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RESEARCH ARTICLE

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Energy transition and environmental quality prospects in leading emerging economies: The role of environmental-related technological innovation

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Abstract

The world has witnessed a significant rise in greenhouse gas emissions since the end of the 20th century as several economies begin to emerge into industrial hubs and manufacturing giants across the globe. Thus, in the wake of global interest in clean energy development and campaign for sustainable climate and ecosystem, the role of the emerging countries in the debate is unarguably vital and demanding. Importantly, this study seeks to examine the commitment of the leading emerging countries (E7) of Brazil, China, India, Indonesia, Mexico, Russia, and Turkey to energy transition and carbon-neutral 2050. We employ the cross-sectionally augmented autoregressive distributed lag approach that accounts for potential country-specific factors to examine the role of environmental-related technological innovations (ERT) in achieving climate neutrality in the E7 over the period from 1992 to 2018. Notably, the findings revealed that a 1 percent increase in ERT yields ~0.33% (short-run) and ~0.17% (long-run) reductions in carbon emission, thus suggesting that the E7 economies could be heading toward environmental sustainability with the application of ERT. Additionally, the result revealed that the application of ERT in the energy utilization profile significantly reduced the undesirable impact of primary energy utilization. However, the result showed that such an impact is not enough to trigger a transition to environmentally desirable cleaner energy that could mitigate carbon emissions. This is because the larger share of the E7 countries' primary energy utilization is from conventional and/or non-renewable energy sources. The environmental Kuznets curve hypothesis is also validated.

KEYWORDS
economic growth, emerging economies, energy utilization, environmental sustainability, innovation, technology

1 | INTRODUCTION

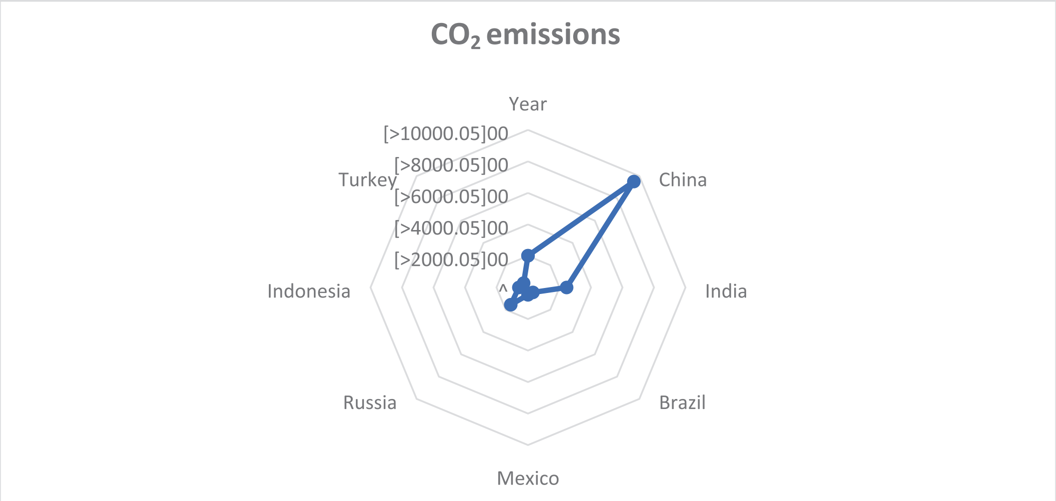
From a historical perspective, advanced economies mainly the United States of America (US) and those in Europe (precisely Western Europe) have dominated the major point of discussion about greenhouse gas (GHG) emissions mitigation following the early industrial revolutions (Alola, Adebayo, et al., 2021; Alola, Akadiri, et al., 2021; Allen, 2009; Friedrich & Damassa, 2014; Kasa, 1973).

However, the world has seen a dramatic change in emissions trajectory and the composition of major emitting economies toward the end of the 20th century until date. This change occurs as many other economies begin to emerge into industrial hubs and manufacturing giants across the globe. Some of the countries in this category have been classified into various groups. As a prominent group of countries, the world's Emerging seven (E7) economies consisting of China, India, Brazil, Mexico, Russia, Indonesia, and Turkey are increasing gaining more attention in the subject of global climate change (Alola & Nwulu, 2021; Etokakpan et al., 2021; Huang et al., 2021; Zoaka et al., 2022).

Based on available reliable data, emissions levels have greatly increased among the E7 economies over the last few decades and this bloc of countries is arguably the largest contributor to the global emissions in recent times. Countries like China have emerged as the top-emitting nation accounting for over 27% of total emissions as of 2017 according to the United Nation Emission Gap Report (UNEP, 2018). Jiang et al. (2022), noted that greenhouse gasses (GHGs) have been a major challenge to global environmental sustainability, and energy-related carbon emissions, in particular, stand out as a major concern in countries like China. Other countries among the E7 also contribute to a significant chunk of the global carbon emissions for instance about 7.1% of the total greenhouse gas (GHG) emissions were attributed to India. In the South and Central America region, Brazil accounts for the highest emissions with about 35.02% of the region's total carbon dioxide emissions (British Petroleum, 2020). Emission is also fast growing in Turkey, Indonesia, Russia, and Mexico as seen in Figure 1. As of 2018, China leads in emission among these countries followed by India, Russia, Indonesia, Mexico, Brazil, and Turkey, respectively, and carbon emission level is yet to peak in most of these economies.

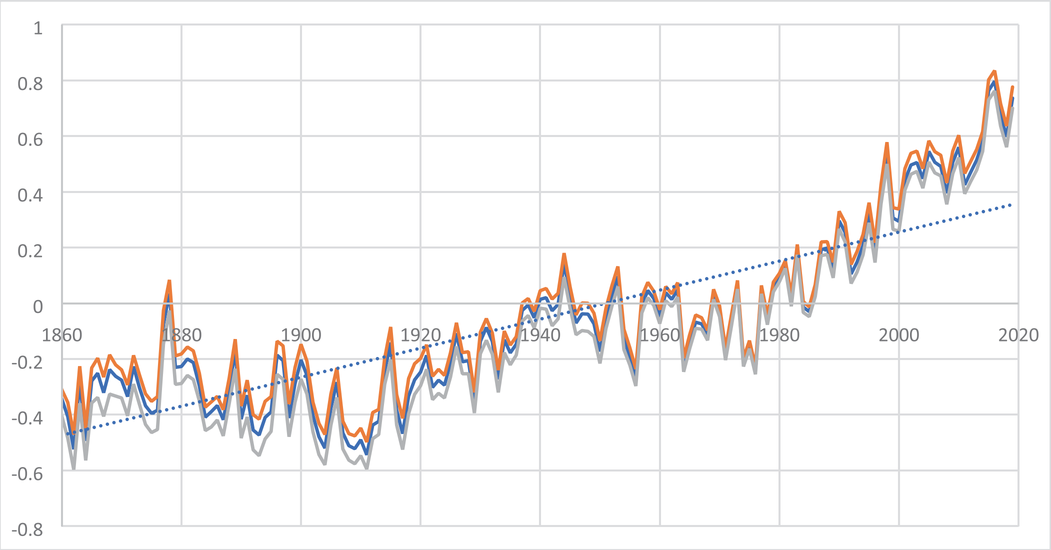
On the other hand, the literature is currently replete with the dangers of unabated emissions of anthropogenic CO_2 and other greenhouse gases (GHGs) emissions (IPCC, 2007,[1]; Jolly et al., 2015; Anderson & Bows, 2011; Alola, Adebayo, et al., 2021; Alola, Akadiri, et al., 2021). Besides, growing emissions levels have been identified as a major factor contributing to rising levels of environmental disasters with predictions of more dangers ahead if nothing is done to curtail cumulative emissions in the meantime (IPCC, 2021; UNEP, 2021). Furthermore, Mora et al. (2018) noted that an approximate 584.4 GtC (gigatons of CO_2) was emitted from human activities including the burning of fossil fuel, industrial activities, and land use between 1860 and 2014. This was also estimated to have resulted in about 0.9 °C of global warming as the global average temperature has maintained an upward trend over the decades as seen in Figure 2.

Therefore, in the wake of the rising potential dangers of climate change and environmental disaster vis-à-vis increasing GHG emission levels, the impact of innovative technology on carbon emission levels and its significance for achieving the global zero-carbon target is gradually attracting the attention of researchers. At the moment, the bulk of the research relating to the environmental impacts of innovation has addressed countries in the OECD bloc and a couple of Asian economies (Álvarez-Herránz et al., 2017; Amin et al., 2020; Godil et al., 2021; Shahbaz, Raghutla, et al., 2020). However, there is the concern that countries in some of these blocs may not necessarily be at the same tier of economic progress or development. To the best of the authors' knowledge, none of the existing studies has addressed the innovation-emission nexus for the specific case of the E7 economies except for the most recent study by Tao et al. (2021). However, just like most studies on other blocs mainly considered the innovation-emission nexus, their study also did not examine whether the expected desirables environmental impact of innovation holds in the E7 when interacting the level of innovations with the weights of the overall energy use per capita among these countries. This aspect is however very crucial when considering the quest for wealth creation as seen in the push to maintain economic growth which is a major trait among all economies and most especially for emerging



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

FIGURE 1 CO_2 emission in the E7 (end of 2018). Authors' computation using data from British Petroleum (2020). Emissions in million tons of CO_2. [Colour figure can be viewed at wileyonlinelibrary.com]



Source: Computed by authors using data from Ritchie & Roser, (2020). The blue color shows the median temperature anomaly (1961-1990) average, while the dotted line is the trendline. The orange and grey lines are for upper and lower confidence intervals respectively. The horizontal axis is for average temperature (°C) and years are on the horizontal axis.

FIGURE 2 Global average temperature trend (1860–2018). Computed by authors using data from Ritchie and Roser (2020). The blue color shows the median temperature anomaly (1961–1990) average, while the dotted line is the trendline. The orange and gray lines are for upper and lower confidence intervals, respectively. The horizontal axis is for average temperature (°C) and years are on the horizontal axis. [Colour figure can be viewed at wileyonlinelibrary.com]

economies. As such, the present study aims to contribute to the developing literature relating to the emerging economies in the following ways;

a. Firstly, by examining the impacts of technological innovations on carbon emission levels while juxtaposing the roles of energy usage in the case of the E7 economies.
b. Secondly, to examine how the interaction between innovation and energy use influence the environmental quality of the E7 Economies.
c. Thirdly, within an income-sustainability framework, the study further aims to examine the EKC conjecture for the E7 countries when technological innovation is being accounted for.

Following the introduction as the first chapter, the other part of this study has been subsequently structured into four sections with the review of the literature in Section 2 while providing the details about the methods of data analysis in Section 3. Subsequently, the discussion of findings comes up in Section 4, and Section 5 wraps up the study with policy matters.

2 | THEORETICAL AND EMPIRICAL UNDERPINNING

The theoretical underpinnings behind this study are the environmental Kuznets curve (EKC) conjecture (Kuznets, 1955) and the Jevons technological innovation paradox (Jevons, 2001). On the aspect of economic growth-environment nexus, the EKC conjecture argues that although the environment may be in jeopardy of pollution at an initial rate of economic growth, the detrimental environmental effects of growth will later clear out at a growth peak after which higher growth would only produce a cleaner environment (Balsalobre-Lorente et al., 2022; Onifade, 2022). To compensate for the initial pollution levels at a higher stage of income according to the EKC conjecture, important factors such as technological innovation among others, have to be integrated into the environment-income nexus.

It is a conventional belief that technological innovations can enhance environmental sustainability, especially from the perspective of improvement in energy efficiency. However, William Stanley Jevons in 1865 (Jevons, 2001) in his seminar work demonstrated that energy efficiency (through innovations) may not really enhance sustainability as often expected through a reduction in aggregate energy consumption or resource use, on the contrary, it would rather increase consumptions. This view has been popularly regarded as the Jevons paradox and the paradox has been a long-held environmental point of discussion among economists. Inter alia, Bunker (1996) argued that large-scale economic production activities for profit-seeking in a typical economy where the focus is on growth can lead to an increase in overall energy use, even in the presence of potential higher energy efficiency that is achievable through energy technological innovations. Hence, the question of what roles technological innovations play in environmental sustainability may not necessarily follow a straightforward answer especially when the issues bordering on energy use and the quest for economic growth are accounted for.

TABLE 1 Summary of empirical studies

The author(s)	Scope of study	The country(s) examined	Empirical methods	Summary of the findings and conclusion
Technological innovation and CO_2 emissions				
Álvarez-Herránz et al. (2017)	1990–2014	28 OECD members	V-lag distribution model	Innovations help to mitigate CO_2 emissions
Godil et al. (2021)	1990–2018	China	QARDL methods	Innovations help to mitigate CO_2 emissions in the transport sector
Jahanger et al. (2022)	1990–2016	73 developing countries	PMG-ARDL	Technological innovations reduce the negative environmental consequences of resource utilization
Erdogan (2021)	1992–2018	BRICS Countries	DCCE	Innovations help to mitigate CO_2 emissions from the building sector
Amin et al. (2020)	1985–2019	Asian Countries	VECM and FMOLS	Innovations help to mitigate CO_2 emissions but energy use induces it
Shahbaz, Nasir, et al. (2020)	1984–2018	China	BARDL	Innovations help to mitigate CO_2 emissions
Baloch et al. (2021)	1996–2016	BRICS Countries	DOLS and FMOLS	Innovations help to mitigate CO_2 emissions
Chen et al. (2020)	1996–2018	96 nations	GNS model	Innovations have no significant contribution toward reducing CO_2 emissions
Wang and Zhu (2020)	2001–2017	China	POLS	Fossil energy innovations induce CO_2 emissions while innovation in renewable mitigates CO_2 emissions
Su et al. (2021)	1990 to 2018	BRICS Countries	Driscoll–Kraay regression	Innovations increase the level of CO_2 emissions
Fan and Hossain (2018)	1974–2016	China & India	ARDL and causality	Both innovation and CO_2 induce growth in the case of China
Growth, energy use and CO_2 emissions				
Shahbaz, Raghutla, et al. (2020)	1870–2017	The UK	Bootstrapping bounds test method	Energy consumption in the UK increases CO_2 emissions levels
Apergis and Payne (2014)	1980–2011	25 OECD members	FMOLS	A rise in economic growth level increases the growth of carbon emissions
Leitão and Balsalobre-Lorente (2021)	1990–2018	EU-28	DOLS and Granger causality	Energy consumption (renewable) helps to reduce CO_2 emissions in the EU
Gyamfi et al. (2021)	1990–2018	G7 nations	AMG and QR	Energy consumption increases pollution levels.
Alola (2019)	1990(Q1)-2018(Q2)	The USA	Dynamic ARDL	Both economic growth and energy use trigger carbon emission levels
Dogan and Aslan (2017)	1995–2011	EU Countries	FMOLS and DOLS	Economic growth reduces emissions but energy consumptions do not
Ozturk and Acaravci (2016)	1980–2006	Island of Malta & Cyprus	ARDL and causality test	CO_2 emissions and energy use trigger economic growth
Shahbaz et al. (2016)	1970(Q1)–2011(Q4)	Malaysia	ARDL	Energy use increases emission intensity and economic growth triggers CO_2 emissions
Bekun et al. (2021)	1995–2016	The E7 countries	CCEMG and AMG	A rise in energy use triggers growth in CO_2 emissions levels
Sarkodie and Owusu (2017)	1971 to 2013	Ghana	Linear regression method	Energy consumption and economic growth increase the level of CO_2 emissions
Adebayo et al. (2021)	1965–2019	South Korea	FMOLS, ARDL, and DOLS	Economic growth is induced by CO_2 emissions levels
Anwar et al. (2021)	1990–2014	Asian Countries	FMOLS and DOLS	Energy consumption (renewable) helps to reduce CO_2 emissions but economic growth triggers emissions

Note: DCCE: UK, United Kingdom; EU, European Union, dynamic common correlated effect; FMOLS, Fully Modified OLS; DOLS, dynamic OLS; QR, quantile regression; AMG, Augmented Mean Group; CCEMG, common correlated effects mean group; POLS, panel ordinary least squares; ARDL, autoregressive distributed lag; OLS, ordinary least squares; GNS, generalized nesting spatial model; BARDL, bootstrapping ARDL.

Clement (2011) examined state-level carbon emissions levels in the United States between 1963 and 1997 while exploring the Jevons paradox within the context of environmental advantages of innovations. His findings show that there are only a few environmental gains from improvements in technology due to capitalism and its political economy. The study showed that although the carbon intensity of all the American states decreased by nearly 30% in the United States between 1963 and 1997, however, there was an increase in total carbon emissions in the country within the same period. The study of York and McGee (2016) also revealed similar results that buttressed Jevons's argument. They studied a panel of selected countries and their finding showed that there is a higher tendency to have higher energy consumption and CO_2 emission from nations with a higher level of energy efficiency. In other words, carbon emission has the tendency to rise in countries with more innovative capacity to improve energy efficiency. This is because the environmental deficits of increased energy consumption rates such as carbon emission due to energy innovation can outweigh the benefits of the increased energy usage itself. Therefore, technological innovations may not really enhance solutions to environmental challenges, especially given the insatiable quest for economic growth that is often propelled by higher energy demand on the ambient of fossil energy consumption. Hence, the validity of the EKC phenomenon also needs to be well scrutinized by accounting for the impact of innovation.

2.1 | Review of empirical studies

Some empirical studies have examined how technological innovation impacts the sustainability of the environment amidst economic growth trends and energy use in different countries and the results have often varied across studies. A vast majority of extant studies have captured environmental quality by the level of carbon emissions. Table 1 contains a list of extant empirical studies in two subdivisions. The first part summarizes the findings of the impact of innovative technologies on carbon emission levels, while the second part summarizes the effects of economic growth and energy usage on emissions levels.

3 | DATA AND EMPIRICAL METHOD

The summarized details of the data used for the empirical analysis are provided in Table 2. The analysis covers observations from the E7 countries between 1992 and 2018. The dataset used did not cover the pre-1992 periods due to restrictions in data availability on technological innovation for some of the countries, especially Turkey and Indonesia.

3.1 | Empirical model

Equation (1) was structured as a baseline model for exploring the roles of technological innovation and energy use in the environmental quality of the E7 Economies. An interaction term between technological innovation proxy and energy use was also incorporated into the model to assess its influence within the framework of the economic growth recorded among the rapidly emerging seven countries.

$$\begin{aligned} \mathrm{Ln}(\mathrm{CO}_{2\mathrm{it}}) = {} & \beta_0 + \beta_1 \mathrm{Ln}\mathrm{Y}_{it} + \beta_2 \mathrm{Ln}\mathrm{Y}^2{}_{it} + \beta_3 \mathrm{Ln}\mathit{INOV}_{it} + \beta_4 \mathrm{Ln}\mathit{EPC}_{it} \\ & + \beta_5 \mathrm{Ln}\mathit{IVEPC}_{it} + \omega_{it} \end{aligned} \quad (1)$$

In the functional Equation (1), the squared values of the amount of carbon emission (Y^2) were introduced to reflect the impact of income expansion to assess whether or not the EKC hypothesis holds in the income-environment nexus when technological innovation is accounted for in agreement with extant studies (Baloch et al., 2021; Gyamfi et al., 2021; Su et al., 2021). Having incorporated technological innovation and energy use proxies to observe their impacts, the variable *IVEPC* denotes the interaction between these two variables of interest in the model. All the variables were utilized in natural logarithm form and the empirical procedures have been detailed in the subsequent subheadings of the methodological section.

3.2 | Empirical procedures

The analytical approach in this study opens with a critical examination of the datasets for an understanding of their properties. Such critical examinations position researchers for making a well-informed decision

TABLE 2 Description of variables

Proxies	Abbreviations	Information	Data origin
Carbon emissions	CO_2	Countries' level of carbon dioxide emissions (presented in million tons)	British Petroleum (2020)
Income	*Y*	The countries' real GDP per capita (current US$)	World Development Indicator (2020)
Technological innovation	*INOV*	Comprises of countries' patents in environment-related technologies (% of total)	OECD (2021)
Energy consumption	*EPC*	Total primary energy consumption per capita	British Petroleum (2020)

Source: Authors' compilation.
Abbreviations: GDP, Gross Domestic Product; BP. British Petroleum; OECD. Organization of Economic Cooperation and Development.

about choices of the right techniques and methodologies vis-à-vis compatibility of approaches with individual data features and variable characteristics. Given the prevailing interconnectivity among economies around the globe that often results in the transfer of economic shocks, similar trends, and patterns among other issues between countries, an examination of likely cross-sectional dependency (CD) in errors among the heterogeneous dataset becomes essential. Chudik and Pesaran (2015) emphasized the significance of paying attention to this test as it is crucial for obtaining robust results while choosing the appropriate heterogeneous panel data estimators. To this end, the study combines the Breusch and Pagan (1980) LM techniques with the duo of Pesaran (2015) LM techniques and Pesaran (2007) CD tests to ascertain the presence of CD. The cruciality of the test has been further reinforced in some empirical research (Adebayo et al., 2022; Erdoğan et al., 2022; Gyamfi et al., 2021; Gyamfi et al., 2022; Onifade, Gyamfi, et al., 2021). The findings relating to the tests affirm the presence of CD (see Section 4 for the full results).

Given the valid insights on the presence of CD, the stationarity test to be adopted for variables and corresponding cointegration examinations must be capable of addressing the CD challenge. As such, the IPS and CIPS techniques were applied in exploring the stationarity properties of the variables. These unit root methodologies are useful for observing variation within panels and the techniques also provide essential features for observing the second-order generation in a typical panel analysis. The equational expression of the CIPS procedures is given in Equation (2), while the corresponding test statistics estimator is presented in Equation (3).

$$\Delta CA_{\mathrm{i,t}} = \Phi_i + \Phi_{\mathrm{i}} Z_{i,t-1} + \Phi_{\mathrm{i}} CA_{\bar{it}-1} + \sum\nolimits_{1=0}^{p} \mathit{\Phi} il \mathit{\Delta} CA_{t-1} + \sum\nolimits_{i=0}^{p} \Phi il \Delta CA_{\mathrm{i,t1}} + \mu_{it}, \tag{2}$$

$$CIPS_{2007} = N^{-1} \sum\nolimits_{i=0}^{n} CDFi. \tag{3}$$

In Equation (3), the CDF reflects the cross-sectional dependent augmented Dickey–Fuller (CADF), while the cross-sectional (CD) averages are captured by $CA_{\bar{it}-1}$ and $\Delta CA_{i,t1}$. Moving on, considering the CD properties of the dataset and having utilized a unit root technique that caters to this panel characteristic, the corresponding cointegrating technique to be adopted needs to also take into cognizance the CD challenge in the sample observation. Therefore, the usual first-generation panel, long-run relationship tests could produce misleading evidence for rejecting a null hypothesis under the cointegration analysis. Hence, the Westerlund (2007) second-generation cointegration technique was applied to bypass the CD limitation and subsequently ensure accuracy with regard to the validity of the decision on the null hypothesis of no cointegration between panel observations. This cointegration method is modeled after an error adjustment process as depicted in Equation (4) to ascertain long-run relationships between variables vis-à-vis the estimated group statistics (Gt, Gα,) as well as panel statistics (Pt, Pα).

$$\Delta Y_{it} = \beta_i D_t + \psi_i Y_{it-1} + \lambda_i X_{it-1} + \sum\nolimits_{j=1}^{pi} \psi_{ij} \Delta Y_{i,t-j} + \sum\nolimits_{j=0}^{pi} \gamma_{ij} \Delta X_{i,t-j} + \varepsilon_{it}. \tag{4}$$

In Equation (4), (ψ_i) captures the error adjustment process while the β_t captures the vector of parameters. On the other hand, there is a possibility of varying the deterministic representations (D_t) of the analysis. For instance, a model can be specified with no deterministic term such that $D_t = 0$, or there could be specification with just the constant term alone such that $D_t = 1$, and both the constant and trend can be captured in the model such that $D_t = (1, t)$. The Westerlund (2007) cointegration method stands to be a well-patronized approach in the related literature (Baloch et al., 2021; Bekun et al., 2021) due to its suitability in dealing with matters such as the CD limitations in panel analysis.

3.2.1 | Long-run and short-run estimations

Considering the outcomes of the preliminary tests, the cross-sectionally augmented autoregressive distributed lag (CS-ARDL) model of Chudik and Pesaran (2015) was adopted for the coefficient analysis. Given the cointegration and unit root evidence that are presented in the results discussion section (Section 4), the panel ARDL approach of Pesaran et al. (1999) could ordinarily be applied, however, Chudik and Pesaran (2015) stressed the disadvantage of doing that, especially in the circumstance where CD characterized the panel sample observation. In such a situation, the CS-ARDL becomes more useful as it utilizes both the mean group (MG) estimator as well as the pooled mean group PMG estimator. The CS-ARDL approach also produces both long-run and short-run estimates, while adjusting the related prediction errors thereby taking care of long-term correlations in panel observation that are characterized by heterogeneous effects. Besides, the approach becomes more useful given the nature of the study's sample observation with relatively small *T* where variables are characterized with a mixed integration order {I(0) or I(1)} (Chudik et al., 2016; Erülgen et al., 2020).

$$\Delta Y_{it} = \delta_{\mathrm{i}} \left\{ Y_{i(t-1)} - \vartheta_i X_{it} \right\} + \sum_{j=1}^{p-1} \beta_{\mathrm{ij}} \Delta Y_{i(t-j)} + \sum_{j=0}^{q-1} \pi_{\mathrm{ij}} \Delta X_{i(t-j)} + \varphi_{\mathrm{i}} + \varepsilon_{it} \tag{5}$$

In the error adjustment procedure of a simplified panel ARDL model, as shown in Equation (5), the adjustment term is represented by $\left\{ Y_{i(t-1)} - \vartheta_i X_{it} \right\}$ while ϑ_i represent the long-run relationship vector. On the other hand, the δ_i coefficient denotes the expected group-specific correction speed which ought to be negative and significant to uphold its validness while the corresponding short-run estimates are captured by the β_{ij} and π_{ij} parameters. The traditional panel ARDL still retains its validity regardless of the cointegration order but the estimates become unreliable if errors are cross-sectionally correlated. Thus, to bypass this setback, the panel CS-ARDL augments the model with the cross-sectional averages of the explanatory variables, the dependent variables, and a combination of their lag values to effectively correct the cross-sectional correlation in the error component.

TABLE 3 Statistical properties of the variables

E7 countries	CO_2 emissions	Technological innovation	Energy consumption	Economic growth
China				
Mean	3.729844	0.884412	1.714709	3.310544
Maxi	3.978049	1.003461	1.978185	3.998986
Mini	3.411824	0.564666	1.420179	2.564027
Std. Dev.	0.210854	0.096611	0.203265	0.467329
India				
Mean	3.098936	0.827484	1.180111	2.879789
Maxi	3.389609	1.050766	1.391285	3.300360
Mini	2.826904	0.447158	1.001982	2.478796
Std. Dev.	0.178365	0.159288	0.123285	0.277843
Brazil				
Mean	2.532210	0.911235	1.692408	3.771047
Maxi	2.702241	1.161667	1.786483	4.122072
Mini	2.335096	0.382017	1.577101	3.414459
Std. Dev.	0.106036	0.220362	0.063615	0.233778
Mexico				
Mean	2.588779	0.946789	1.782952	3.876469
Maxi	2.678469	1.170555	1.820915	4.038577
Mini	2.447141	0.416641	1.738009	3.594196
Std. Dev.	0.078104	0.191694	0.027311	0.130574
Russia				
Mean	3.188598	1.030554	2.282383	3.715925
Maxi	3.316508	1.192846	2.364279	4.203431
Mini	3.159880	0.912753	2.230459	3.124099
Std. Dev.	0.035995	0.061286	0.030637	0.343500
Indonesia				
Mean	2.518847	0.927612	1.344231	3.197972
Maxi	2.763967	1.311966	1.487555	3.590380
Mini	2.205565	0.365488	1.143253	2.666469
Std. Dev.	0.169072	0.251092	0.103408	0.295841
Turkey				
Mean	2.372414	0.870992	1.740040	3.792023
Maxi	2.598909	1.329805	1.895211	4.100880
Mini	2.157550	0.580925	1.587141	3.356090
Std. Dev.	0.134117	0.146548	0.092809	0.251901

Source: Computed by Author.

Note: Std Dev. denotes standard deviation, while Maxi and Mini denote the maximum and the minimum values in that order.

Hence, the augmented representation of the model for the CS-ARDL is given in Equation (6).

$$\Delta Y_{it} = \delta_i \left\{ Y_{i(t-1)} - \vartheta_i X_{it} + \alpha_i^{-1} n_i \overline{Y}_t + \alpha_i^{-1} Y_i \overline{X}_t \right\} + \sum_{j=1}^{p-1} \beta_{ij} \Delta Y_{i(t-j)} + \sum_{j=0}^{q-1} \pi_{ij} \Delta X_{i(t-j)} + \sum_{j=0}^{p-1} \lambda_{ik} \Delta \overline{Y}_{i(t-j)} + \sum_{j=0}^{q-1} Y_{ik} \Delta \overline{X}_{i(t-j)} + \varphi_i + \varepsilon_{it} \quad (6)$$

In Equation (6), the cross-sectional average of the variables Y_{it} and X_{it} are denoted by $\overline{Y}_t$ and $\overline{X}_t$, respectively, while the level components of the cross-sectional averages are utilized in capturing the long-run equilibrium interactions as encapsulated in the bracket. The pace of equilibrium correction is denoted by δ_i, while ϑ_i captures the needed long-run estimates. The results of the estimates were provided in the discussion section. From there, the estimates from the panel PMG-ARDL approach of Pesaran et al. (1999) were also reported for sensitivity checks and comparative analysis before finalizing the analysis with a granger causality report following the Dumitrescu and Hurlin (2012) causality approach.

TABLE 4 Correlation evidence

Variables	$LnCO_2$	LnY	LnY^2	LnINOV	LnEPC	LnIVEPC
$LnCO_2$	1					
p-value	–					
LnY	−0.1506**	1				
p-value	(0.0385)	–				
LnY^2	−0.1481**	0.9979***	1			
p-value	(0.0419)	(0.0000)	–			
LnINOV	0.0884	0.3078***	0.3070	1		
p-value	(0.2262)	(0.0000)	(0.0000)	–		
LnEPC	0.2295***	0.7152***	0.7076***	0.3281	1	
p-value	(0.0015)	(0.0000)	(0.0000)	(0.0000)	–	
LnIVEPC	0.2170***	0.6214***	0.6187***	0.7718***	0.8448***	1
p-value	(0.0027)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	–

Source: Computed by author.
***Statistical relevance of value at the 1% level.
**Statistical relevance of values at the 5% level.

TABLE 5 Cross-sectional dependency result

Technique(s)	Breusch and Pagan (1980) LM test	Pesaran (2007) CD test	Pesaran (2015) LM test
Equation (1)	426.83***	20.58***	62.62***
Estimated P-value	(0.0000)	(0.0000)	(0.0000)

***Statistical relevance of value at the 1% level.

4 | FINDINGS AND DISCUSSION

A summary of the descriptive statistics for individual country variables and a sample correlation matrix for the panel observations heralded the presentation of data and empirical discussion as seen in Tables 3 and 4 respectively. The highest level of average carbon emissions throughout the study is recorded in China followed by Russia, India, Mexico, Brazil, Indonesia, and Turkey, respectively. China also takes the lead in the amount of energy consumption on average over the sample period. As for the correlation among the variables, economic growth and energy use are positively correlated with carbon emission while no significant correlation can be seen between emission and energy innovations. The correlation output partly reveals just a handful of information which is certainly not sufficient as it does not show the true magnitude of impacts of these variables on the emission level. Hence, some other vital preliminary analyses were conducted to take into cognizance the nature of the data set.

Further results from the preliminary evaluations confirmed that the dataset for the study suffers from cross-sectional dependence (CD) as seen in Table 5. All the test statistics lend credence to the presence of CD and as such, the unit-root test conducted also took cognizance of this crucial issue. In Table 6, the findings from the CD-compactible unit root tests (CIPS and IPS) reveal that all data are differenced stationary [I(1)] datasets except for the technology innovation data set and the interaction term that are stationary at the level which implies that they are I(0) proxies. This result necessitates that long-run estimators that are compatible for mixed order of integration among variables must be applied if there is evidence of cointegration among the variables. As such, following the confirmation of the long-run relationship among variables by both panel and group statistics of the Westerlund (2007) approach in Table 6, the study adopted the CS-ARDL panel estimator to examine the long-run coefficients as reported in Table 7.

4.1 | Coefficient and causality estimates

The output of the empirical results from the CS-ARDL model provides critical information that is apt for policy directives for the E7 economies unlike the results from the PMG techniques that are unreliable due to the challenges of CD that have been established in the preliminary analysis. Hence, following the CS-ARDL estimates in Table 7, the results reveal that both energy consumption and economic growth (real income levels) occur as significant drivers of environmental pollution in the E7 countries. According to the estimates, a percent rise in energy consumption level and economic growth levels induce pollution from CO_2 emissions by 0.51% and 0.68%, respectively. The observed impacts of these two variables reflect the destructive

TABLE 6 Unit root and cointegration results

	CIPS approach		*IPS approach*	
	Intercept and trend		**Intercept & trend**	
	$D_t = (1, t)$		$D_t = (1, t)$	
List of variables	**For level analysis**	**Analysis at the first difference**	**For level analysis**	**Analysis at the first difference**
LnCO$_2$	−2.203	−3.991***	−2.0462	−4.6616***
Ln*Y*	−3.044**	−4.984***	−1.6719	−4.2803***
Ln*Y*^{2}	−2.674	−4.834***	−1.6984	−4.1915***
Ln*INOV*	−5.005***	−6.059***	−4.6623***	−7.7833***
Ln*EPC*	−2.011	−3.521***	−2.0420	−4.3389***
Ln*IVEPC*	−4.868***	−5.877***	−4.4028***	−7.6138***

Westerlund cointegration

Model 1	**Group**		**Panel**	
LnCO$_2$ = f(Ln*Y*), (Ln*Y*^{2}), (Ln*INOV*), (Ln*EPC*), and (Ln*IVEPC*)	**Gτ**	**Gα**	**Pτ**	**Pα**
Statistics	−1.718***	−1.906 ***	−4.309***	−4.577***
Robust *p*-value	0.0000	0.0000	0.0000	0.0000

Source: Computed by author.
***Statistical relevance of value at the 1% level.
**Statistical relevance of value at the 5% level.

TABLE 7 Long- and short-run coefficient estimates

	Long-run coefficients				**Country-specific ECT (PMG)**		
List of variables CO$_2$ (explained)	**CS-ARDL Estimates**	***P*-value**	**PMG Estimates**	***P*-value**	**E7 countries**	**Estimates**	***P*-values**
Ln*Y*	0.6869***	0.0005	1.3738***	0.0000	China	−0.0764***	0.0000
Ln*Y*^{2}	−0.0976***	0.0003	−0.2549***	0.0000	India	−0.4774***	0.0001
Ln*INOV*	−0.1733**	0.0430	−0.2313	0.3626	Brazil	−0.0055***	0.0017
Ln*EPC*	0.5107***	0.0000	1.4496***	0.0000	Mexico	-0.0135***	0.0000
Ln*IVEPC*	0.0963**	0.0310	0.2335	0.2552	Russia	0.0115	0.0000
	Short-run coefficients				Indonesia	−0.0153***	0.0000
ECT	−0.9753***	0.0000	−0.0834	0.2116	Turkey	−0.0075***	0.0004
ΔLn*Y*	1.2936***	0.0002	0.1049	0.6954			
ΔLn*Y*^{2}	−0.1848***	0.0001	−0.0131	0.7089			
ΔLn*INOV*	−0.3340**	0.0420	−0.1153	0.3702			
ΔLn*EPC*	1.0064***	0.0000	0.9599***	0.0000			
ΔLn*IVEPC*	0.1863**	0.0310	0.0462	0.5517			
C	−1.9753***	0.0000	−0.0413	0.1829			
No. regressors	5		5				
No. Observations	175		175				
No. group	7		7				

Source: Computed by author.
***Statistical relevance of values at the 1% level.
**Statistical relevance of value at the 5% level.

consequences of the environmentally detrimental economic growth push among the E7 countries. The upward trend in the level of economic growth is anchored on increased energy demands that are essentially sustained by fossil fuel usage which is known to constitute the largest chunk of the total primary energy consumption in the emerging seven (E7) economies. The observed environmentally

TABLE 8 Panel causality evidence

	Zbar-stat				
Variables	LnCO_2	Ln*Y*	Ln*INOV*	Ln*EPC*	Causality scheme
LnCO_2	–	6.8921***	5.2775***	7.7935***	$\text{LnCO}_2 \rightarrow \text{Ln}Y, \text{Ln}INOV, \text{Ln}EPC$
Ln*Y*	2.4578**	_	3.5610***	3.2986***	$\text{Ln}Y \rightarrow \text{LnCO}_2, \text{Ln}INOV, \text{Ln}EPC$
Ln*INOV*	1.0329	−0.3135	_	2.6499***	$\text{Ln}INOV \rightarrow \text{Ln}EPC$
Ln*EPC*	3.4722***	5.1593***	4.8878***	_	$\text{Ln}EPC \rightarrow \text{LnCO}_2, \text{Ln}Y, \text{Ln}INOV$

Source: Computed by author.
***Statistical relevance of value at the 1% level.
**Statistical relevance of value at the 5% level.

destructive impacts of economic growth and energy consumption, in the long run, are also consistent with the short-run estimates from the model. Also, there is a two-way causality between energy consumption, economic growth, and carbon emissions among these countries as seen in Table 8. The overall results resonate with some empirical information on the nexus among these variables as obtainable in some extant empirical studies, howbeit, some of the studies were in different climes and used other techniques (Alola, 2019; Sarkodie & Owusu, 2017; Shahbaz et al., 2016). The current findings further buttress the empirically substantiated arguments in support of the need for the E7 nations to address their energy portfolios such that the proportion of conventional energy use in total primary energy consumption is reduced to the barest minimal. In this regard, going by several empirical results on the roles of renewables in improving environmental quality as seen in the extant literature (Erdoğan et al., 2021; Onifade, Alola, et al., 2021; Usman & Balsalobre-Lorente, 2022), more investments in renewable energy would help to further position the E7 economies on the expected environmental sustainability path.

On the other hand, technological innovations produced some succoring shreds of evidence for environmental sustainability among the E7 countries. The estimated CS-ARDL model shows that a percent growth in technological innovation reduces emissions levels by 0.17% in the long run. This nexus is also validated in the short-run dynamics although with a much higher magnitude compared to what is obtainable in the long-run dynamics. This is an indicator for policymakers and authorities in the E7 to leverage on the instrumentality of technological innovation for environmental gains. The results complement a couple of studies in the literature on the beneficial roles of innovation in combating environmental menace (Amin et al., 2020; Shahbaz, Raghutla, et al., 2020; Tao et al., 2021).

However, on the aspect of the impacts of the interaction between innovation and energy consumption, the empirical analysis produced contrary evidence for upholding the innovation-environmental sustainability nexus as a percent rise in the interaction of these variables significantly induces pollution from CO_2 emission by around 0.096%. Although this magnitude is relatively low compared to the impacts of other variables, it, however, portends crucial information about the E7 economies. A possible explanation for this result among the emerging seven (E7) countries is that the environmental gains from innovations tend to be significantly undermined or at least overwhelmed by the magnitude of the impacts of the unsustainable energy portfolios that features environmentally detrimental energy sources as the largest share of the overall total primary energy consumption. Another important point is that the innovation being witnessed among the E7 countries vis-à-vis the energy required to actualize their desired economic growth target has perhaps mainly accelerated higher rates of overall energy use rather than creating a reduction in energy intensity via higher efficiency as expected. Thus, the scenario at play partly aligns with the arguments of Jevons (Jevons, 2001) that innovations may not enhance overall environmental sustainability as expected by a reduction in energy consumption on a broad scale, even though it can reduce carbon emissions levels. Besides, looking at the granger causality in Table 8, it can be further observed that the only directional causality from innovations relates to energy consumption and the latter variable has witnessed exponential growth in the E7 countries over the last couple of decades (British Petroleum, 2020).

Lastly, while a detrimental impact of economic growth was confirmed in the study in terms of environmental sustainability, there is also evidence that this detrimental effect is expected to be neutralized by income expansion as seen by the significant negative impact of the income square coefficient in the CS-ARDL model. This result thus approves the EKC conjecture for the E7 countries within the income-sustainability framework when technological innovation is accounted for thereby lending credence to some evidence in support of the EKC validity in emerging economies (Baloch et al., 2021). In the results in Table 7, there is no evidence that the system will adjust to equilibrium under the PMG approach as the overall coefficient estimate for the ECT was found to be statistically insignificant despite the possibility of equilibrium adjustment in the country-specific short-run subcategory. This finding further reveals the shortcomings of the PMG technique in the presence of cross-sectional dependency. On the other hand, the CS-ARDL estimates reveal that there will be a significant adjustment to equilibrium for the system following the significant negative value of the ECT (−0.9753). In a nutshell, the use of the lagged cross-sectional averages in the CS-ARDL technique proved to be a better option to the PMG approach as it has taken care of any cross-correlation in residuals owing to identified common factors among observations.

5 | CONCLUSION AND POLICY REFLECTION

The impacts of technological innovation and energy use on the environmental quality of the E7 economies have been explored in this study. While doing so, the interaction between the variables was also incorporated into the model to assess its influence among the E7 economies using data covering 1992–2018. The result confirmed the EKC conjecture and suggested that innovation cushions pollutant emissions in the E7 economies. Both energy consumption and economic growth were found to be an adversary to the sustainability of the environment in these emerging economies. Furthermore, while innovation cushions pollutant emissions among the countries, its desirable environmental impacts become unnoticeable when interacting with the level of energy consumption among these economies. A major explanation for this development lies in the overwhelming share of conventional energy use in the overall energy portfolios of the E7 economies. As such, the gains from innovations can be said to be undermined in the E7. The causality results also provided some corroborative evidence for the estimates and these inform useful policy directives for the E7 economies and other emerging economies at large.

5.1 | Policy

Considering that the environmental-related technological innovation shows a mitigation impact on carbon emission, more responsibility is bestowed on the emerging economies to ensure technology and innovation-driven investments. Moreover, because environmental-related technological innovation has the potential of moderating the role of primary energy utilization on carbon emission, this further suggests that more intervention should be geared toward energy-specific technologies and innovations. By so doing, more desirable outcomes about the mitigation of carbon emissions could be attained over time, especially with the right attitude toward environmental responsibility.

In concrete terms, the authorities of the E7 nations can take advantage of diverse approaches to exploiting the environmental benefits of innovations including the adoption of a public–private partnership model in funding and promoting research and development (R&D) projects about environmental protection. The authorities of the E7 economies should also prioritize adequate funding and supports for established research institutions, technical and tertiary institutions, and other ingenious establishments that are saddled with specific environmental targets. Furthermore, there is a need for the E7 nations to address their energy portfolios such that the proportion of conventional energy use in total primary energy consumption is reduced to the barest minimum. In this regard, the authorities of the E7 should be committed to providing adequate investment supports for innovative technologies, especially renewable energy technologies to rightly position the E7 economies on the expected environmental sustainability path.

5.2 | Limitations and the future research directions

The current study adopts novel approaches for the empirical analysis from the case of the E7 economies thus providing a solid foundation for more investigations to be conducted in other blocs. However, while the roles of energy use were aggregated in total primary energy consumption in the current study, future studies can extend the established framework to examine the roles of disaggregated energy use (individual energy types) within the innovation-environmental nexus analysis for the E7 countries or other blocs.

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AVAILABILITY OF DATA AND MATERIALS

The data for this present study are sourced from the database of the World Development Indicators (https://data.worldbank.org), the British Petroleum (BP) Statistical Review of World Energy data (http://www.bp.com/statisticalreview) and the Organization of Economic Cooperation and Development (OECD) (https://data.oecd.org/envpolicy/patents-on-environment-technologies).

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CONFLICT OF INTEREST

I wish to disclose here that there are no potential conflicts of interest at any level of this study.

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ENDNOTE

[1] IPCC is the Intergovernmental Panel on Climate Change.

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