.000)	− 1.241 (0.026)	1.646 (0.083)	0.223 (0.000)
	$\ln^3$(GDP)	–	–	− 0.475 (0.065)	0.334 (0.045)
	ln(REC)	− 1.275 (0.000)	− 0.514 (0.000)	–	–
	ln(POP)	–	–	0.0495 (0.002)	0.0179 (0.020)
Error correction term		− 0.146 (0.020)	− 0.209 (0.074)	− 0.076 (0.045)	− 0.206 (0.030)
Short-run relationship	ln(GDP)	− 2.025 (0.492)	1.360 (0.727)	− 3.587 (0.297)	− 5.642 (0.013)
	$\ln^2$(GDP)	0.882 (0.417)	− 0.461 (0.742)	2.356 (0.288)	5.368 (0.013)
	$\ln^3$(GDP)	–	–	− 4.558 (0.276)	1.702 (0.013)
	ln(REC)	− 0.490 (0.246)	0.03 (0.962)	–	–
	ln(POP)	–	–	0.0464 (0.165)	0.041 (0.012)
	Constant	1.730 (0.747)	− 27.618 (0.074)	14.684 (0.462)	0.144 (0.643)
Residuals	I(0)	I(0)	I(0)	I(0)	I(0)

p-values in brackets

Table 10 Dynamic and Pesaran common correlated effects estimators to explain CO_2 emissions in G7 and BRICS countries using RKC (basic model) *Source*: own calculations in Stata 16

Variable	Coefficients			
	Dynamic common correlated effects estimator-pooled		Pesaran common correlated effects mean group estimator	
	BRIC countries	G7 countries	BRIC countries	G7 countries
$Ln(CO_{2t-1})$	0.311 (0.010)	0.301 (0.023)	–	–
$\ln(GDP_t)$	− 2.481 (0.064)	2.646 (0.009)	− 2.500 (0.082)	2.893 (0.092)
$\ln^2(GDP_t)$	0.145 (0.062)	− 1.165 (0.009)	0.548 (0.098)	− 0.106 (0.095)
$\ln(REC_r)$	− 0.593 (0.009)	− 0.502 (0.023)	− 0.338 (0.098)	0.081 (0.001)
Constant	–		0.088 (0.098)	5.971 (0.671)

p-values in brackets

Table 11 Dynamic and Pesaran common correlated effects estimators to explain CO_2 emissions in G7 and BRICS countries using EKC (basic model) *Source*: own calculations in Stata 16

Variable	Coefficients			
	Dynamic common correlated effects estimator-pooled		Pesaran common correlated effects mean group estimator	
	BRIC countries	G7 countries	BRIC countries	G7 countries
$Ln(CO_{2t-1})$	0.557 (0.046)	0.361 (0.067)	–	–
$\ln(GDP_t)$	− 1.7303 (0.095)	2.617 (0.078)	− 2.024 (0.093)	2.45 (0.075)
$\ln^2(GDP_t)$	0.969 (0.093)	− 1.26 (0.078)	1.265 (0.093)	0.505 (0.071)
$Ln^3(GDP_t)$	− 0.0748 (0.095)	3.904 (0.079)	− 0.161 (0.079)	− 0.297 (0.078)
$\ln(POP_r)$	0.03 (0.099)	0.034 (085)	0.039 (0.010)	0.014 (0.045)
Constant	–	–	7.837 (0.061)	5.571 (0.091)

p-values in brackets

Table 12 Pool mean groups (PMG) regressions to explain the CO_2 emissions in G7 and BRIC countries Source: own calculations in Stata 16

	Variable	Coefficients (RKC)		Coefficients (EKC)	
		BRIC countries	G7 countries	BRIC countries	G7 countries
Long-run relationship	ln(GDP)	− 2.554 (0.000)	2.890 (0.000)	− 2.112 (0.000)	2.898 (0.000)
	$\ln^2$(GDP)	0.240 (0.000)	− 1.335 (0.000)	1.57 (0.000)	− 0.445 (0.000)
	$\ln^3$(GDP)	–	–	− 0.226 (0.000)	0.667 (0.000)
	ln(REC)	− 0.258 (0.000)	− 0.788 (0.000)	–	–
	ln(POP)	0.149 (0.000)	0.336 (0.000)	0.632 (0.075)	0.198 (0.087)
	ln(ECFR)	− 0.527 (0.000)	− 0.447 (0.000)	− 0.620 (0.045)	− 0.337 (0.040)
	ln(EPU)	− 0.046 (0.000)	− 0.223 (0.000)	− 0.539 (0.047)	− 0.112 (0.043)
Error correction term		− 0.438 (0.043)	− 0.556 (0.023)	− 0.017 (0.075)	− 0.438 (0.030)
Short-run relationship	ln(GDP)	− 1.065 (0.180)	3.987 (0.225)	− 1.192 (0.381)	2.889 (0.334)
	$\ln^2$(GDP)	1.030 (0.162)	− 3.456 (0.000)	1.534 (0.393)	− 1.567 (0.446)
	$\ln^3$(GDP)	–	–	− 1.172 (0.405)	− 1.345 (0.778)
	ln(REC)	− 0.159 (0.740)	− 0.203 (0.456)	–	–
	ln(POP)	0.152 (00,803)	0.129 (0.788)	0.955 (0.051)	0.337 (0.662)
	ln(ECFR)	− 0.016 (0.940)	0.033 (0.989)	− 0.043 (0.866)	0.054 (0.678)
	ln(EPU)	0.017 (0.359)	0.043 (0.778)	0.0144 (0.521)	0.053 (0.780)
	Constant	8.96 (0.434)	9.020(0.556)	− 17.688 (0.754)	10.223 (0.600)
Residuals		I(0)	I(0)	I(0)	I(0)

Table 13 Dynamic and Pesaran common correlated effects estimators to explain CO_2 emissions in G7 and BRICS countries using RKC (basic model) *Source*: own calculations in Stata 16

Variable	Coefficients			
	Dynamic common correlated effects estimator-pooled		Pesaran common correlated effects mean group estimator	
	BRIC countries	G7 countries	BRIC countries	G7 countries
$\ln(CO_{2t-1})$	0.465 (0.012)	0.264 (0.006)	–	–
$\ln(GDP_t)$	− 2.146 (0.077)	2.276 (0.074)	− 1.380 (0.099)	2.853 (0.024)
$\ln^2(GDP_t)$	0.234 (0.078)	− 0.849 (0.074)	1.004 (0.014)	− 2.603 (0.028)
$\ln(REC_r)$	− 0.531 (0.089)	− 0.089 (0.072)	− 0.584 (0.079)	− 0.149 (0.000)
$\ln(POP_r)$	0.153 (0.077)	0.037 (0.035)	0.264 (0.041)	0.07 (0.064)
$\ln(ECFR)$	− 0.212 (0.058)	0.138 (0.058)	− 0.343 (0.012)	0.059 (0.087)
$\ln(EPU)$	− 0.056 (0.037)	− 0.013 (0.041)	− 0.066(0.012)	− 0.024 (0.047)
Constant	–	–	2.259 (0.935)	50.389 (0.796)

p-values in brackets

Table 14 Dynamic and Pesaran common correlated effects estimators to explain CO_2 emissions in G7 and BRICS countries using EKC (basic model) *Source*: own calculations in Stata 16

Variable	Coefficients			
	Dynamic common correlated effects estimator-pooled		Pesaran common correlated effects mean group estimator	
	BRIC countries	G7 countries	BRIC countries	G7 countries
$Ln(CO_{2t-1})$	0.568 (0.072)	0.330 (0.013)	–	–
$\ln(GDP_t)$	− 3.512 (0.09)	2.955 (0.048)	− 3.971 (0.056)	2.334 (0.09)
$\ln^2(GDP_t)$	1.670 (0.09)	− 1.921 (0.047)	2.617 (0.063)	− 1.522 (0.004)
$Ln^3(GDP_t)$	− 0.0680 (0.09)	0.028 (0.084)	− 0.228 (0.075)	0.346 (0.005)
$\ln(POP_r)$	0.106 (0.072)	0.071 (0.047)	0.0732(0.023)	0.039 (0.084)
$\ln(ECFR)$	− 0.354 (0.085)	0.172 (0.073)	− 0.432 (0.022)	0.119 (0.041)
$\ln(EPU)$	− 0.075 (0.062)	− 0.052 (0.079)	− 0.063 (0.058)	− 0.045 (0.097)
Constant	–	–	432.869 (0.558)	3.641 (0.923)

p-values in brackets

added economic freedom and economic policy uncertainty in logarithms.

Table 8 shows similar results regarding the relationship between GDP and CO_2 emissions. The speed of adjustment is more than double compared to the basic models. In G7 speed of adjustment is 55.6% in the case of G7 countries for RKC and 43.8% for the same group in the case of EKC.

See also Tables 8 and 12.

According to Tables 8 and 9 in the RKC, economic freedom has a negative impact on CO_2 emissions for BRIC countries and a positive one for G7 countries. On the other hand, a higher economic policy uncertainty reduced pollution in both groups of countries.

See Table 13.

Table 10 confirms the N-shaped relationship for BRIC and the inversely N-shaped one for G7 countries. These results show that in BRIC countries, economic growth is associated with an increase in pollution, while in G7 countries, it is possible to have economic growth with fewer CO_2 emissions.

See Table 14.

The negative impact of economic freedom on pollution might be explained by the progress in the transition to environmental-friendly industries in BRIC. However, more efforts are required to ensure sustainable growth. Moreover, higher policy uncertainty reduces economic activity, which implies less pollution.

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Declarations

Conflicts of Interest The authors declare no conflict of 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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