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How do technological innovation and renewables shape environmental quality advancement in emerging economies: An exploration of the E7 bloc?

Stephen Taiwo Onifade[1] | Festus Victor Bekun[2,3] | Agboola Phillips[4] | Mehmet Altuntaş[5]

[1]Faculty of Economics and Administrative Sciences, Department of International Trade and Logistics, KTO Karatay University, Konya, Turkey

[2]Faculty of Economics Administrative and Social Sciences, Istanbul Gelisim University, Istanbul, Turkey

[3]Adnan Kassar School of Business, Department of Economics, Lebanese American University, Beirut, Lebanon

[4]Mechanical Engineering Department, College of Applied Engineering, King Saud University (Al Muzahimiyah Branch), Riyadh, Saudi Arabia

[5]Faculty of Economics, Administrative and Social Sciences, Department of Economics, Nisantasi University, Istanbul, Turkey

Correspondence
Festus Victor Bekun, Faculty of Economics Administrative and Social Sciences, Istanbul Gelisim University, Istanbul, Turkey.
Email: fbekun@gelisim.edu.tr

Abstract

Emissions from several emerging economies currently constitute the largest contributions to the global carbon emissions levels thereby triggering concerns on the prospects for achieving global environmental sustainability-related goals (SGDs-13 and 11). Thus, this research examines whether technological innovation and renewables pose any moderating roles in the environmental quality advancements of rapidly emerging economies using the bloc of the emerging seven (E7) economies. The empirical framework of the study capitalizes on the strengths of the novel CS-ARDL technique in addressing the pitfalls of cross-sectional dependence (CD) from common factors that marred the understudied panel observations for the bloc between 1992 and 2018. The long-run estimations provide crucial insights into the environmental sustainability dynamics of the E7 bloc. First, the observed impacts of the rapid economic expansion alongside the fast-growing energy consumption were significantly detrimental to environmental sustainability over the period of study (1992–2018). Second, the duo of technological innovations and renewables place the E7 on an environmental sustainability path as they significantly dampen the CO_2 emissions level in the bloc. Third, the inverted U-shape growth-emission conjecture of the EKC was confirmed for these groups of emerging economies within the innovation-environment nexus exploration. Fourthly, although both innovations and renewable energy consumption enhance sustainability, however, the magnitude of their desirable environmental impacts is quite low compared to the observed impacts of the pollution damages created by the observed energy consumption-driven economic growth expansion in the bloc over the years. Overall, the results are indicative that the E7 needs to do more in terms of investments in environmental-related technological innovations and the expansion of renewables in overall energy portfolios to harness the inherent benefits of the duo to position the bloc on a sustainability path. More recommendations for environmental sustainability enhancement from technological innovation and renewable perspectives were further enunciated for the E7 bloc in the main text.

KEYWORDS
economic growth, emerging economies (E7), environmental sustainability, renewables, technological innovations

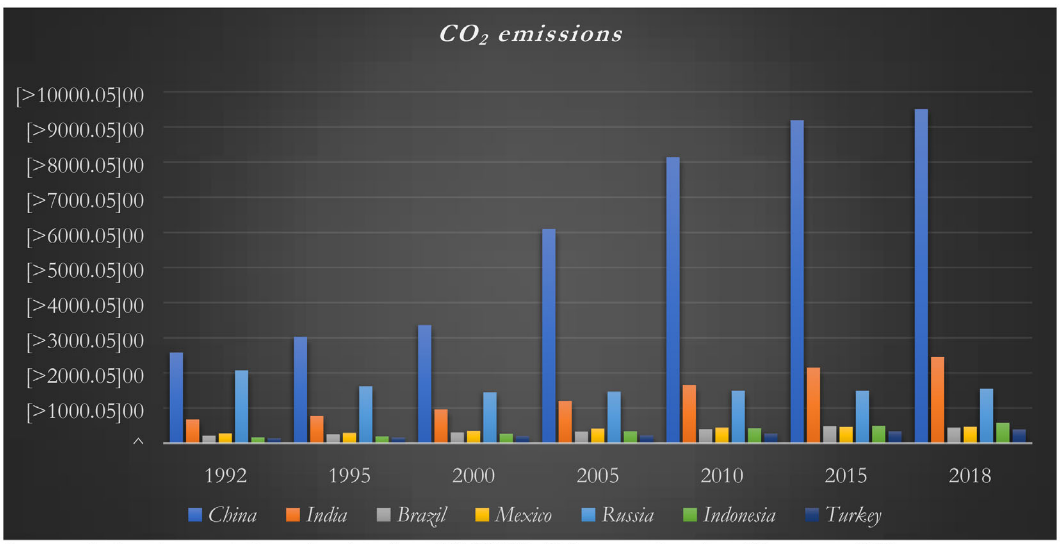
1 | INTRODUCTION

Greenhouse gases (GHG) emissions have historically been on an upward trajectory over the years and a critical review of current emissions statistics suggests that there are no signals of likely desirable abatement vis-à-vis the prevailing global energy portfolios and the quest for economic expansion among nations. For instance, global carbon dioxide (CO_2) emissions levels in the mid-1960s were estimated to be around 11,207.7 million tons (BP, 2020). However, CO_2 emissions have witnessed significant consecutive growths over the next five subsequent decades with an estimated 34,169.0 million tons of CO_2 by the end of 2019 (BP, 2020). Thus, implying that carbon emissions levels have increased more than threefold from what they used to be in the mid-60s. This development alongside other environmental degradation issues has culminated in climate-related disasters which have been reported to have intensified in recent times (IPCC, 2007; IPCC, 2021; UNEP, 2021).

In the meantime, the environmental literature is replete with evidence of causal nexus between energy use and GHG emissions as countries pursue their economic goal agenda (Apergis & Payne, 2014; Chen et al., 2021; Dogan & Ozturk, 2017; Gyamfi et al., 2021; Gyamfi, Onifade, et al., 2022; Shahbaz, Nasir, et al., 2020; Sinha et al., 2020; Zameer et al., 2020). While economic growth on the ambit of energy consumption is historically linked to advanced industrialized economies of Europe and America, the vigor for economic expansion has been renewed in many other economies in recent times (UNEP, 2018). In this regard, the emerging seven (E7) economies are a major group of interest among others. Energy-related developments in this bloc including China, Russia, India, Mexico, Indonesia, Brazil, and Turkey have huge roles to play in global environmental sustainability. The E7 bloc currently leads in global carbon emissions levels and maintaining the prevailing energy portfolios to sustain economic growth portends a higher risk of GHG emissions.

Energy consumption has substantially grown in the E7 over the years as seen in Figure A1 in the Appendix, and this bloc accounts for a significant share of the global primary energy use (BP, 2020). China alone for instance accounts for over 23% of global primary energy consumption in 2018 with about 135.77 exajoules of energy consumption up from the estimated 5.52 exajoules of consumption in the mid-1960s (BP, 2020). This amount represents a staggering 2359.6% increase in energy use over these periods. Similar trends in energy use are also obtainable in other E7 economies (Adebayo et al., 2022; Alola et al., 2021; Gyamfi, Bekun, et al. 2022). As of the end of 2019, India, Russia, and Indonesia account for about 5.83%, 5.1%, and 1.52% of global primary energy use, while about 2.12%, 1.32%, and 1.11% of global energy consumption are attributed to Brazil, Mexico, and Turkey, respectively. In a nutshell, the E7 economies jointly account for around 41.26% share of global primary energy use in 2019 (BP, 2020).

Given the aforementioned huge energy demands and considering the share of conventional fuels in the total energy consumption, the E7 economies also have the leading records in CO_2 emissions. Total emissions have grown substantially in all of the E7 countries as seen in Figure 1 thus making the bloc the largest contributor to global



Source: Authors' computation using data from BP (2020). Values are given in million tons of CO_2

FIGURE 1 CO_2 emission in the E7 economies (1992–2018). Source: Authors' computation using data from BP (2020). Values are given in million tons of CO_2 [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 1 Patents in environment-related technologies in the E7 economies (1992–2018)

Year	China	India	Brazil	Mexico	Russia	Indonesia	Turkey
1992	9.71	2.8	12.18	2.61	10.57	17.65	6.5
1995	9.88	5.74	10.78	4.91	9.82	4.53	21.37
2000	3.67	4.49	4.78	3.59	12.46	13.74	7.57
2005	6.44	5.82	8.37	9.56	10.7	6.57	7.52
2010	9.61	11.06	12.43	14.03	11.21	11.9	5.62
2015	7.71	9.62	13.51	9.39	8.18	13.96	9.3
2018	8.35	8.5	11.65	12.7	8.86	7.19	6.27

Source: Computed using data from the Organization for Economic Co-operation and Development (OECD, 2021).

carbon emissions in recent times. China accounts for the largest share of global carbon emissions with around 28.75% of total CO_2 emissions in 2019 while, other E7 economies all together contribute around 17.33% of CO_2 emissions in the same year thus making the E7 bloc accountable for 46.08% of global carbon emissions in 2019 (BP, 2020).

The emergence of economic and industrial hubs across the globe has necessitated more demand for energy use and there is a need for collective climate actions given the dynamics of conventional energy resources in the overall global energy portfolios that have put the world in jeopardy of unabated greenhouse gases emissions. The world is exploring various channels to address the challenges of GHG emissions and the options of innovative technologies are not being left out.

Available data from the OECD database as seen in Table 1 details the record of improvements in environmental-related technological innovations recorded among the E7 economies. Inter alia, the question of whether these technological advancements have helped in fostering environmental sustainability vis-à-vis the actualization of the global quest for carbon neutrality has therefore become very imperative. Although the energy literature is very vast, there are only a few studies on the environmental impacts of innovative technologies (Álvarez-Herránz et al., 2017; Chen & Lee, 2020; Su et al., 2021). Besides, most of the existing studies addressed the case of OECD countries at large and less attention has been paid to the specific case of the E7 economies as a unique bloc despite the growing literature. As such, the present study aims to:

a. Firstly, examine whether environmental-related technological innovations have any moderating effect on carbon emission levels while accounting for the roles of renewable energy consumption in the E7 economies.
b. Secondly, to re-examine the validness of the EKC conjecture in an innovation-environment nexus following the reported validity of this hypothesis in other frameworks in the extant literature of the individual or combine E7 Economies (Onifade & Alola, 2022; Bekun et al., 2021; Jahanger et al., 2022).
c. Thirdly, to examine whether the implementation of an energy conservation agenda constitutes any significant threat to the economic growth quest in the E7 bloc.

Aside from the introduction in the first section of this manuscript, the remainder of the manuscript is arranged into four separate sections starting with the literature review and methodology in sections 2 and 3, followed by the empirical results discussions in section four. The study was concluded with recommendations and suggestions for policymakers and stakeholders in section 5.

2 | THE THEORETICAL UNDERPINNINGS

The theoretical underpinnings for the environmental impacts of technological innovation in this study follow the conceptual framework of the Stochastic Impacts by Regression on Population, Affluence, and Technology commonly known as the STIRPAT model by Dietz and Rosa (1997). The model provides some fundamental augmentations to the traditional IPAT model of Ehrlich and Holdren (1971). Based on the traditional IPAT model that posits that environmental impacts (*I*) are fundamentally a function of three main human-related activities namely population (*P*), affluence (*A*), and technology (*T*), Dietz and Rosa (1997) augmented the model stochastically as seen in Equation (1).

$$(I_{it}) = \alpha_0 P^{\beta}{}_{it} A^{\delta}{}_{it} T^{\gamma}{}_{it} \omega_{it} \quad (1)$$

In the STIRPAT Equation (1), *i* represents individual countries ranging from 1 to *N* while *t* represents the time that ranges from 1 to *T*. On the other hand, the estimated parameter coefficients are represented by $\beta, \delta, and\, \gamma$ while all variables remained as previously stated. ω_{it} represents the stochastic or error term in the model. The STIRPAT model has gained more popularity in recent times due to the growing influence of human activities on the environment and the adoption of the model for empirical analysis has received attention among researchers in the wake of the clamor for environmental sustainability (Fan et al., 2006; Ghazali & Ali, 2019; Wang et al., 2013). However, the technology components have only received little attention in the empirical literature over the years in contrast to the other components (population and affluence) which have often been explored in extant studies (Ghazali & Ali, 2019; Shahbaz et al., 2016). As such, in recent times, there is a gradual rise in studies relating to the environmental impacts of the technological component, and innovations in emerging economies are gradually attracting some attention as the composition of emissions has significantly risen in many of the emerging economies in recent times.

2.1 | An empirical literature review

Available empirical evidence in most cases shows that technological innovations can be helpful in the context of environmental quality advancement (Álvarez-Herránz et al., 2017; Amin et al., 2020; Baloch et al., 2021; Erdogan, 2021; Godil et al., 2021). Also, Alola and Onifade (2022) argued that technological innovation in different energy portfolios significantly yields environmental benefits. However, some studies have produced unconventional evidence that technological innovations could be a detrimental tool for environmental sustainability or in some cases can even have no essential benefits as far environmental sustainability is concerned (Chen & Lee, 2020; Su et al., 2021; Wang & Zhu, 2020).

Álvarez-Herránz et al. (2017) used V-lag distribution modeling to examine the environmental impacts of innovations in a group of 28 OECD nations. Their study covers the period between 1990 and 2014 and the findings show that technological innovations mitigate CO_2 emissions among the selected OECD countries. The studies of Erdogan (2021) and Baloch et al. (2021) also provide similar evidence that supports the findings of Álvarez-Herránz et al. (2017) but for the case of the BRICS economies. Baloch et al. (2021) used the dynamic ordinary least square and fully modified least square approaches to examine data between 1996 and 2016, while Erdogan (2021) on the other hand adopted the dynamic common correlated effect when exploring the environmental impacts of innovations for data between 1992 and 2018. Nevertheless, both studies reached a relatively close conclusion that innovations are beneficial to the environmental quality of the BRICS bloc.

As for the E7 economies, the case of China has attracted more attention compared to any other member of the E7 countries being the largest emitting nation in the bloc. Shahbaz, Raghutla, et al. (2020) used the bootstrapping ARDL method to study the environmental effects of innovations in China and the findings show that innovation mitigates emissions in China for the period between 1984 and 2018. The findings from a different study by Godil et al. (2021) also complement the results from Shahbaz, Raghutla, et al. (2020). Godil et al. (2021) also examined the case of China using the quantile ARDL method for data between 1990 and 2018 and they affirm that innovations significantly reduce CO_2 emissions specifically in the case of the Chinese transport sector.

Despite the aforementioned studies that produced evidence in the affirmative of the beneficial environmental impact of innovations, there are other studies with contrary results. Besides, Onifade, Alola, et al. (2021), argued that the impacts of innovation are not substantial enough to pave way for a transition to environmentally desirable cleaner energy that could help reduce carbon emissions. The study of Su et al. (2021) for the BRICS shows that technological innovations can be counterproductive to environmental sustainability by inducing the level of carbon emissions. However, the measures of technological innovation in their study raise some points of concern about the environmental-related conclusions that were drawn from the study. A limitation of the study is that only the advancements in communication and information technologies were utilized as proxies for technological innovations. The study of Chen and Lee (2020) also reveals that there are no significant global environmental benefits from innovations as expected from the perspective of overall contributions towards the reduction of CO_2 emissions. Their conclusions were drawn from the empirical examination of a group of ninety-six (96) countries around the world using the spatial econometric modeling approach. This finding partly supports the evidence from Su et al. (2021) even though the approaches to innovation measurement differ. Hence, it can still be said that there is no consensus on the environmental impacts of technological innovations in the empirical literature going by available evidence.

To the best of the authors' knowledge, none of the existing studies has addressed the innovation-emission nexus by considering the specific case of the group of the major emerging seven (E7) economies as a single bloc. Besides, the study of Wang and Zhu (2020) for China shows specifically that the levels of innovations may increase emissions or reduce emission levels depending on the energy portfolios. As such, this study while examining the environmental impacts of technological innovations amidst the overall primary energy consumption in the E7 economies (the majority of which consist of conventional energy forms), the study also examines whether innovations have any moderating effect on environmental pollution levels in the E7 bloc when renewable energy consumption levels are also accounted for.

3 | METHODOLOGY: DATA AND PROCEDURES OF ANALYSIS

To explore the roles of technological innovations and renewables in the environmental prospects of the E7 nations amidst the growing energy demands in these rapidly emerging economies, relevant data were drawn from the Organization for Economic Co-operation and Development (OECD, 2021) database, the World Bank (WDI, 2020), and British Petroleum (BP, 2020). The scope for the current study was streamlined to cover the sample frame between 1992 and 2018 and this decision was informed by the available statistical record on innovations in the OECD database. Equation (2) was specified following the logarithm transformation of the STIRPAT specification in Equation (1).

$$LnCO_{2it} = \alpha_0 + \alpha_1 LnI_{it} + \alpha_2 LnI^2{}_{it} + \alpha_3 LnTNOV_{it} + \alpha_4 LnEG_{it} + \alpha_5 LnRW_{it} + \mu_{it} \quad (2)$$

The environmental impacts in the study were captured by the levels of carbon emissions among the emerging nations as represented by CO_2. The figures for the emissions levels are provided in million tons of carbon dioxide and the data are openly accessible in the BP database. The records of individual E7 countries' patents in environment-related technologies were used to capture the roles of technology innovations as denoted by *TNOV* in Equation (2). To capture the impacts of the growth in energy use, the amount of the overall primary energy consumption was taken for all the countries in per capita values as represented by *EG*. The variable *RW* was used to account for the total renewable energy consumption levels in the overall energy portfolios of the E7 economies while exploring the roles of innovations in the environmental impacts model. It should be noted that although paramount attention was paid to the technology component in this study, the variables utilized also partly capture the influence of other components in the STIRPAT framework. For instance, the income component covers concerns about affluence while both the energy consumption and income components also reflect the population aspects as they were taken on a per capita basis. This step is advantageous since the emerging countries are not necessarily at the same tier of economic progress or development.

The income level or economic growth is proxied by individual countries' real gross domestic product (GDP) per capita measured in the current (US$) as denoted by the variable *I*. Considering the quest for wealth creation that is often triggered by the need to maintain increasing income growth, which is a major trait in many emerging economies, the study incorporates the squared values of income variables into the model. This step provides the opportunity to examine whether the environmental Kuznets Curve (EKC) conjecture stands among the E7 economies. The rationale behind the EKC conjecture is that income expansion at a later stage would cancel out the initial environmental damages from economic growth. Testing this hypothesis could be beneficial for policy directives, especially among emerging economies like the E7. As such, many contemporary studies have not bypassed this analysis (Dogan & Ozturk, 2017; Shahbaz, Nasir, et al., 2020). Thus, in the current study, the findings can further reveal whether a higher level of affluence can mar or make environmental prospects among the E7 economies.

3.1 | Procedures of analysis

The procedures for the empirical analysis in this research open with an overall essential review of the obtained datasets to unfold the basic statistical features of the data for each variable of interest. These preliminary data checks help to ensure a strong foundation for empirical analysis and prevent errors in the selection of methodological approaches as certain sample characteristics may have effects on the suitability or robustness of findings from various econometrical techniques. As such, following the stance of Chudik and Pesaran (2015) regarding the selection of estimators for heterogeneous panel data sets, the preliminary checks begin with an exploration of any possible cross-sectional dependency (CD) in errors among the heterogeneous dataset of the study. This step has been argued to be crucial, especially in the era of global economic interrelationships among nations that can pave way for potential common shocks in different economies across international boundaries. As such, to ascertain the presence of CD in the dataset, the empirical analysis features a combination of CD tests including the Breusch and Pagan (1980) LM techniques, and the CD test of Pesaran (2007) which was complemented by the LM techniques of Pesaran (2015). Some contemporary studies have also performed and enunciated more on the significance of the CD tests (Gyamfi et al., 2021; Onifade, Alola, et al., 2021; Onifade, Gyamfi, et al., 2021). In a simple panel representation as seen in Equation (3), (*i*) shows the cross-section dimension from 1 to *N* while the time (*t*) ranges from 1 to *T*, the assertion that there is no cross-section dependence from a null hypothesis would imply that Cov $(\mu_{it}, \mu_{jt}) = 0$. On the other hand, an alternative hypothesis for the existence of CD in at least a set of the understudied cross-sections would mean that $\text{Cov}(\mu_{it}, \mu_{jt}) \neq 0$.

$$Y_{it} = \alpha_{oi} + \alpha_{1i} X_{it} + \mu_{it} \tag{3}$$

$$CD = \sqrt{\left(\frac{2T}{N(N-1)}\right)} \left(\sum_{i=1}^{N-1} \sum_{J=i+1}^{N} \hat{\rho_{ij}}\right) \tag{4}$$

$$\hat{\rho_{ji}} = \hat{\rho_{ij}} = \frac{\sum_{t-1}^{T} \hat{\mu_{i,t}} \hat{\mu_{j,t}}}{\left(\sum_{t=1}^{T} \hat{\mu_{it}^{2}}\right)^{\frac{1}{2}} \left(\sum_{t=1}^{T} \hat{\mu_{jt}^{2}}\right)^{\frac{1}{2}}} \tag{5}$$

The obtained test statistics for the observed residuals (μ) is expected to be asymptotically distributed in a manner that CD∼N(0, 1) in Equation (4) and (5). This approach has some benefits as it is useful for relatively small sample observations and it is also robust for capturing slope heterogeneity while accounting for weak-correctional dependence in panel observations (Xu, 2018; Pesaran, 2015). Following the analysis, there were indications of CD as reported in the results discussion chapter (see section 4.0). As far as testing for unit root is concerned, this development relating to the CD must be accounted for. Therefore, the study adopts the second-generation panel IPS and CIPS techniques for the unit root analysis in a bid to understand the integration orders of the panel variables. The CIPS approach for the unit root test (Pesaran, 2007) is a second-generation model of the Im et al. (2003) technique (IPS). The test statistics estimator for the CIPS is presented in Equation (7) following the obtained empirical results from the evaluation of the CIPS procedures from the expression in Equation (6). The cross-section (CD) averages are captured by $CA_{\bar{i}t\text{-}1}$ and $\Delta CA_{i,t1}$ in Equation (7), while the CDF reflects the cross-sectional dependent augmented Dickey–Fuller (CADF).

$$\Delta CA_{i,t} = \Phi_i + \Phi_i Z_{i,t-1} + \Phi_i CA_{\bar{i}t-1} + \sum_{1=0}^{p} \mathit{\Phi il} \Delta CA_{t-1} + \sum_{i=0}^{p} \Phi \mathrm{i\,l} \Delta CA_{i,t1} + \mu_{it} \tag{6}$$

$$CIPS_{2007} = N^{-1} \sum_{i=0}^{n} CDFi \tag{7}$$

Subsequently, the study utilized the Westerlund (2007) cointegration test for establishing a long-run relationship for the panel observation. This approach also caters for the observed CD characteristics of the panel dataset, unlike popular first-generation panel cointegration tests that often produce misleading results for rejecting the null hypothesis in a panel cointegration test. In Equation (8), ψ_t represents the vector of parameters for the cointegration test while (β_i) denotes the error adjustment term. As for the deterministic specifications (D_t) for the model, it could vary from ($D_t = 0$) signifying that there is no deterministic term, to a model with only a constant term ($D_t = 1$), and there could also be a specification with both constant and trend ($D_t = 1, t$).

$$\Delta Y_{it} = \psi_i D_t + \beta_i Y_{it-1} + \gamma_i X_{it-1} + \sum\nolimits_{j=1}^{pi} \beta_{ij} \Delta Y_{i,t-j} + \sum\nolimits_{j=0}^{pi} \lambda_{ij} \Delta X_{i,t-j} + \varepsilon_{it} \tag{8}$$

The Westerlund (2007) technique utilizes the error adjustment process to establish long-run relationships among panel variables by producing two estimated statistical values namely; the panel statistics (Pt, Pα) and the group statistics (Gt, Gα,) based on the evaluation of Equation (8). This panel cointegration approach has proved to be relevant in contemporary studies to overcome the CD pitfalls while exploring the long-run relationship in panel observations (Adedoyin et al., 2021; Alola et al., 2019; Onifade, Alola, et al., 2021; Onifade, Gyamfi, et al., 2021). Hereafter, the study proceeds to evaluate the long-run influence of the interaction among the panel observation in the baseline model.

3.2 | Coefficient estimations (long-run and short-run analysis)

The study adopted the novel Cross-Sectionally Augmented Autoregressive Distributed Lag (CS-ARDL) approach of Chudik and Pesaran (2015) to explore both the long-run and short-run coefficient estimations following the findings from the various pre-estimations analysis on the unit root properties of variables and the evidence of cointegration among them. It is worthy to note that the CS-ARDL technique offers more advantages to the current study since the estimator produces reliable and robust estimates even in the presence of cross-sectional dependence which is a mare hurdle in the present study. Besides, the application of this estimator is not restrained by a mixed order of integration among panel observations and the estimation of common correlated impacts by the techniques further helps in accounting for any possible heterogeneity (Chudik & Pesaran, 2015; Mehmood, 2021; Wang et al., 2020). Although the application of the popular panel ARDL approach of Pesaran et al. (1999) is also compatible with mixed order of integration {I(0) or I(1)} in panel observation, however, its estimates tend to be unreliable when there are fundamental issues of CD and therefore CS-ARDL technique is preferable (Chudik et al., 2016; Erülgen et al., 2020). This technique utilizes a combination of the mean group (MG) estimator as well as the pooled mean group (PMG) estimators and it produces long-run and short-run coefficients while adjusting prediction errors to account for any long-term correlations in panel observation with heterogeneous effects (Chudik et al., 2016).

$$\Delta Y_{it} = \delta_i \{ Y_{i(t-1)} - \vartheta_i X_{it} \} + \sum_{j=1}^{p-1} \beta_{ij} \Delta Y_{i(t-j)} + \sum_{j=0}^{q-1} \pi_{ij} \Delta X_{i(t-j)} + \varphi_i + \varepsilon_{it} \tag{9}$$

$\{ Y_{i(t-1)} - \vartheta_i X_{it} \}$ denotes the adjustment term of a simplified panel ARDL model with error mechanism process as seen in Equation (9) while ϑ_i denotes the vector of the long-run relationship. On the other hand, the anticipated group-specific speed of adjustment which is expected to be negative and significant is represented by the δ_i coefficient while β_{ij} and π_{ij} parameters capture the short-run estimates. Furthermore, the CS-ARDL technique circumvents the pitfalls in the traditional panel ARDL by augmenting the latter with the cross-sectional averages of both explanatory and explained variables, and a combination of their lag values thereby correcting the cross-sectional correlation in the error component as seen in Equation (10).

$$\begin{aligned} \Delta Y_{it} = {} & \delta_i \{ Y_{i(t-1)} - \vartheta_i X_{it} + \alpha_i^{-1} n_i \overline{Y}_t + \alpha_i^{-1} Y_i \overline{X}_t \} + \sum_{j=1}^{p-1} \beta_{ij} \Delta Y_{i(t-j)} \\ & + \sum_{j=0}^{q-1} \pi_{ij} \Delta X_{i(t-j)} + \sum_{j=0}^{p-1} \lambda_{ik} \Delta \overline{Y}_{i(t-j)} + \sum_{j=0}^{q-1} Y_{ik} \Delta \overline{X}_{i(t-j)} + \varphi_i + \varepsilon_{it} \end{aligned} \tag{10}$$

$\overline{Y}_t$ and $\overline{X}_t$ respectively, represent the cross-sectional averages of the variables Y_{it} and X_{it} as seen in Equation (10), while the level components of the cross-section averages are taken to obtain the corresponding long-run equilibrium interactions as reflected in the bracket in Equation (10). ϑ_i shows the long-run estimates while δ_i represents the speed of equilibrium adjustment. Moving on, having applied the CS-ARDL approach first, we also provided the estimates from the PMG-ARDL estimator for a comparative analysis and robustness checks for the CS-ARDL results. Although the traditional panel PMG-ARDL approach also offers some of the highlighted benefits from the CS-ARDL like providing estimates for both short-run and long-run effects, however, it loses its accuracy and reliability when panel observations are marred with CD pitfalls such as in the current study. Nevertheless, its outcomes may lend credence to the superiority and robustness of the former approach. The empirical analysis closes with the report of a granger causality analysis for the panel variables using the Dumitrescu and Hurlin (2012) technique. All the findings from the estimations were reported and subsequently discussed in the result discussion section.

4 | DISCUSSION OF RESULTS

Simple descriptive statistics of the panel data were provided in Table 2 to begin the results discussions. The table shows figures on both the central tendency of the data distribution as well as the dispersion of the data coupled with the results of the simple linear relationship between the variables as shown in the results of the

TABLE 2 Simple descriptive statistics of variables

Variable(s)	$LnCO_2$	LnI	LnI^2	LnTNOV	LnEG	LnRW
Mean	2.8613	3.5062	12.5039	0.9141	1.6766	−1.2846
Median	2.6747	3.5614	12.6840	0.9439	1.7047	−1.1920
Maximum	3.9780	4.2034	17.6688	1.3298	2.3642	0.7638
Minimum	2.1575	2.4787	6.1444	0.3654	1.0019	−3.2441
Std. Dev.	0.4783	0.4596	3.1237	0.1800	0.3430	0.9481
Correlation						
Variables	$LnCO_2$	LnI	LnI^2	LnTNOV	LnEG	LnRW
$LnCO_2$	1					
p-value	–					
LnI	−0.1506b	1				
p-value	(.0385)	–				
LnI^2	−0.1481b	0.9979a	1			
p-value	(.0419)	(.0000)	–			
LnTNOV	0.0884	0.3078a	0.3070a	1		
p-value	(.2262)	(.0000)	(.0000)	–		
LnEG	0.2295a	0.7152a	0.7076a	0.3281a	1	
p-value	(.0015)	(.0000)	(.0000)	(.0000)	–	
LnRW	0.1397c	0.2355a	0.2335a	0.0155	−0.2307a	1
p-value	(.0550)	(.0011)	(.0012)	(.8323)	(.0014)	–

Source: Computed by the author. a, b, and c reflect the statistical relevance of values at 1%, 5%, and 10% levels in that order.

TABLE 3 CD test outputs

Methods	Breusch and Pagan (1980) LM Test	Pesaran (2007) CD Test	Pesaran (2015) LM Test
For Equation (2)	165.39a	8.65a	22.28a
p-value	(.0000)	(.0000)	(.0000)

Source: Computed by the author. Note: a, b, and c reflect the statistical relevance of values at 1%, 5%, and 10% levels in that order.

correlation. A negative relationship is observable between income level and carbon emissions while a positive linear relationship is seen between emissions levels and the trio of innovation, renewable energy use, and total primary energy consumption. The simple linear relationship from the correlation result does not produce reliable results as it does not necessarily reflect the inherent statistical properties of observations which are very paramount in shaping the long-run interactions among variables. As such, the unit root properties of the variable were reported in Table 4 following the outputs of the CD properties examination that are reported in Table 3. The null of no cross-sectional dependence was rejected for the panel sample in Table 3 while the results of the unit root analysis produced sufficient evidence that variables are mainly differenced stationary, that is, *I(1)* except for the technological innovation variable which came out to be stationary at the level in both the IPS and CIPS tests.

Given the observed mixed order of integration of the panel dataset, the Westerlund cointegration was applied to examine the level relationship among variables and the outputs are detailed in Table 4. Both the panel statistics and the group statistics indicate the presence of long-run connection among the samples understudied for the E7 economies. This pave way for the possibility of exploring the anticipated long-run panel coefficients.

4.1 | Long-run and short-run coefficient estimates

The long-run coefficients have been detailed in Table 5. As previously noted in the methodology section, the CS-ARDL technique also produced the short-run estimates as an additional insight for overall analysis. The findings from the PMG estimator were also reported alongside the CS-ARDL outputs in the table. From the empirical findings from the CS-ARDL approach, overall energy use poses existential threats to environmental quality among countries in the E7 bloc. There is a significant rise in carbon dioxide emissions level by about 0.60% for every 1.0% increase in per capita energy use among these countries. This result is a reflection of the environmentally detrimental effects of conventional energy consumption that overwhelmingly dominates the energy portfolio among these rapidly emerging

TABLE 4 Unit root and level relationship results

	CIPS		IPS			
Variables list	Trend specification $D_t = (1, t)$		Trend specification $D_t = (1, t)$			
	I(0)	I(1)	I(0)		I(1)	
$LnCO_2$	−2.203	−3.991a	−2.0462		−4.6616a	
LnI	−3.044b	−4.984a	−1.6719		−4.2803a	
LnI^2	−2.674	−4.834a	−1.6984		−4.1915a	
LnTNOV	−5.005a	−6.059a	−4.6623a		−7.7833a	
LnRW	−2.420	−4.634a	−1.7126		−4.6422a	
LnEG	−2.011	−3.521a	−2.0420		−4.3389a	
Cointegration (Westerlund, 2007)						
Model			Group stat.		Panel stat.	
$LnCO_2$ = f(LnI), (LnI^2), (LnTNOV), (LnEG), (LnRW)			Gτ	Gα	Pτ	Pα
Statistics			−2.531a	−5.322a	−5.598a	−5.836a
Robust *p*-value			.0000	.0000	.0000	.0000

Note: Computed by the author. a, b, and c reflect the statistical relevance of values at 1%, 5%, and 10% levels in that order.

TABLE 5 Long-and short-run coefficient estimates

	Long-run estimates				Country-specific ECT (PMG)		
Variables CO_2 (Explained)	CS-ARDL estimates	*p*-value	PMG estimates	*p*-value	E7 Countries	Estimates	*p*-values
LnI	0.2892*a*	.0000	0.0418	.4828	China	−0.2994*a*	.0001
LnI^2	−0.0431*a*	.0000	−0.0068	.4321	India	−0.2742b	.0110
LnTNOV	−0.0043*b*	.0470	−0.0031	.7042	Brazil	−0.3223b	.0107
LnRW	−0.0228*b*	.0190	−0.0316a	.0000	Mexico	−0.3889a	.0003
LnEG	0.6080*a*	.0000	1.2242a	.0000	Russia	−0.5626a	.0001
	Short-run Coefficients				Indonesia	−0.8480a	.0002
ECT	−0.9602*a*	.0000	-0.5397a	.0000	Turkey	−1.0822a	.0001
ΔLnI	0.5667*a*	.0000	0.1819	.5335			
$ΔLnI^2$	−0.0841*a*	.0001	−0.0281	.4748			
ΔLnTNOV	−0.0081*b*	.0440	0.0002	.9643			
ΔLnRW	−0.0434*b*	.0170	0.0018	.8744			
ΔLnEG	1.1837a	.0000	0.4731a	.0067			
C	−1.9602*a*	.0000	0.2667	.0016			
No. Regressors	5		5				
No. Observations	182		182				
No. Group	7		7				
CD-statistics	−1.54	0.1230	2.02b	0.0432			

Source: Computed by Author. Computed by the author. a, b, and c reflect the statistical relevance of values at 1%, 5%, and 10% levels in that order.

economies. The proportion of fossil energy use (mainly oil, gas, and coal) in total primary energy consumption by the end of 2019 is as high as 85.13%, 91.04%, 87.88%, and 53.87% in China, India, Russia, and Brazil. As for Mexico, Turkey, and Indonesia, fossil fuel consumption still accounts for 91.45%, 81.15%, and 93.93% of the total primary energy use (BP, 2020). As such, energy use significantly drives environmental pollution in the E7. These findings further resonate with the reported adverse environmental effects of conventional energy use in the literature (Erdoğan et al., 2021; Onifade, Alola, et al., 2021; Onifade, Gyamfi, et al., 2021; Ozturk & Acaravci, 2016). The observed short-run impact of energy consumption is consistent with the long-run estimates and the total primary energy consumption is also found to be granger causing carbon emissions in these emerging economies as seen in the causality report in Table 6.

The estimations for the environmental influence of economic growth also mirror what was obtainable under the primary energy use scenario. The rapid economic growth recorded in the E7 bloc was found to be environmentally detrimental for the period of study as

TABLE 6 Panel causality evidence

Variables	Zbar-Stat $LnCO_2$	LnI	LnTNOV	LnRW	LnEG	Causality flow
$LnCO_2$	_	6.8921a	6.5803a	4.6516a	10.9645a	LnCO2 → LnI, LnTNOV, LnRW, LnEG
LnI	2.4578b	_	3.5610a	4.9580a	4.3530a	LnI → LnCO2, LnTNOV, LnRW, LnEG
LnTNOV	1.0329	−0.3135	_	1.8171c	2.6499a	LnTNOV → LnRW, LnEG
LnRW	2.1889b	1.9393c	1.5420	_	8.0261a	LnRW → LnCO2, LnI, LnEG
LnEG	3.4722a	5.1593a	4.8878a	3.9440a	_	LnEG → LnCO2, LnI, LnTNOV, LnRW

Source: Computed by Author. Note: Computed by the author. a, b, and c reflect the statistical relevance of values at 1%, 5%, and 10% levels in that order.

evidenced by the rise in carbon dioxide emissions by about 0.28% for every 1% economic expansion. This result reaffirms the energy consumption-led growth that the majority of the E7 countries have witnessed over the last couple of decades. This submission regarding the observed growth-environment nexus is further enunciated in the causality results in Table 6 where it can be seen that primary energy consumption per capita significantly granger causes growth in the E7 bloc. Hence, the current findings reaffirm the growth emissions nexus in extant studies (Akadiri & Adebayo, 2021; Bekun et al., 2021; Onifade, 2022a; Onifade, 2022b; Shahbaz, Nasir, et al., 2020).

On the other hand, the long-run estimations provide crucial insights into the moderating roles of technological innovations and renewables in environmental degradation trends among the countries in the E7 bloc. Although both innovations and renewable energy consumption enhance sustainability, the magnitude of the desirable environmental impacts of the former is quite low compared to the latter. Carbon emission levels are significantly reduced by just 0.0043% for every 1% rise in technological innovations while a percentage rise in renewable energy utilization on the other hand also cushions emissions by 0.0228%. Although these findings are desirable for the environment, however, the obtained impact levels are quite low compared to the magnitude of the damages created to the environment in terms of CO_2 inducement from economic growth and total primary energy consumption per capita among the E7. The long-run estimates are consistent with the short-run impacts of the variables although the magnitude of the environmental impacts of both innovations and renewables are stronger in the short-run dynamics. Overall, these results are indicative that the E7 needs to do more in terms of investments in environmental-related technological innovations and the expansion of renewables in overall energy portfolios to harness the inherent benefits of the duo towards positioning the E7 economies on the path of environmental sustainability. Innovations are an essential tool for environmental sustainability enhancement of the E7 as it stands to help in boosting renewable energy consumption among these emerging economies. This stance is further supported by the observed one-way causality flowing from innovations to renewables as seen in Table 6. The current study thus buttresses the reported desirable environmental impacts of innovations on carbon emission in the Chinese transport sector (Godil et al., 2021) and some reported cushioning impacts of renewables on rising CO_2 emissions in different economies (Dogan & Ozturk, 2017; Erdoğan et al., 2022; Godil et al., 2021). Besides, the causality evidence in Table 6 also reveals a two-way causality between renewables and emissions showing that the E7 economies can combat environmental degradation by leveraging on higher levels of renewable energy consumption levels that are enhanced by more investments in technological innovations.

As for the examination of the EKC conjecture, although economic growth is found to be detrimental to the environment among the E7, the evidence from the squared income values shows that real income growth in time will offset the initial environmental damages from economic growth in terms of reduction in CO_2 emissions level, thus validating the inverted U-shape growth-emission conjecture of the EKC for these group of emerging economies over the period of study. These results corroborate the EKC validity for the E7 from some existing studies (Onifade & Alola, 2022; Baloch et al. 2021). In essence, the E7 economies can eventually capitalize on their income level for environmental gains over time given a broader level of economic expansion. The possibility of attaining this U-turn effect of the economic growth-environmental quality nexus is not beyond reach as some other blocs like the G7 have been noted to have witnessed enhanced environmental quality levels from their economic growth (Ahmed et al., 2021).

Lastly, although the PMG estimator produced some insightful results that are slightly similar in some respect to the CS-ARDL, however, the overall validness of the entire results from the PMG estimator is generally questionable and as such cannot be relied on for policy directives. The p-value of (0.0432) for the CD test for a null of cross-sectional independence for the residuals in the PMG outputs shows that the approach fails to address the fundamental issues of CD. As for the coefficient estimates from the CS-ARDL technique, the probability value of 0.1230 for the estimated CD statistics with −1.540 implies that the null hypothesis of cross-sectional independence cannot be rejected. This, further buttresses the importance of applying the CS-ARDL technique in this study as it helps to address the resultant CD challenges from common factors in observations by utilizing the lagged cross-sectional averages to augment the regression analysis.

5 | CONCLUSIONS

The present study explores the moderating roles of technological innovation and renewables on environmental degradation among the E7 economies. The current study capitalizes on the strength of the novel CS-ARDL technique in addressing the pitfalls of CD from common factors that marred the understudied panel observations for the group of the rapidly emerging economies between 1992 and 2018. Following the essential preliminary analysis that establishes the long-run relationship among the understudied variables, the application of the adopted CS-ARDL technique offers the benefit of obtaining both the long-run and short-run dynamics of the impacts of the explanatory variables on environmental impact as measured by the levels of carbon emission among the E7 countries. First, the findings enunciated the moderating roles of technological innovation and renewables on environmental degradation among the E7 economies as the rise of both renewables and innovation significantly dampens CO_2 emission levels. Second, the results reveal that the rapid economic expansion recorded among the E7 bloc was environmentally detrimental for the period of study as evident by its influence in significantly inducing carbon dioxide emissions in the E7 bloc. Third, the growing energy demands that have boosted total primary energy consumption in the E7 over the years have further exacerbated environmental pollution by inducing CO2 emissions levels in the bloc throughout the study. Although both innovations and renewable energy consumption enhance sustainability, however, the magnitude of their desirable environmental impacts is quite low compared to the observed impacts of the pollution damages created by the observed energy consumption-driven economic growth expansion in the bloc over the years. While both growth and energy use induce emissions, the inverted U-shape growth-emission conjecture of the EKC hypothesis was found to be valid for the group of the emerging seven (E7) economies.

5.1 | Policy recommendations

To harness the environmental benefit of innovations, more emphasis should be laid on investment in green technologies to foster the consumption of more renewable and alternative energy resources. Such investments will not only help to boost energy production to meet the immediate overall high energy demand in the emerging (E7) economies, but it will further aid higher efficiency which can eventually pave way for less overall energy use in the long run. It is also expedient for policymakers in the E7 to strategize on energy portfolio diversification away from fossil energy resources utilization to renewable, especially in critical sectors where energy demands are higher such as in the transport sector and the industrial sector including manufacturing industries and construction industries among others. Policymakers must ensure that priorities are given to these energy-intensive sectors as an integral part of any initiatives for technological innovation.

Furthermore, while adhering to the ultimate goal of carbon neutrality in the near future, investments in innovative energy technologies are not only going to help in boosting renewable energy production and consumption for a more sustainable environment alone, but they are equally going to be vital for a better level of efficiency in the production and consumption of conventional energy in the meantime to enhance lower carbon emissions through lesser consumption rate. Hence, the E7 bloc needs to boost research and development (R&D) spending to foster the frontiers of scientific research that can contribute to the advancements of the available technologies on one hand while initiating the developments of newer technologies on the other hand.

Lastly, since carbon emissions levels granger causes real growth levels, policy implementations for energy conservation must be well thought out, carefully designed, and strategically implemented to avoid economic setbacks while pursuing environmental sustainability goals. Environmental sustainability push through a drastic energy consumption reduction strategy may be deemed counterproductive for economic growth among these rapidly emerging economies and as such, energy conservation plans have to be gradually implemented strategically in the E7 over time.

5.2 | Directions for future study

Drawing from the established broad insights on the moderating roles of technological innovations and renewables in the E7 economies from the current study, future studies can be tailored towards the explorations of the roles of other factors contributing to the energy portfolio dynamics of the E7. For instance, an exploration of the demographic components in each of the economies may also provide additional insights on policy directives for a country-specific basis for the E7 economies.

ORCID

Stephen Taiwo Onifade https://orcid.org/0000-0003-1497-7835
Festus Victor Bekun https://orcid.org/0000-0003-4948-6905

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APPENDIX A

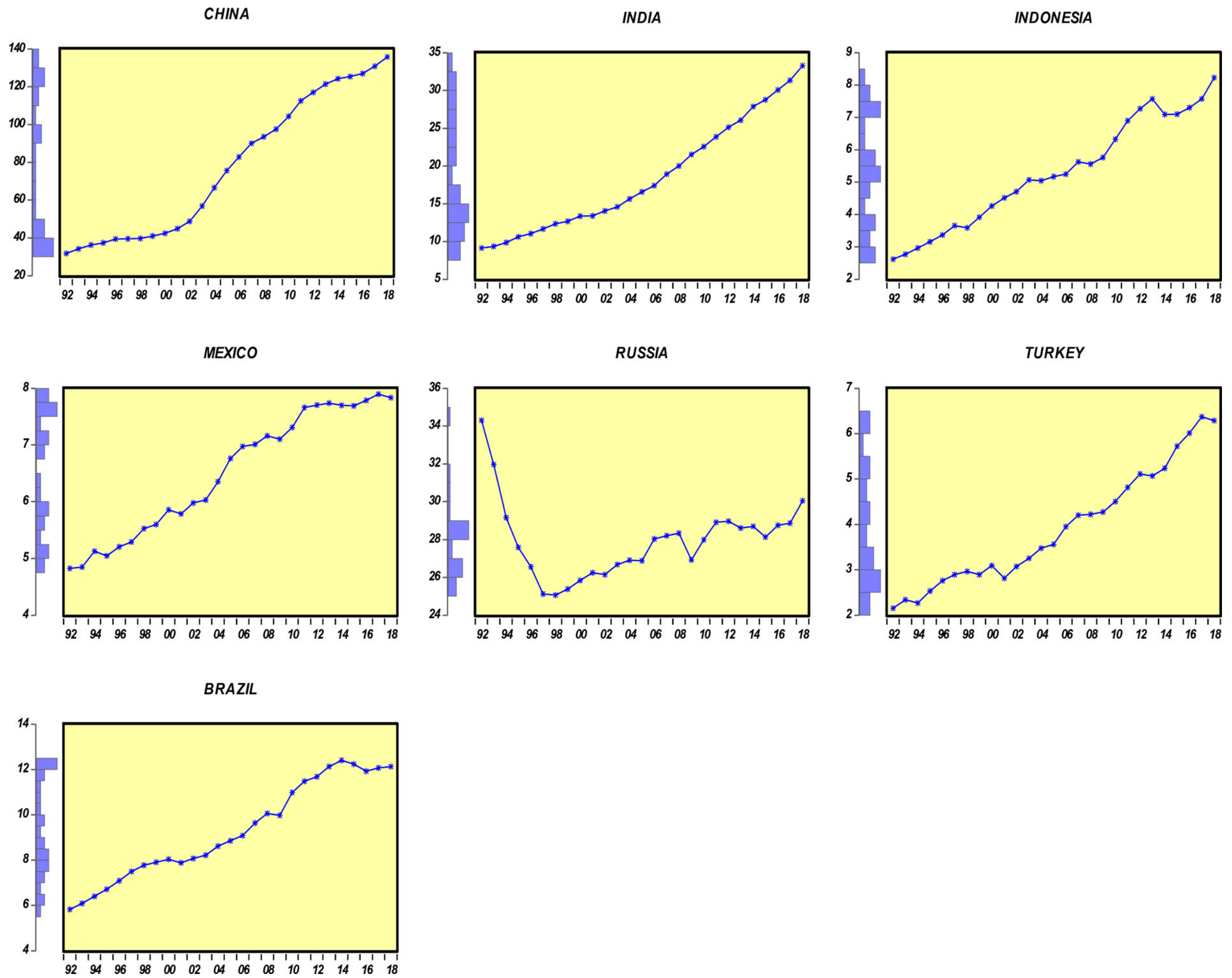

FIGURE A1 Primary energy consumption in the E7 economies (1992–2018). Source: Authors' computation using data from BP (2020). Values are given in exajoules of energy consumption [Colour figure can be viewed at wileyonlinelibrary.com]