



INVESTIGATING ECONOMY GROWTH, RENEWABLE ENERGY, HUMAN CAPITAL AND ENVIRONMENTAL TECHNOLOGY INTERACTION IN CO₂ EMISSIONS IN HETEROGENEOUS EMERGING ECONOMIES

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Abstract

Research background: CO₂ emissions are a major driver of climate change, especially in heterogeneous emerging countries.

Purpose: This research investigates the impact of economic growth, financial development, renewable energy consumption, environment-related technology, and human capital on CO₂ emissions in heterogeneous emerging countries.

Research methodology: The study analysed data from 1994 to 2019 across twelve heterogeneous emerging countries. Utilizing the Cross-Sectional Autoregressive Distributed Lags (CS-ARDL) econometric approach, the results indicated findings over both the short and long term. Robustness is tested using the Augmented Mean Group (AMG) and Common Correlated Effects Mean Group (CEMG) estimators, while Dumitrescu-Hurlin causality examines the bidirectional relationships.

Results: The results show that, in both the short and long term: (1) economic growth increases CO₂ emissions, (2) renewable energy use reduces emissions, and (3) the interaction of human capital and environmental technology lowers emissions. Further, the Dumitrescu-Hurlin causality tests show

a bidirectional relationship between CO₂ emissions, economic growth, financial development, and human capital.

Novelty: This study provides policy recommendations to foster sustainable development and reduce CO₂ emissions, specifically in heterogeneous emerging countries.

Keywords: Carbon dioxide emissions; economic growth; financial development; renewable energy

JEL classification: C22; E21

Introduction

Climate change has become one of the most urgent global challenges because it affects environmental sustainability, economic stability, food security, public health, and energy systems (Alam, 2022; Aluwani, 2023; Ben Jebli, Ben Youssef, 2019). Among the various greenhouse gases, carbon dioxide (CO₂) remains the dominant contributor to global warming due to its large volume and long atmospheric persistence. In recent decades, international efforts such as the Paris Agreement and the Sustainable Development Goals (SDGs), particularly Goals 7 and 13, have emphasized the urgency of reducing carbon emissions and transitioning toward sustainable energy systems (United Nations, 2015a, 2015b). Empirical evidence shows that CO₂ emissions from a large set of heterogeneous emerging economies expanded faster than the global average during 2010–2018, a trajectory that could undermine efforts to limit warming to 2°C or the aspirational 1.5°C target (Cui et al., 2020). Given this context, understanding the proximate and structural determinants of emissions is essential for designing effective, country-sensitive mitigation strategies (Aydin, 2014).

In 2022, heterogeneous emerging countries such as Indonesia recorded a 5.3% growth in Gross Domestic Product (GDP), increasing from 3.7% in 2021. However, this growth was accompanied by a 31% increase in energy consumption and 728.9 million metric tons of CO₂ emissions, reflecting an 18.3% rise from the previous year (Ministry of Energy and Mineral Resource, 2022). Similarly, China experienced rapid GDP growth alongside rising energy consumption and CO₂ emissions. Energy consumption increased by 5.7%, exceeding GDP growth for the first time since 2005, while CO₂ emissions rose by 5.2% (National Bureau of Statistics of China, 2023). These examples illustrate the persistent trade-off between economic expansion and environmental sustainability in heterogeneous emerging and transitioning

economies, highlighting structural dependence on fossil fuels and carbon-intensive production systems.

Several structural and socioeconomic factors shape emission patterns in heterogeneous emerging economies. Economic growth often increases industrial activity, transportation demand, and energy consumption, thereby intensifying carbon emissions. Financial development may have a dual effect, as it can stimulate environmentally harmful investment in carbon-intensive sectors while also enabling funding for clean technologies and renewable energy infrastructure. Renewable energy is expected to reduce dependence on fossil fuels, whereas technological progress may lower carbon intensity through efficiency gains and innovation. Human capital also plays an important role by improving environmental awareness, supporting technological adaptation, and strengthening institutional capacity for sustainable development (Haini, 2021; Hussain et al., 2022; Saqib, Abbas, et al., 2024).

A large and growing literature has examined specific drivers of CO₂ emissions. Financial development matters because financial systems determine capital allocation, which in turn shapes sectoral investment and energy-intensity (Ang, 2007; Beck et al., 2000). Empirical findings are mixed: some studies find that deeper, more efficient financial systems support investment in cleaner technologies and thus reduce emissions (Tamazian et al., 2009), whereas others show that financial expansion can finance polluting activities and increase environmental degradation (Boutabba, 2014; Park, Shin, 2017). Parallel strands of research document the mitigating effects of renewable energy deployment on emissions and the substantial inertia in the global energy mix, where fossil fuels continue to dominate broadly (Egbetokun et al., 2020; Mohanty, 2012; Saqib, Abbas, et al., 2024). Moreover, studies on environment-related technologies (ERT) emphasise that targeted technological adoption, such as smart grids and energy-efficient systems, can reduce emissions if accompanied by complementary policies and absorptive capacity (Li et al., 2023; Shahbaz et al., 2022). Human capital is likewise double-edged: it can accelerate growth (and thus energy use) while also enabling technological diffusion and sustainable practices that curb emissions (Gong et al., 2020; Inglesi-Lotz, 2016; Saqib et al., 2024).

Despite this substantial body of work, gaps remain. Most empirical studies have focused on one or two determinants in isolation or emphasize advanced economies, which limits applicability to the heterogeneous contexts of heterogeneous emerging countries (Habiba, Xinbang, 2022; Lean, Lee, 2022). In particular, the interactive role of human capital in enabling the environmental benefits of ERT has received limited systematic attention in the cross-country studies of heterogeneous emerging economies. Additionally, heterogeneous

institutional settings, differing levels of renewable penetration, and variation in financial systems imply that single-variable findings may not generalize across countries. Addressing these shortcomings requires an integrated framework that concurrently assesses economic growth, financial development, renewable energy shares, ERT adoption, and human capital, while explicitly testing interaction effects that capture conditional mitigation pathways.

This study responds to these gaps by providing a holistic empirical assessment of CO₂ emission determinants in a panel of heterogeneous emerging economies. Specifically, the study analyses the joint effects of economic growth, financial development, renewable energy consumption, environment-related technology, and human capital on CO₂ emissions, while also examining whether human capital amplifies the emission-reducing potential of ERT. Methodologically, the paper employs estimators suited for heterogeneous panels and cross-sectional dependence to ensure robust inference across diverse country contexts. By integrating these factors, the study contributes to the literature in three ways: (1) it offers an inclusive empirical model tailored to heterogeneous emerging economies, (2) it evaluates interaction mechanisms particularly the human capital $\times$ ERT channel that are central to policy design, and (3) it derives policy-relevant implications for aligning growth, finance, and technology policies with decarbonisation objectives (Habiba, Xinbang, 2022; Lean, Lee, 2022; Shahbaz et al., 2022).

Collectively, the findings aim to inform targeted policy measures that reconcile development and climate goals such as directing financial flows to clean investments, scaling renewable capacity, and investing in skills that enable effective technology adoption which support equitable and resilient low-carbon transitions in heterogeneous emerging economies which are consistent with international commitments.

1. Literature review

1.1. The Environmental Kuznets Curve

The Environmental Kuznets Curve (EKC) posits an inverted U-shaped relationship between per-capita income and pollution: emissions rise during early industrialization and decline once structural change and technological improvements take hold (Grossman, Krueger, 1991; Htike et al., 2022; Purcel, 2020). Empirical tests produce mixed results with some samples and pollutants conforming to the EKC, while others show monotonic or context-dependent patterns because turning points depend on energy intensity, technology diffusion, institutional quality, and policy (Alola, Ozturk, 2021; Baloch et al., 2021; Fernández et al., 2018; Sarkodie,

Ozturk, 2020). In emerging economies, higher energy intensity, slower adoption of clean technologies, and weaker regulation often delay or weaken EKC dynamics, implying that growth-emissions links must be studied alongside sectoral, technological, and financial factors to capture realistic emission trajectories (Habiba, Xinbang, 2022; Lean, Lee, 2022). However, recent empirical studies have shown that the EKC hypothesis does not consistently hold across countries, particularly in heterogeneous emerging and transitioning economies, where structural constraints, energy dependency, and institutional differences may alter this relationship (Ang, 2007; Beck et al., 2000).

1.2. Financial development and CO₂ Emissions

Financial development shapes how economies allocate capital across sectors and technologies (Ang, 2007; Beck et al., 2000). Theoretically, deeper and more efficient financial systems can facilitate investment in clean technology, thereby reducing emissions. Conversely, expanded finance can lower the cost of capital for polluting industries, and thus accelerating emissions in the short term (Ang, 2007; Park, Shin, 2017). However, empirical studies reflect this ambiguity: Tamazian et al. (2009) report that financial liberalisation in BRICS contributed to emission reductions through efficiency gains, whereas Boutabba (2014) and Raza et al. (2020) document positive links between financial development and CO₂ in specific national contexts. These divergent findings indicate that the environmental effect of financial development is conditional on regulatory incentives, the orientation of credit flows, and the maturity of green financial instruments.

1.3. Renewable Energy and CO₂ emissions

Transitioning the energy mix toward renewables is a central mitigation strategy and has been shown to lower emissions when penetration is meaningful (Avagyan, 2020; Saqib, Abbas, et al., 2024). However, fossil fuels still represent the bulk of global energy supply, limiting near-term decarbonization potential (Egbetokun et al., 2020; Mohanty, 2012). Empirical studies have documented that increases in renewable shares are associated with improvements in environmental quality especially CO₂ emissions, with emerging elasticities across regions (Saqib, Usman, et al., 2024; Usman, Balsalobre-Lorente, 2022). Policy frameworks such as the SDGs and the Paris Agreement create enabling conditions, but national capacities to mobilize finance, upgrade grids, and manage intermittency determine the realized environmental benefits of renewables (Aydin, 2014; Sachs et al., 2019).

1.4. Environment-related technology (ERT) and CO₂ emissions

Environment-related technologies including smart grids, energy-efficient infrastructure, and advanced renewables can reduce CO₂ emissions but their effectiveness depends on diffusion, complementarities, and institutional support (Li et al., 2023; Shahbaz et al., 2022). Empirical evidence suggests that ERT adoption reduces emissions when coupled with adequate policy, infrastructure, and skills; absent these, ‘rebound’ or scale effects may blunt gains (Shahbaz et al., 2022). Thus, assessing ERT impacts requires attention to absorptive capacity and the role of complementary factors such as human capital and finance.

1.5. Human capital and CO₂ emissions

Human capital influences emissions through at least two channels. Higher skills and education foster productivity and growth (which may increase energy demand), while also enhancing the capacity to adopt and optimize clean technologies and practices that lower CO₂ emissions (Gong et al., 2020; Inglesi-Lotz, 2016). Empirical studies offer mixed evidence: some document short-run increases in energy use associated with human capital-driven expansion, whereas others document long-run environmental gains through technology diffusion and behavioral change (Bano et al., 2018; Pablo-Romero, del P., Sánchez-Braza, 2015). Measurement choices (enrolment, years of schooling, or composite indices) further influence empirical outcomes (Barro, Lee, 2013; Benos, Zotou, 2014; Psacharopoulos, 1994). Nevertheless, existing studies rarely examine the interaction between human capital and environmental technology, leaving a gap in understanding how these factors jointly influence emissions, particularly in heterogeneous emerging economies characterized by emerging development levels.

1.6. Interaction effects of Environmental related Technology and Human Capital

Although the literature supplies robust findings on individual determinants, it is limited in integrating these drivers simultaneously and in testing interaction effects notably whether human capital conditions the environmental effectiveness of ERT. Several strands point toward such conditionality: financial structures mediate investment in clean technologies (Beck et al., 2000), renewable deployment requires supportive institutions and skills (Saqib, Abbas, et al., 2024), and ERT benefits depend on absorptive capacity (Li et al., 2023). Yet empirical cross-country studies that jointly model economic growth, financial development, renewable energy, ERT, and human capital while explicitly testing interaction channels are scarce for heterogeneous emerging economies (Habiba, Xinbang, 2022; Lean, Lee, 2022).

2. Research methodology

The panel data cover carbon emissions, economic growth, financial development, renewable energy, environmental technology, and human capital for heterogeneous emerging countries from 1994 to 2019. The chosen period is sufficiently long to capture persistent trends, structural change, and long-run interactions among the variables. The sample is restricted at 2019 to exclude the disruptions associated with the COVID-19 pandemic and ensuing geopolitical tensions, which are likely to have introduced structural breaks and abnormal volatility into the series. Focusing on the pre-2020 period thus provides a more stable empirical setting for examining long-run relationships. This period ensures sufficient data to capture long-term trends and structural changes. Table 1 outlines the data sources and variable descriptions.

Table 1. Variable description and sources

Symbols	Variables	Description	Sources
GHG	Green House Gass (Carbon Dioxide Emissions)	Total greenhouse gas emissions (kt of CO ₂ equivalent)	WDI
GDP	Economic Growth	GDP per capita (constant 2015 US\$)	WDI
ERT	Environment-Related Technologies	Development of environment-related technologies, percent all technologies	OECD
FDI	Financial Development	Financial development index	IMF
REC	Renewable Energy	Percentage of Renewable energy consumption	WDI
HCI	Human Capital	Human Capital Index	Penn World Table

Source: own elaboration based on data from IMF (2024), OECD (2024), Pen World Table (2024), and WDI (2024).

Since this study focuses on heterogeneous emerging economies, the sample consists of countries classified within key heterogeneous emerging market groups, including BRICS (Brazil, Russia, India, China, and South Africa), MINT (Mexico, Indonesia, Nigeria, and Türkiye), and the heterogeneous emerging Markets of Central and Eastern Europe (CEE) (Czech Republic, Poland, Hungary, and Greece). Nigeria, despite its frequent inclusion in the MINT grouping, is excluded because of incomplete data coverage over the study period. The classification of the Czech Republic and Poland is not entirely uniform across institutional frameworks. However, both countries are included in MSCI Emerging Markets country indexes, providing a market-based justification for their inclusion (MSCI, 2025). In addition, the descriptive statistics show that their observed values remain broadly within the range of the other sample countries across the principal variables used in the analysis, indicating empirical comparability rather than a clear separation from the rest of the panel. Subject to data

availability and the objectives of the study, the final sample comprises 12 countries: Brazil, China, the Czech Republic, Greece, Hungary, India, Indonesia, Mexico, Poland, Russia, South Africa, and Turkiye.

This study proposes the following model illustrated in formula 1

$$\ln(GHG_{i,t}) = \beta_0 + \beta_1 \ln(GDP_{i,t}) + \beta_2 (FDI_{i,t}) + \beta_3 (REC_{i,t}) + \beta_4 (ERT_{i,t}) + \beta_5 (HCI_{i,t}) + \varepsilon_{i,t} \quad (1)$$

$$\ln(GHG_{i,t}) = \beta_0 + \beta_1 \ln(GDP_{i,t}) + \beta_2 (FDI_{i,t}) + \beta_3 (REC_{i,t}) + \beta_4 (ERT_{i,t}) + \beta_5 (HCI_{i,t}) + \beta_6 (ERT * HCI)_{i,t} + \varepsilon_{i,t} \quad (2)$$

In this model, i represents the cross-section of heterogeneous emerging countries, while t represented the selected annual period from 1994 to 2019. Formula 1 represents the base model, while Formula 2 incorporates an interaction between environment-related technology and the human capital index. The constant term and coefficient parameters of the model are denoted by β_0 and $\beta_1 - \beta_6$ for each respective series. The random error term is represented as ε . The GHG and GDP variables are natural logarithmically transformed, as suggested by Saqib et al., (2024). This study employed several steps in the econometric process to test the impact of economic growth, financial development measures, renewable energy consumption, environment-related technology, and human capital on carbon dioxide emissions. These econometric processes aim to test the quality of the model and conduct robustness tests to demonstrate that the results are robust under various conditions.

Step 1. Identify Slope Homogeneity and Cross-sectional Dependency

The slope homogeneity (SH) test is first conducted to determine whether the slope coefficients are identical across countries or vary across panel members. This is followed by the cross-sectional dependence (CD) test, which examines whether the panel units are interconnected through common shocks or unobserved common factors (Pesaran, 2004). In this study, slope homogeneity is initially tested using the procedure developed by Pesaran and Yamagata (2008). Since this test does not account for heteroskedasticity or serial correlation in the error term (Hussain et al., 2022) the heteroscedasticity and autocorrelation-consistent (HAC) robust version by Blomquist and Westerlund (2013) is also considered. Subsequently, cross-sectional dependence is examined using the Pesaran CD, Friedman CD, and Frees CD statistics. (De Hoyos, Sarafidis, 2006).

Step 2. Assessment of stationarity

The stationarity of variables is tested by the Cross-section Augmented Dickey-Fuller (CADF), Cross-section Im, Pesaran, and Shin (CIPS) tests proposed by Pesaran (2007), and Levin, Lin, and Chu (LLC) by to avoid spurious regressions. Within the CS-ARDL framework, the variables should be integrated by order zero, $I(0)$, or order one, $I(1)$, but not of order two, $I(2)$. The CADF test is employed because it explicitly accounts for cross-sectional dependence, while the CIPS test provides a corresponding panel-level unit root assessment. The LLC test is also included to complement the analysis, particularly for panels with a relatively long time dimension, under the assumption of a common unit root process across cross-sectional units.

Step 3. Analysis of Cointegration

The Westerlund test is employed to assess whether a long-run equilibrium relationship exists among the variables in the presence of cross-sectional dependence, which is a common feature of panel data analysis (Westerlund, 2007). This analysis is relevant within the CS-ARDL framework because the model enables the estimation of both short-run dynamics and long-run coefficients when the variables are cointegrated. The Westerlund test is therefore considered appropriate, as it accounts for cross-sectional dependence arising from common shocks or unobserved common factors.

Step 4. Long-run estimation: the Cross-Sectional Autoregressive Distributed Lag Approach

The long-run estimation in this study was conducted using the Cross-Sectional Autoregressive Distributed Lag Approach (CS-ARDL). This method is suitable for panel data analysis and allows for the investigation of long-run relationships, and accommodates both cross-sectional dependence and heterogeneity in panel data (Chudik, Pesaran, 2015). CS-ARDL is presented in the following model.

$$y_{i,t} = \alpha_i + \sum_{j=1}^p \phi_{i,j} y_{i,t-j} + \sum_{j=0}^q \beta_{i,j} x_{i,t-j} + \lambda_i \bar{y}_t + \sum_{j=0}^q \delta_{i,j} \bar{x}_{t-j} + \varepsilon_{i,t} \quad (3)$$

The variables p and q represent the lagged values of each element. In addition, in this context, $y_{i,t}$ represents the dependent variable, which refers to GHG. While $x_{i,t}$ Encompasses all the independent variables, including GDP, ERT, FDI, REC, HCI, and HCI*ERTC.

Step 5. Robustness test

In this study, the augmented mean group (AMG) and Common Correlated Effects Mean Group (CCEMG) were used as robustness tests. The AMG technique addresses issues such as CD, non-stationarity, endogeneity, and slope heterogeneity that are inherent in longitudinal data analysis (Eberhardt, Bond, 2009). The CCEMG method addresses key issues in panel data such as dependence, non-stationarity, endogeneity, and slope heterogeneity (Pesaran, 2006).

Step 6. Causality Analysis

To investigate the causal relationships among the chosen series, this study employed panel heterogeneous causality tests as formulated by Dumitrescu and Hurlin (2012). The test is used to assess whether past values of one variable contain predictive information about another variable. Its use is appropriate in this study because it allows the causal relationship to vary across countries, rather than imposing a homogeneous structure on all panel members. This is particularly relevant in a multi-country panel context, where economic relationships may differ across cross-sectional units.

3. Results and Discussion

Table 2 presents descriptive statistics of the data. The descriptive statistics indicate substantial heterogeneity across countries in the sample. China records the highest mean level of $\ln\text{GHG}$, whereas Hungary has the lowest. The highest average $\ln\text{GDP}$ is observed in Greece, while India exhibits the lowest. Renewable energy consumption (REC) is highest in Brazil and lowest in Russia, suggesting marked differences in energy structure across countries. For human capital (HCI), the Czech Republic has the highest mean and India the lowest. Overall, the summary statistics suggest that although the sampled countries share some broad heterogeneous emerging-market characteristics, there remains considerable cross-country variation in macroeconomic, environmental, and structural indicators.

Next, Table 3 presents the SH test results, showing that regression slopes differ across groups. Both the Pesaran and Yamagata (2008) test and the HAC-adjusted test by Blomquist and Westerlund (2013) yielded significant results, rejecting the SH hypothesis and supporting the use of heterogeneous panel methods.

Table 2. Descriptive statistics

Country	Variable	Mean	Std. Dev.	Min	Max	Skewness	Kurtosis
1	2	3	4	5	6	7	8
All sample country	lnGHG	13.220	1.325	10.930	16.360	0.284	2.546
	ERT	0.101	0.032	0.018	0.214	0.001	0.328
	lnGDP	8.790	0.818	6.370	10.090	0.668	3.521
	REC	0.187	0.146	0.032	0.534	0.021	2.479
	FDI	0.435	0.094	0.253	0.680	0.008	2.535
	HCI	2.660	0.533	1.578	3.674	0.284	1.974
Brazil	lnGHG	13.704	0.172	13.388	13.936	-0.330	1.833
	ERT	0.096	0.035	0.030	0.153	-0.360	2.022
	lnGDP	8.944	0.129	8.758	9.129	-0.005	1.392
	REC	0.451	0.020	0.413	0.489	-0.039	2.110
	FDI	0.516	0.115	0.324	0.663	-0.326	1.524
	HCI	2.373	0.384	1.831	3.091	0.338	1.930
China	lnGHG	15.825	0.435	15.178	16.360	-0.179	1.376
	ERT	0.085	0.016	0.040	0.112	-0.822	3.442
	lnGDP	8.275	0.641	7.233	9.226	-0.069	1.628
	REC	0.196	0.079	0.113	0.311	0.393	1.370
	FDI	0.483	0.100	0.354	0.638	0.275	1.651
	HCI	2.413	0.166	2.100	2.699	-0.044	2.211
Czech Rep	lnGHG	11.820	0.078	11.676	11.933	-0.376	1.775
	ERT	0.117	0.020	0.083	0.154	-0.086	2.093
	lnGDP	9.607	0.194	9.262	9.914	-0.210	1.740
	REC	0.096	0.038	0.052	0.159	0.406	1.542
	FDI	0.402	0.060	0.310	0.476	-0.170	1.452
	HCI	3.585	0.096	3.322	3.674	-1.461	4.066
Greece	lnGHG	11.569	0.139	11.273	11.747	-0.567	2.111
	ERT	0.117	0.044	0.051	0.213	0.449	2.159
	lnGDP	9.867	0.124	9.661	10.089	0.325	2.109
	REC	0.109	0.041	0.071	0.185	0.767	1.832
	FDI	0.520	0.087	0.373	0.680	0.001	2.110
	HCI	2.869	0.161	2.614	3.135	0.047	1.777
Hungary	lnGHG	11.118	0.101	10.927	11.229	-0.539	1.817
	ERT	0.094	0.027	0.033	0.133	-0.179	2.173
	lnGDP	9.272	0.201	8.930	9.621	-0.301	2.077
	REC	0.097	0.047	0.046	0.172	0.277	1.361
	FDI	0.439	0.082	0.274	0.571	-0.215	2.516
	HCI	3.150	0.187	2.866	3.417	-0.100	1.536

1	2	3	4	5	6	7	8
India	lnGHG	14.603	0.295	14.149	15.050	0.096	1.584
	ERT	0.086	0.024	0.054	0.134	0.280	1.880
	lnGDP	6.949	0.373	6.374	7.573	0.149	1.778
	REC	0.411	0.064	0.326	0.505	-0.053	1.369
	FDI	0.440	0.031	0.357	0.509	-0.390	3.970
	HCI	1.892	0.171	1.578	2.171	-0.134	2.057
Indonesia	lnGHG	13.525	0.161	13.215	13.836	0.066	2.249
	ERT	0.103	0.045	0.023	0.196	0.118	2.624
	lnGDP	7.805	0.256	7.487	8.267	0.377	1.750
	REC	0.383	0.094	0.198	0.534	-0.363	2.024
	FDI	0.323	0.038	0.253	0.396	-0.079	2.077
	HCI	2.264	0.120	2.007	2.417	-0.745	2.392
Mexico	lnGHG	13.294	0.129	13.029	13.434	-0.651	2.034
	ERT	0.102	0.032	0.042	0.153	-0.304	2.178
	lnGDP	9.161	0.062	8.993	9.244	-0.995	3.662
	REC	0.105	0.014	0.090	0.133	0.719	2.095
	FDI	0.345	0.044	0.262	0.401	-0.285	1.643
	HCI	2.535	0.150	2.273	2.777	-0.116	1.913
Poland	lnGHG	12.825	0.051	12.758	12.948	0.928	3.120
	ERT	0.115	0.034	0.018	0.176	-0.453	3.866
	lnGDP	9.123	0.304	8.568	9.619	-0.134	1.897
	REC	0.089	0.028	0.059	0.156	0.957	3.007
	FDI	0.399	0.063	0.276	0.478	-0.360	1.660
	HCI	3.135	0.177	2.831	3.458	0.053	1.970
Russia	lnGHG	14.619	0.042	14.533	14.699	-0.439	2.739
	ERT	0.113	0.017	0.081	0.163	0.856	4.511
	lnGDP	8.882	0.288	8.415	9.206	-0.418	1.515
	REC	0.035	0.002	0.032	0.039	0.222	1.828
	FDI	0.473	0.066	0.334	0.576	-0.624	2.647
	HCI	3.221	0.161	2.856	3.434	-0.822	2.817
South Africa	lnGHG	13.039	0.170	12.729	13.227	-0.510	1.709
	ERT	0.110	0.027	0.070	0.169	0.284	2.183
	lnGDP	8.602	0.138	8.373	8.742	-0.403	1.487
	REC	0.117	0.040	0.077	0.186	0.626	1.719
	FDI	0.465	0.088	0.286	0.593	-0.379	2.314
	HCI	2.378	0.299	1.977	2.908	0.243	1.725

1	2	3	4	5	6	7	8
Turkiye	lnGHG	12.719	0.256	12.287	13.129	0.093	1.764
	ERT	0.083	0.032	0.038	0.214	2.462	11.346
	lnGDP	8.988	0.260	8.590	9.405	0.224	1.727
	REC	0.159	0.037	0.114	0.241	0.686	2.203
	FDI	0.415	0.072	0.293	0.503	-0.291	1.551
	HCI	2.152	0.200	1.844	2.514	0.187	1.963

Source: own elaboration.

Table 3. Slope homogeneity test results

Test	Model	Delta	Adjusted Delta
Mean Variance Biased Adjusted SH tests – Pesaran and Yamagata (2008)	Model 1	15.208***	17.791***
	Model 2	6.909***	8.303***
HAC – Blomquist and Westerlund (2013)	Model 1	7.685***	8.989***
	Model 2	2.397***	2.880***

*** significant at 1%.

Source: own elaboration.

Table 4. Cross-sectional dependence

P-CD		Residual Dependence	
variable	CD-test	model	CD-test
lnGHG	4.292***	Model 1	CD _{Pesaran}
ERT	6.548***		CD _{Friedman}
lnGDP	33.911***		CD _{Frees}
REC	-0.406	Model 2	CD _{Pesaran}
FDI	27.951***		CD _{Friedman}
HCI	28.885***		CD _{Frees}
HCI*ERTC	10.999***		

*** significant at 1%.

Source: own elaboration.

Table 4 presents the Pesaran CD (P-CD) test results, revealing significant cross-sectional dependence at the 1% level for most variables except REC. Residual dependence is detected in both models by the CD Frees test, despite mixed results from other tests. These findings justify the use of robust estimators like CCEMG and AMG. Next, Table 5 presents the results of the

stationarity tests using the CADF, CIPS, and LLC unit root methods. Most of the variables are found to be stationary at the first difference, I(1). This finding is significant because the stationarity of variables is a fundamental assumption for further analysis, such as co-integration and long-run estimation.

Table 5. Stationary test results

Variable	CADF		CIPS		LLC	
	I(0)	I(1)	I(0)	I(1)	I(0)	I(1)
lnGHG	-2.148*	-4.051***	-0.952	-4.188***	-1.239	-4.866***
ERT	-4.652***	-6.096***	-3.98***	-8.083***	-3.724***	-9.708***
lnGDP	-1.518	-2.894***	-0.822	-3.361***	-0.961	-3.795***
REC	-2.404**	-4.25***	-0.836	-4.382***	-0.110	-3.380***
FDI	-2.116	-5.011***	-1.548	-4.953***	-2.546***	-8.199***
HCI	-1.850	-1.694	-0.435	-1.975**	1.256	-2.101**
HCI*ERTC	-4.614***	-6.091***	-3.472***	-7.916***	-2.136**	-9.499***

* significant at 10%; ** significant at 5%; *** significant at 1%.

Source: own elaboration.

The Westerlund co-integration test results are shown in Table 6. The results also show robust P-value after bootstrapping for eight hundred times. The result of the test statistics Gt, Pt, and Pa all have significant values. This result provides strong evidence suggesting a potential co-integrating relationship among the variables in the model. This finding is crucial for subsequent long-run estimations because it suggests that the variables share common long-term dynamics and that their linear combination is stationary.

Table 6. Westerlund cointegration test

Model	Statistic	Value	Z-value	P-value	P-value robust
Model 1	Gt	-3.982	-6.072	0.000	0.001
	Ga	-12.844	-0.505	0.307	0.000
	Pt	-14.882	-6.844	0.000	0.000
	Pa	-14.604	-2.863	0.002	0.000
Model 2	Gt	-3.525	-3.732	0.000	0.004
	Ga	-9.804	1.683	0.954	0.004
	Pt	-13.415	-5.071	0.000	0.000
	Pa	-11.988	-0.784	0.217	0.000

Source: own elaboration.

Table 7. CS-ARDL estimation

Short Run			Long Run		
variable	coefficient	p-value	variable	coefficient	p-value
Model 1					
lnGDP	0.269	0.008	lnGDP	0.143	0.004
FDI	0.039	0.559	FDI	0.016	0.602
REC	-1.505	0.000	REC	-0.758	0.000
ERT	0.049	0.578	ERT	0.023	0.608
HCI	-0.009	0.923	HCI	-0.075	0.887
ECM(-1)	-1.979	0.000			
Model 2					
lnGDP	0.341	0.013	lnGDP	0.181	0.007
FDI	-0.019	0.797	FDI	-0.010	0.780
REC	-1.329	0.002	REC	-0.694	0.001
ERT	3.077	0.163	ERT	1.789	0.126
HCI	0.164	0.270	HCI	0.087	0.285
HCI*ERT	-1.584	0.086	HCI*ERT	-0.909	0.079
ECM(-1)	-1.945	0.000			

Source: own elaboration.

Table 7 shows that lnGDP has a significant positive impact on CO₂ emissions in both the short and long term, highlighting economic growth as a strong predictor of environmental degradation. This supports the view that increased economic activity leads to higher energy consumption and emissions (Gormus, Aydin, 2020; Mehmood, 2022; Saqib, Abbas, et al., 2024). Sectoral analysis further illustrates this trend. In manufacturing, economic growth boosts production and energy demand, largely fueled by fossil sources, thus driving up emissions (Rosita et al., 2021). In agriculture, mechanization and land-use changes increase emissions through fuel use, deforestation, and chemical inputs (Aluwani, 2023; Ben Jebli, Ben Youssef, 2019). The service sector also contributes, with rising energy use in commercial buildings and transportation tied to urban expansion and economic activity (Alam, 2022; Haldar, Sharma, 2022). Overall, the results emphasize that without cleaner energy transitions, economic development across sectors poses substantial environmental challenges.

The results show that higher levels of REC significantly reduce CO₂ emissions in both the short and long term. This supports the idea that adopting renewable sources like solar, wind, hydro, and biomass effectively replaces fossil fuels and lowers emissions (Mehmood, 2022). (Raza et al., 2020) stated that renewable energy sources generate little to no air pollution and

are environmentally friendly. In addition, they play a crucial role in reducing greenhouse gas emissions. In contrast, ERT and HCI do not show significant individual effects on emissions reduction, suggesting that improvements in these areas alone are insufficient. However, their interaction has a significant negative impact on CO₂ emissions, highlighting the importance of combining skilled human resources with green technologies. This synergy is essential, as the effective implementation and optimization of environmental technologies depend on a capable and educated workforce.

Table 8. AMG and CCEMG test

AMG			CCEMG		
variable	coefficient	p-value	variable	coefficient	p-value
Model 1					
lnGDP	0.223	0.000	lnGDP	0.280	0.027
FDI	0.165	0.038	FDI	0.009	0.921
REC	-2.228	0.000	REC	-1.779	0.000
ERT	0.0700	0.341	ERT	0.109	0.253
HCI	0.087	0.209	HCI	0.102	0.625
Model 2					
lnGDP	0.254	0.000	lnGDP	0.273	0.039
FDI	0.129	0.044	FDI	0.024	0.764
REC	-1.910	0.000	REC	-1.594	0.000
ERT	4.363	0.082	ERT	1.382	0.089
HCI	0.233	0.025	HCI	0.202	0.508
HCI*ERTC	-1.886	0.065	HCI*ERTC	-0.660	0.058

Source: own elaboration.

Table 8 presents robustness checks using AMG and CCEMG estimators. Results confirm that economic growth, renewable energy use, and the interaction between human capital and environmental technology significantly affect CO₂ emissions, which are consistent with CS-ARDL findings. However, unlike CS-ARDL and CCEMG, the AMG model identifies FDI as having a significant positive effect on emissions. This should be interpreted with caution, as AMG is less effective in controlling cross-sectional dependence, and the result may reflect model-specific sensitivities. Despite this statistical caution, there is a potential link between financial development and CO₂ emissions, for example Zhang, Y.J. (2011), Shoaib et al. (2020), and Raza et al., (2020) found that financial development contributes to higher emissions by promoting investment, industrial expansion, and energy use. Another key finding

is that ERT has a significant positive impact on CO₂ emissions in Model 2 for both AMG and CCEMG. This suggests that heterogeneous emerging countries are still in a transitional phase, where inefficiencies, increased energy demand, or rebound effects from technology use may temporarily raise emissions.

Table 9. D-H causality test

Hypothesis	W-stat	Statistics	Prob.	Remarks
$\ln\text{GDP} \rightarrow \ln\text{GHG}$	4.013	7.381	0.000	$\ln\text{GDP} \leftrightarrow \ln\text{GHG}$
$\ln\text{GHG} \rightarrow \ln\text{GDP}$	1.777	1.905	0.056	
$\text{FDI} \rightarrow \ln\text{GHG}$	4.405	8.341	0.000	$\text{FDI} \leftrightarrow \ln\text{GHG}$
$\ln\text{GHG} \rightarrow \text{FDI}$	3.960	7.251	0.000	
$\text{REC} \rightarrow \ln\text{GHG}$	6.160	12.641	0.000	$\text{REC} \rightarrow \ln\text{GHG}$
$\ln\text{GHG} \rightarrow \text{REC}$	1.464	1.144	0.252	
$\text{ERT} \rightarrow \ln\text{GHG}$	1.288	0.706	0.479	$\ln\text{GHG} \rightarrow \text{ERT}$
$\ln\text{GHG} \rightarrow \text{ERT}$	4.141	7.695	0.000	
$\text{HCI} \rightarrow \ln\text{GHG}$	3.960	7.251	0.000	$\text{HCI} \leftrightarrow \ln\text{GHG}$
$\ln\text{GHG} \rightarrow \text{HCI}$	3.999	7.346	0.000	

Source: own elaboration.

To further ensure the robustness of the findings, a causality test was conducted. Table 9 displays the results of the D-H causality test. Specifically, the results indicate bi-causal or two-way relationships for $\ln\text{GDP}$, FDI , and HCI . This suggests that each of these variables is not only influenced but is also influenced by others, highlighting the complex interdependence that is crucial for understanding the multifaceted nature of economic systems. In contrast, the analysis revealed uni-causal or one-way relationships in which REC affects $\ln\text{GHG}$ and $\ln\text{GHG}$ affects ERT . These findings illustrate the directional influence of renewable energy initiatives on reducing carbon output and how changes in CO₂ emissions can spur adaptations and innovations in environmental technology.

Conclusions

In conclusion, the primary driver of environmental change is widely acknowledged to be the rapid increase in greenhouse gases, particularly carbon dioxide emissions, especially in heterogeneous emerging countries at various stages of industrialization. The study's aims have been achieved, demonstrating the impact of economic growth, financial development,

renewable energy consumption, environment-related technology, and human capital on CO₂ emissions in twelve heterogeneous emerging countries: Brazil, China, Czech Republic, Greece, Hungary, India, Indonesia, Mexico, Poland, Russia, South Africa, and Türkiye from 1994 to 2019. Using the CS-ARDL method, The main findings showed both the short and long term: (1) economic growth increases CO₂ emissions, (2) renewable energy use reduces emissions, and (3) the interaction of human capital and environmental technology lowers emissions. This result remains consistent when using AMG and CCEMG as robustness tests.

The results challenge a simple EKC interpretation for heterogeneous emerging economies: economic growth here is associated with higher CO₂ in both the short and long run, and emission reductions occur only when structural conditions notably renewable adoption and the interaction of human capital with environment-related technology ($HCI \times ERT$) are present. In other words, decarbonization in these contexts depends on complementary capacities (technological capability and skills) rather than growth alone. Accordingly, the general implications suggest economy growth cannot be relied on to deliver environmental gains and policymakers must fast-track renewables through subsidies, finance instruments, and grid investments while simultaneously investing in education and workforce training that enable effective ERT deployment. Integrated measures that link finance, technology, and human-capital development will maximize the emission-reducing payoff of clean technologies.

Although these conclusions are derived from the full sample, their policy priority may differ across country groups due to variations in economic structure, energy dependence, and institutional capacity. However, these differences should be understood in terms of relative emphasis rather than completely distinct policy prescriptions, since the main policy directions remain broadly relevant across the sample. For BRICS and MINT countries, policy priority should be decarbonizing heavy industry and scaling renewables by combining regulatory standards with de-risking instruments for clean investments. Financial authorities should mainstream climate risk in lending, promote green bonds and sustainability-linked finance, and attach workforce-training conditions to subsidies or concessional finance to ensure ERT is effectively absorbed. For EU member states and economies in transition toward EU integration, advancing the Green Deal requires the faster implementation of building renovation programs, closer coordination between renewable energy auctions and grid infrastructure investment, stricter industrial permitting in line with the Emissions Trading System (ETS), and the use of carbon revenues to support just transition funds. In parallel, regulators should reinforce disclosure requirements, improve EU taxonomy alignment, and strengthen climate stress testing in the banking sector.

This study, however, has its limitations. This study focused only on direct and long-term impacts without capturing potential non-linear effects. Future research could incorporate non-linear modelling approaches and structural break analyses to better capture dynamic changes in emissions, particularly in the context of global disruptions such as the COVID-19 pandemic and recent geopolitical tensions. Additionally, the study was constrained by the period and the selection of emerging countries. Further research could expand the dataset to include more recent data and a more specific selection of emerging countries. Future studies may also differentiate between groups of countries, such as EU members and non-EU emerging economies, to better account for institutional and regulatory differences influencing CO₂ emissions. Future studies might also refine measurements of CO₂ emissions, financial development, environment-related technology, and the human capital index and then examine more potential interactions among these variables

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