ENERGY CONSUMPTION PATTERNS, CARBON EMISSIONS AND ECONOMIC GROWTH IN BRICS NATIONS: NAVIGATING ENVIRONMENTAL CHALLENGES AND SUSTAINABLE DEVELOPMENT INITIATIVES

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Abstract. This study investigates the long-run relationship between carbon dioxide (CO_2) emissions, renewable energy consumption (REC), economic growth (GDP), and technological innovation (TEC) in the BRICS nations (Brazil, Russia, India, China, and South Africa) over the period of 1990–2023. Using Fully Modified Ordinary Least Squares (FMOLS) and Dynamic Ordinary Least Squares (DOLS) estimators, the study explores the energy-growth-emissions nexus. The findings confirm that economic growth (GDP) follows the Environmental Kuznets Curve (EKC) hypothesis, where higher GDP correlates with lower emissions in the long run, driven by cleaner technologies. However, technological innovation and renewable energy consumption show a complex relationship with emissions. Technological innovation is positively associated with CO_2 emissions, suggesting the rebound effect, where initial efficiency gains increase energy demand. Additionally, the study finds that renewable energy consumption is positively linked with CO_2 emissions, indicating that increased demand for energy may outpace the decarbonization effect of renewables. The panel causality tests reveal bidirectional feedback loops between REC-CO_2 and TEC-CO_2, emphasizing the need for synchronized policy interventions. Policy recommendations include promoting green technological innovation, scaling renewable energy adoption, and implementing carbon pricing mechanisms to decouple economic growth from emissions. The results highlight the importance of tailored strategies for each BRICS nation to achieve sustainable development goals, specifically SDGs 7, 8, and 13, ensuring a low-carbon future while fostering inclusive growth.
Keywords: *BRICS nations, carbon emissions, renewable energy, economic growth, technological innovation, environmental Kuznets curve*

Introduction

The BRICS nations Brazil, Russia, India, China, and South Africa are key players among emerging markets, significantly impacting global energy use, carbon emissions, and economic performance. Together, they contribute a rising share of the world's energy consumption, emit a major portion of global carbon dioxide, and generate a large share of global GDP. As these countries continue to industrialize and urbanize, their energy use

trends are shaping progress toward key Sustainable Development Goals (SDGs), especially SDG 7 (Affordable and Clean Energy), SDG 8 (Decent Work and Economic Growth), and SDG 13 (Climate Action). The 2020s are critical: the BRICS must find a way to grow their economies while minimizing environmental damage in check (Osabohien et al., 2024; Nwanchukwu et al., 2022; United Nations, 2023; Wang et al., 2025a, b).

Recent data highlights the complex link between energy use, emissions, and economic growth across these countries. Studies show that using fossil fuels tends to raise emissions, while renewables help cut pollution without constraining back growth (Mehta et al., 2024; Khan et al., 2025; Wang et al., 2025b). Still, the balance between economic growth and environmental protection is different in each country. China and India are rapidly growing and still depend heavily on fossil fuels. In contrast, Brazil relies mostly on renewables. Russia's oil and gas-heavy system and South Africa's coal-based energy make their green transitions more complicated (Caporin et al., 2024; Saryal et al., 2025; Zaho and Chen, 2022).

BRICS countries vary in how they use energy due to their different industrial and technological stages. China uses the most energy in the world, mainly due to manufacturing and heavy industry. Despite being a leader in renewable energy investments, China still approves new coal plants, which conflicts with its green goals (The Guardian, 2025). India's growing population and industry are pushing its energy use higher, expected to peak around 2040. Yet, fossil fuels still dominate. Russia relies heavily on oil and gas exports, which raises its carbon footprint. Brazil leans on hydro, while South Africa is still tied to coal (SANEDI, 2024).

Research based on the Environmental Kuznets Curve (EKC) suggests that the income-emissions link in BRICS countries does not always follow the usual inverted U-shaped curve (Biyase et al., 2024). Differences in industry type, government policies, and technology affect when and how emissions start to fall (Erkılıç et al., 2025). That means policies need to be tailored to each country instead of using a one-size-fits-all model.

Carbon emissions are the clearest sign of the BRICS nations' energy challenges. China and India together are responsible for more than one-third of global CO_2 emissions, mainly due to their industries and coal power (Carbon Brief, 2025; Zheng et al., 2022). Russia's emissions come from energy exports and wasteful energy use. South Africa has high per-person emissions due to its coal-heavy power grid (Reuters, 2024). Brazil is unique it gets most of its electricity from hydro, but emissions are still rising due to transportation and deforestation (Mehta et al., 2024).

Research shows that using more renewables and improving energy efficiency helps lower emissions over time (Khan et al., 2025). However, how fast this happens depends on things like government quality, financial systems, and access to technology (Caporin et al., 2024). Countries with strong green finance tend to invest more in low-carbon projects, while those that depend on mining and fossil fuels move slower. BRICS countries must find a balance between staying competitive and meeting environmental goals through smart policy planning.

Economic growth in BRICS has typically been energy-hungry, but there is growing proof that it does not have to be. New technologies and good policies can help economies grow without increasing emissions (Mehta et al., 2024; Osabohien et al., 2025a, b). Green growth focuses on innovation, efficient use of resources, and renewable energy as ways to grow sustainably. That fits well with SDG 8, which promotes jobs and inclusive development.

China's green industries solar, wind, and electric vehicles are creating jobs and cutting emissions (Carbon Brief, 2025). India is investing in solar energy and efficiency through

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initiatives like the National Solar Mission and PAT (Perform, Achieve and Trade). South Africa's Just Energy Transition Programme supports communities affected by the shift away from coal by offering retraining and protections (Wang et al., 2025b; SANEDI, 2024). These efforts show how green policies can serve both economic and climate goals.

Still, tensions between growth and sustainability remain. Russia's dependence on fossil fuel exports and South Africa's energy security worries show how economic needs can slow down clean energy efforts. To be sustainable in the long run, BRICS countries need to align their energy, climate, and economic policies while encouraging innovation and circular economy practices to cut emissions and remain competitive (Erkılıç et al., 2025).

Because energy, emissions, and growth are closely tied, BRICS countries need policies that support the Sustainable Development Goals. SDG 7 calls for wider access to affordable clean energy. SDG 13 requires stronger climate action. SDG 8 promotes sustainable and decent work. These goals are interlinked and must be pursued together.

According to the UN (2023) and World Bank (2023), progress toward SDG 7 is still uneven. Many rural areas still lack clean cooking solutions and reliable energy. While most BRICS countries have near-universal electricity, there are gaps in energy quality, affordability, and access to renewables. Localized solutions, like solar programs in India and Brazil, show promise. On the other hand, South Africa's unstable electricity grid highlights the need to combine clean energy with system reliability (Osabohien et al., 2025a; Dou et al., 2025).

For SDG 13, achieving net-zero targets like China's by 2060 and India's by 2070 requires clear short-term goals and systems for tracking progress (Climate Action Tracker, 2024). Stronger climate rules, carbon pricing, and access to international finance are also key. Just transition strategies are critical, especially in coal-reliant areas, to reduce social harm during the shift (SANEDI, 2024).

SDG 8 connects these transitions by encouraging green jobs, innovation, and economic change. Renewables offer big job opportunities from making solar panels to installing wind turbines. China's clean energy sector has already created millions of jobs, and India is expected to add 1.5 million green energy jobs by 2030 (Osabohien et al., 2025a, b; Mission Impact, 2023). With the right education and training, these shifts can boost both economic strength and social inclusion.

The broad objective of this study is to analyse the relationship between carbon dioxide (CO_2) emissions, renewable energy consumption (REC), technological innovation (TEC), and economic growth (GDP) in the BRICS nations (Brazil, Russia, India, China, and South Africa). While the specific objectives are: To assess the long-run relationship between CO_2 emissions and key variables (renewable energy consumption, GDP, and technological innovation) in BRICS nations; To evaluate the impact of technological innovation on CO_2 emissions, considering both positive and negative effects, and to understand how technological advancements might inadvertently increase emissions in the short term; To investigate the role of renewable energy consumption in reducing carbon emissions, analysing whether its growth has been sufficient to decarbonize the energy mix in the BRICS countries; To examine the Environmental Kuznets Curve (EKC) hypothesis by analysing how economic growth influences emissions over time, specifically in the context of BRICS economies.

The BRICS countries face a complex mix of industrialization, technological change, and policy reform in their quest for sustainable development. Research shows strong long-term ties between energy use, emissions, and growth. The challenge is turning these links into greener outcomes. Cutting the tie between emissions and growth without

slowing the economy will require joint efforts at all levels government, industry, and international partners.

Future plans should combine renewable energy growth with digital and financial innovations. Strengthening institutions, sharing technology across borders, and directing trade and investment toward low-carbon projects are essential. Policies must also include gender equality and social fairness to make sure the energy transition benefits everyone.

In the end, for BRICS countries to achieve sustainable development, they must strike a balance between economic goals and protecting the environment. By aligning their national strategies with SDG 7, SDG 8, and SDG 13, they can help steer the world toward a cleaner, fairer, and more resilient energy future.

Literature review

Empirical studies in recent years have deepened the understanding of the interrelationship between energy consumption, carbon emissions, and economic growth across the BRICS economies by applying advanced econometric models capable of addressing cross-sectional dependence, dynamic heterogeneity, and non-linear transmission effects. Mehta and Shah (2024), employing a nonlinear panel quantile regression for BRICS from 2000–2023, revealed that renewable energy use and digitalisation significantly reduce emissions, while financial development exerts asymmetric effects emissions rise more rapidly with fossil energy expansion than they fall with equivalent renewable substitution.

Anser et al. (2024) applied a panel vector autoregressive (VAR) model and established bidirectional causality among energy consumption, technological innovation, and carbon emissions, highlighting innovation as a transmission mechanism that moderates environmental degradation over the long term.

Mngumi et al. (2024), using the Augmented Mean Group (AMG) estimator combined with Dumitrescu–Hurlin causality for BRICS data spanning 1990–2021, demonstrated that financial development, FDI, and innovation significantly decrease emissions, whereas industrialisation and aggregate energy use contribute positively to CO_2 levels, implying that structural transformation remains energy-intensive in emerging markets. In a related context, Yadav et al. (2024) adopted a panel interaction model integrating green finance and governance, finding that governance effectiveness amplifies the emission-reducing impact of renewable investments. Hasan (2023), using panel cointegration and Granger causality tests, validated a U-shaped Environmental Kuznets Curve (EKC) in BRICS economies, indicating that income growth initially raises but eventually reduces emissions once a specific development threshold is surpassed.

Erkılıç et al. (2025) applied a panel cointegration framework combining renewable energy use, globalization, and growth indicators, showing that increased openness reinforces the decoupling effect of renewable energy on emissions, while weak integration limits this potential. Sezgin et al. (2024) employed Westerlund–Edgerton bootstrap cointegration and JKS causality tests, establishing bidirectional causality between renewable energy, human capital, and emissions; they found that renewable energy and education contribute to emissions reduction, but regulatory uncertainty in the business climate can counteract these benefits.

Shekhawat et al. (2025) utilized a cross-sectional ARDL (CS-ARDL) approach for BRICS (1990–2019) and confirmed that economic growth and financial globalization

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exacerbate emissions, whereas renewable energy, digitalisation, and green innovation mitigate them, reaffirming the centrality of technology in climate mitigation.

Li et al. (2024), using panel cointegration and error-correction models, reported that renewable energy consumption and environmental taxation significantly reduce CO_2 emissions, whereas resource rents and trade openness intensify environmental pressures. Kaya et al. (2024), applying the pooled mean group (PMG) approach, linked social investments and public health spending to long-term emissions reductions, arguing for a broader developmental interpretation of the SDGs beyond energy variables. Wang and Guo (2025) advanced methodological innovation by using particle-swarm-optimized grey breakpoint models to forecast BRICS emissions; their results indicated multiple structural breaks aligned with energy policy shifts, demonstrating that conventional linear models underestimate volatility in carbon trends.

Audi et al. (2023) combined FMOLS, DOLS, and panel quantile regression for 1991–2022 data, confirming an inverted U-shaped EKC in BRICS economies. They also revealed that coal dependency dominates lower quantiles, while the influence diminishes in higher quantiles, reflecting heterogeneous transition stages among member states. Similarly, Caporin et al. (2024) applied Fully Modified OLS (FMOLS) and Dynamic OLS (DOLS) on extended BRICS data, uncovering both U and N-shaped relationships between income and emissions, with governance and water stress conditions determining the curvature of the EKC.

Hasan (2023) corroborated this using panel cointegration across 1990–2020, showing fossil fuel consumption as the most significant emissions driver, while trade openness and renewable energy act as long-run mitigants. In assessing the role of financial and digital innovation, Sadiq et al. (2024) employed second-generation dynamic panel models and found that green finance and eco-innovation reduce emissions intensity by improving capital efficiency and stimulating renewable deployment. Zhang et al. (2024) extended this analysis by incorporating fintech development and natural resource rents, concluding that fintech enhances the effectiveness of renewable energy in curbing emissions, provided regulatory quality remains high. Similar outcomes were observed by Osabohien et al. (2024) using panel NARDL and interaction terms for digitalisation and finance; their results revealed a complementary relationship where ICT infrastructure strengthens the emissions-mitigating role of clean energy investment.

Liu (2024) examined panel data on natural resource rents and energy intensity in BRICS, demonstrating that resource dependency amplifies carbon emissions unless offset by targeted green investments and environmental policy enforcement. Dilanchiev et, al (2023), through panel quantile regression, identified that urbanisation initially raises emissions but subsequently promotes efficiency gains via better transport infrastructure and compact city design, contingent on renewable integration. Hlongwane and Khobai (2024) adopted ARDL-based growth modelling and found that renewable energy positively influences GDP growth while reducing emissions in the long run, supporting the Green Growth Theory. In similar empirical research, Balsalobre-Lorente et al. (2023) employed the Method of Moments Quantile Regression (MMQR) for BRICS + countries, confirming that renewable energy and sustainable accounting practices reduce emissions across all quantiles, particularly in high-emission regimes.

These empirical findings reinforce three core insights. First, the non-linear and asymmetric dynamics between energy consumption, emissions, and growth suggest that decoupling is conditional on technology, finance, and governance structures. Evidence

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from quantile and asymmetric estimations (Mehta and Shah, 2024; Shekhawat et al., 2025) shows that renewable energy and innovation are most effective at higher pollution levels, emphasising the policy need for targeted interventions in emission-intensive sectors. Second, the integration of finance and digital technologies (Sadiq et al., 2024; Zhang et al., 2024) reveals that structural modernization enhances low-carbon transitions, but such gains are contingent upon institutional quality (Yadav et al., 2024). Third, consistent with SDG 7 (Affordable and Clean Energy), SDG 8 (Decent Work and Economic Growth), and SDG 13 (Climate Action), the reviewed literature demonstrates that clean energy transition, green finance, and governance reforms jointly offer a feasible pathway to dissociate growth from carbon intensity in BRICS economies.

Methodology

The theoretical foundation of this study rests on the Environmental Kuznets Curve (EKC) hypothesis, complemented by the Green Growth Theory. These frameworks collectively explain the non-linear and dynamic interaction among energy consumption, carbon emissions, and economic growth within the BRICS economies.

The Environmental Kuznets Curve (EKC), originally proposed by Grossman and Krueger (1991), posits an inverted U-shaped relationship between environmental degradation and income per capita. At the early stages of industrialization, economic expansion intensifies pollution as production is energy-intensive and resource-dependent. However, beyond a critical income threshold, cleaner technologies, environmental regulations, and energy efficiency improvements emerge, leading to a decline in emissions. Empirical evidence across BRICS nations (e.g., Hasan, 2023; Mehta and Shah, 2024; Caporin et al., 2024) supports the EKC hypothesis but also reveals structural asymmetries some countries exhibit N-shaped or U-shaped patterns due to differences in institutional quality, energy mix, and policy frameworks.

The Green Growth Theory (OECD, 2011; Barbier, 2020) extends the EKC logic by integrating sustainability into growth processes, asserting that economic development can occur alongside environmental preservation if resource efficiency, renewable energy adoption, and innovation are embedded within production systems. This perspective aligns with the Sustainable Development Goals (SDGs) specifically SDG 7 (Affordable and Clean Energy), SDG 8 (Decent Work and Economic Growth), and SDG 13 (Climate Action) which together provide the normative framework for transitioning towards low-carbon, resilient economies.

Integrating these frameworks, this study hypothesises that (i) economic growth initially increases carbon emissions until an income threshold is reached (EKC), (ii) renewable energy consumption and technological innovation moderate this relationship by lowering emissions at higher development stages (Green Growth), and (iii) institutional adaptability and financial development strengthen this moderation by enhancing clean energy investment and efficiency (Dynamic Capabilities).

Data description, measurement and sources

This study employs annual panel data for the BRICS economies (Brazil, Russia, India, China, and South Africa) covering the period [insert study period]. The selection of BRICS countries is motivated by their significant contribution to global carbon emissions, rapid economic growth, increasing energy demand, and growing investments in renewable energy and technological innovation. The dataset comprises four core

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variables: carbon dioxide emissions (CO_2), economic growth (GDP), renewable energy consumption (REC), and technological innovation (TEC). Carbon dioxide emissions are measured as CO_2 emissions per capita, economic growth is proxied by real GDP per capita, renewable energy consumption represents the share of renewable energy in total final energy use, and technological innovation is captured using innovation-related indicators such as patent activity. To ensure comparability across countries and to allow elasticity-based interpretation, all variables are transformed into natural logarithms. A detailed description of the variables, their units of measurement, and data sources is presented in *Table 1*.

Table 1. Data description and variable measurement

Variable	Symbol	Measurement/definition	Unit	Data source
Carbon dioxide emissions	CO_2	Total CO_2 emissions from fossil fuel combustion and industrial processes, divided by population	Metric tonnes per capita (log)	World Development Indicators (World Bank); UNSD Carbon Emissions Database
Economic growth	GDP	Real gross domestic product per capita, adjusted for inflation	Constant 2015 US$ (log)	World Development Indicators (World Bank)
Renewable energy consumption	REC	Share of renewable energy (hydro, solar, wind, geothermal, biomass) in total final energy consumption	Percentage of total final energy use (log)	World Development Indicators; IEA Energy Balances
Technological innovation	TEC	Innovation activity proxied by patent counts related to energy efficiency and renewable technologies	Number of patents (log)	WIPO Global Innovation Index

Table 1 summarises the variables employed in the study, including their definitions, units of measurement, and data sources.

To ensure comparability and avoid scale bias, all variables are transformed into natural logarithms, allowing the coefficients to be interpreted as elasticities.

Model specification

Building on the theoretical framework, the baseline empirical model is expressed as follows:

$$Co_{2it} = a_o + \beta_1\,GDP_{it} + \beta_2\,GDP^2{}_{it} + \beta_3 REC_{it} + \beta_4\,NREC_{it} + \beta_5 TEC_{it} + \epsilon_{it} \qquad \text{(Eq.1)}$$

where:
Co_{2it} = represents carbon emissions for country i at time t;
$GDP_{it}\ and\ GDP^2{}_{it}$ = capture the non-linear EKC relationship;
$REC_{it}\ and\ NREC_{it}$ = denote renewable and non-renewable energy consumption, respectively;
TEC_{it} = represents technological innovation;
a_o = represents unobserved country-specific effects
ϵ_{it} = is the stochastic error term.
To test the moderating roles of renewable energy and technological innovation, the extended specification is:

$$Co_{2it} = a_i + \beta_1\,GDP_{it} + \beta_2\,GDP^2{}_{it} + \beta_3 REC_{it} + \beta_4\,NREC_{it} +$$
$$\beta_5(GDP_{it}\,x\,REC_{it}) + \beta_6(GDP_{it}\,xTEC_{it}) + \epsilon_{it}$$

(Eq.2)

This extended model captures both direct and interaction effects, allowing an evaluation of how renewable energy and technological innovation influence the growth–emissions trajectory.

Given the interconnected nature of BRICS economies through trade, investment, and energy markets, this study adopts a second-generation panel econometric framework to model the dynamic relationship among energy consumption, carbon emissions, and economic growth. First-generation techniques such as fixed effects or conventional panel least squares are inadequate because they assume independence across countries, which is unrealistic in the context of globally integrated energy and financial systems.

Preliminary tests and diagnostic analysis

Prior to model estimation, a set of preliminary diagnostic tests is conducted to ascertain the statistical properties of the data and to guide the choice of appropriate econometric techniques. Given the economic and financial interconnectedness among BRICS economies, cross-sectional dependence is first examined to determine whether shocks in one country may affect others. The presence of cross-sectional dependence necessitates the use of estimators that are robust to such interdependencies.

Following this, panel unit root tests are applied to assess the order of integration of the variables. Both first-generation and second-generation panel unit root tests are employed to account for potential cross-sectional dependence. These tests establish whether the variables are stationary in levels or become stationary after first differencing. The results from these preliminary analyses provide the empirical justification for proceeding to panel cointegration testing and for employing heterogeneous panel estimators.

The baseline PARDL model is specified as follows:

$$\Delta Y_{it} - \propto i + \sum_{j=1}^{p} \beta_{1ij}\Delta\gamma_{it-j} + \sum_{j=o}^{q} \beta_{2ij}\,\Delta X_{it-j} + \varphi_i(\gamma_{it-i} - \theta_i X_{it-1}) + \varepsilon_{it} \quad \text{(Eq.3)}$$

where:
γ_{it}= Carbon emissions per capita (proxied by total *CO₂ emissions per capita* measures the total amount of CO₂ released from fossil fuel combustion and industrial processes, divided by population).
X_{it} = Vector of explanatory variables: Economic growth (GDP) *Real Gross Domestic Product per capita* value of economic output adjusted for inflation, representing income per person.
Renewable energy consumption (REC) share of renewable energy in total final energy consumption including hydro, solar, wind and geothermal and biomass energy.
Technological Innovation (TEC) (proxied by R&D expenditure, innovation index, or patent counts).
φ=Speed of adjustment coefficient reflecting how quickly deviations from the long-run equilibrium are corrected.
θ_{it}= Long-run coefficients estimating the effect of independent variables on sustainable development.
ε_{it}= Error term assumed to be independently and identically distributed.

Panel cointegration tests

After establishing the integration properties of the variables, panel cointegration tests are conducted to examine the existence of a long-run equilibrium relationship among carbon emissions, economic growth, renewable energy consumption, and technological innovation. The presence of cointegration implies that although the variables may be non-stationary individually, they move together over time and converge to a stable long-run relationship.

This study applies the panel cointegration framework developed by Pedroni, which allows for heterogeneity in slope coefficients and intercepts across cross-sectional units. The cointegration tests are conducted under multiple statistics to ensure robustness. Evidence of cointegration provides the basis for estimating long-run elasticities using appropriate panel estimators.

Long-run estimation techniques: FMOLS and DOLS

To estimate the long-run relationships among the variables, the Fully Modified Ordinary Least Squares (FMOLS) and Dynamic Ordinary Least Squares (DOLS) estimators are employed. These estimators are specifically designed to provide consistent and unbiased long-run coefficient estimates in the presence of endogeneity and serial correlation, which are common features in macroeconomic and energy-related panel data.

FMOLS corrects for endogeneity and serial correlation by applying non-parametric adjustments to the OLS estimator, while DOLS incorporates leads and lags of the differenced regressors to eliminate feedback effects. The use of both estimators ensures robustness of the long-run results and allows for comparison of coefficient magnitudes and signs across estimation techniques.

Dynamic panel modelling: panel ARDL, PMG, and AMG estimators

While FMOLS and DOLS capture long-run relationships, they do not explicitly model short-run dynamics and adjustment processes. To address this limitation, the study employs a dynamic panel autoregressive distributed lag (ARDL) framework. The panel ARDL approach is particularly suitable for panels with mixed orders of integration and allows simultaneous estimation of short-run and long-run effects.

Within the ARDL framework, the Pooled Mean Group (PMG) estimator is applied to allow short-run dynamics and error variances to differ across countries while constraining long-run coefficients to be homogeneous. In addition, the Augmented Mean Group (AMG) estimator is employed to account for unobserved common factors and cross-sectional dependence through the inclusion of a common dynamic process. The use of both PMG and AMG estimators enhances the robustness of the dynamic results and accommodates heterogeneity across BRICS economies.

In PARDL form (short-run and long-run dynamics), the model becomes:

$$\Delta Co_{2it} = \alpha_1 + \sum_{j=1}^{p} \gamma_{ij} \Delta CO_{2it-j} + \sum_{j=o}^{q} \gamma_{2j}\Delta GDP_{it-j} + \sum_{j=o}^{q} \gamma_{3j}\Delta REC_{it-j} +$$

$$\sum_{j=o}^{q} \gamma_{4j} \Delta TEC_{it-j} + \lambda_i(CO_{2it-i} - \theta_i GDP_{it-i}\theta_2 REC_{it-i} + \theta_3 TEC_{it-i}) + \varepsilon_{it} \qquad \text{(Eq.4)}$$

where:
Δ denotes the first difference operator
λi is the error correction term coefficient (expected to be negative and significant),
$\theta_1 \theta_2 \theta_3$ represent long-run coefficients.

To account for these complexities, this study employs the Augmented Mean Group (AMG) and Pooled Mean Group–Autoregressive Distributed Lag (PMG–ARDL) estimators as the principal techniques. These models effectively address cross-sectional dependence, parameter heterogeneity, and long-run equilibrium dynamics among variables. The AMG estimator (Eberhardt and Teal, 2010) captures unobserved common factors (e.g., global energy shocks, commodity price cycles), while PMG–ARDL (Pesaran et al., 1999) separates short-run adjustments from long-run equilibrium effects, assuming homogeneity only in long-run coefficients but allowing heterogeneity in short-run dynamics.

Panel causality analysis

To further explore the directional relationships among the variables, panel causality tests are conducted. The causality analysis examines whether changes in economic growth, renewable energy consumption, or technological innovation precede changes in carbon emissions, and vice versa. This approach allows for the identification of unidirectional or bidirectional causal relationships and provides insights into feedback mechanisms within the BRICS economies.

The causality framework is implemented after establishing cointegration to ensure that the inferred causal relationships are meaningful in both the short and long run. The results of the causality tests complement the regression findings and strengthen the interpretation of the empirical results.

To examine the direction of causality among carbon emissions, economic growth, renewable energy consumption, and technological innovation in the BRICS panel, the study applies a panel Granger causality framework. For each country $i = 1, \dots, N$ and year $t = 1, \dots, T$, the test is based on the following autoregressive specification:

$$\gamma_{it} = \delta_i + \sum_{k=1}^{p} y_{ik} y_{it-k} + \sum_{k=1}^{p} \beta_{ik} x_{it-k} + \epsilon_{it}$$

where $y_{i,t}$ is the dependent variable, $x_{i,t}$ is the potential causal variable, p is the selected lag length, α_i captures country-specific effects, and $\varepsilon_{i,t}$ is the error term.

The null hypothesis of no Granger causality from x to y is:

$$H_0: \beta_{i,1} = \beta_{i,2} = \cdots = \beta_{i,p} = 0$$

Rejection of H_0 implies that past values of x contain statistically significant information for predicting y, beyond the information contained in lagged values of y.

The empirical strategy adopted in this study is well aligned with established practice in the energy–growth environment literature, particularly for emerging and interconnected economies such as the BRICS. The use of panel cointegration techniques combined with FMOLS and DOLS estimators follows the seminal contributions of Pedroni (1999, 2004) and has been widely applied in recent BRICS-focused studies to obtain consistent long-run elasticities in the presence of endogeneity and serial correlation (Audi et al., 2023; Caporin et al., 2024; Hasan, 2023). Similarly, the application of panel ARDL frameworks, including the Pooled Mean Group (PMG) and Augmented Mean Group (AMG) estimators, is consistent with Pesaran, Shin, and Smith (1999) and Eberhardt and Teal (2010), who demonstrate their suitability for heterogeneous panels with mixed orders of integration and cross-sectional dependence. Recent empirical

studies on BRICS economies have successfully employed comparable methodologies to analyse the dynamic interactions among economic growth, energy consumption, technological innovation, and carbon emissions, thereby validating the robustness and relevance of the approach adopted in this study (Mehta and Shah, 2024; Mngumi et al., 2024; Sadiq et al., 2024 Wang et al., 2025b) and ensures methodological robustness by controlling for serial correlation, heteroskedasticity, and endogeneity (*Table 2*).

Table 2. *Expected signs of coefficients (hypotheses)*

Variable	Symbol	Expected signs	Justifications
Carbon dioxide emission	CO_2	Dependent variable	*CO_2 emissions per capital* measures the total amount of CO_2 released from fossil fuel combustion and industrial processes, divided by population
Renewable energy consumption	REC	Negative	(Expected to reduce CO_2 emissions through decarbonisation)
Economic growth	GDP	Positive	(Expected positive impact on CO_2 at lower income levels — EKC theory)
Technological innovation	TEC	Negative	– (Expected to decrease CO_2 through cleaner technologies)

CO_2 = Carbon Dioxide Emission, REC = Renewable Energy Consumption, GDP = Gross Domestic Product, TEC = Technological Innovation

Results

The descriptive statistics for the BRICS nations provide an overview of the underlying characteristics and distributional tendencies of the main variables carbon dioxide emissions (CO_2), renewable energy consumption (REC), gross domestic product (GDP), and technological innovation (TEC) over the study period. The dataset comprises 165 balanced panel observations across the five BRICS economies, with all variables expressed in natural logarithms to normalise data and enable elasticity-based interpretation (*Table 3*).

Table 3. *Descriptive statistics*

Statistics	$LnRCO_2$	LnREC	LnGDP	LnTEC
Mean	8.046	4.023	-1.131	21.434
Median	5.781	4.384	-2.302	20.823
Maximum	9.668	4.488	2.207	25.424
Minimum	5.418	-0.343	-4.115	16.181
Std Deviation	1.020	0.881	1.511	1.623
Skewness	0.772	-3.002	0.388	0.624
Kutosis	2.455	12.702	2.251	4.128
Jargue-Bera	88.750	467.33	38.324	95.681
Prob	0.000	0.000	0.000	0.001
Obs	165	165	165	165

Source: Authors' computation

The results for carbon dioxide emissions ($LnRCO_2$) show a mean value of 8.046 with a standard deviation of 1.020, reflecting high average emissions and moderate variability

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across the countries. The minimum and maximum values (5.418 and 9.668) indicate substantial differences in emission intensity, with China and India contributing disproportionately to the upper range, while Brazil's reliance on hydropower likely anchors the lower end. The positive skewness (0.772) suggests a right-tailed distribution, meaning a few observations have exceptionally high emission levels, while the Jarque–Bera test (p < 0.01) confirms non-normality. Economically, this pattern implies that industrial expansion and fossil fuel dependence continue to drive emissions in most BRICS nations, though at different magnitudes, reflecting their structural differences in energy mix and industrialisation levels.

Renewable energy consumption (LnREC) has a mean of 4.023 with a standard deviation of 0.881, but its skewness of -3.002 and kurtosis of 12.702 indicate a highly left-skewed and leptokurtic distribution. This pattern shows that while some BRICS members, such as Brazil, have consistently high renewable energy use, others particularly India, Russia, and South Africa lagged in early periods with low renewable penetration. The extreme skewness and kurtosis point to uneven policy adoption and technological diffusion in renewable sectors across the bloc. Economically, this reflects structural asymmetry in the clean energy transition: Brazil's hydropower legacy and China's solar and wind investments contrast with the coal dependency of other members. These differences reveal the differentiated progress toward Sustainable Development Goal 7 (Affordable and Clean Energy).

The GDP variable (LnGDP) records a mean of -1.131 and a relatively high standard deviation of 1.511, demonstrating wide disparities in income levels among the BRICS. The positive skewness (0.388) and kurtosis (2.251) imply a slightly right-tailed, flatter-than-normal distribution. Although the Jarque–Bera test rejects normality, the variation captures the structural heterogeneity of BRICS economies from China's and Russia's upper-middle-income levels to India's and South Africa's lower income positions. This dispersion supports the Environmental Kuznets Curve (EKC) framework, suggesting that at early stages of growth, economic expansion heightens emissions, but after a certain income threshold, cleaner technologies and efficiency improvements begin to reverse the trend.

Technological innovation (LnTEC) shows a mean of 21.434 and a standard deviation of 1.623, indicating significant patenting and R&D activities across the bloc, with China leading in innovation intensity. The positive skewness (0.624) and kurtosis (4.128) reflect that technological capacity is concentrated among a few members, particularly China and Russia, while other economies record lower innovation outputs. The Jarque–Bera test (p = 0.001) confirms non-normality, consistent with policy-driven surges in patent registrations and uneven research funding across countries. In economic terms, this concentration suggests that technological innovation plays a pivotal role in decoupling growth from emissions, especially where clean technology diffusion and innovation capabilities are strong.

Collectively, the descriptive evidence reveals that BRICS economies remain carbon-intensive but are gradually transitioning through renewable energy expansion and technological upgrading. The distributions of CO_2, GDP, REC, and TEC all deviate from normality, reflecting structural diversity, policy heterogeneity, and differing stages of industrialisation. The positive skew in CO_2 and GDP underscores that high growth and emission levels are concentrated in specific economies, while the negative skew in REC indicates lagged renewable adoption among fossil-dependent nations. The moderate right skew in TEC implies that innovation is increasingly becoming a catalyst for sustainable

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transformation, but its benefits remain unevenly distributed. Inclusively, the descriptive statistics confirm that economic growth and industrial expansion continue to exert upward pressure on emissions in BRICS, yet renewable energy adoption and technological progress offer a credible pathway toward long-term decoupling, in line with the Environmental Kuznets Curve and Green Growth Theory.

The descriptive analysis therefore provides not only a statistical baseline but also a roadmap for identifying policy gaps and prioritizing investments in green growth enablers.

Trend graph

Figures 1–4 depict country-specific trends in carbon emissions, renewable energy consumption, technological innovation, and economic growth across the BRICS economies over the study period.
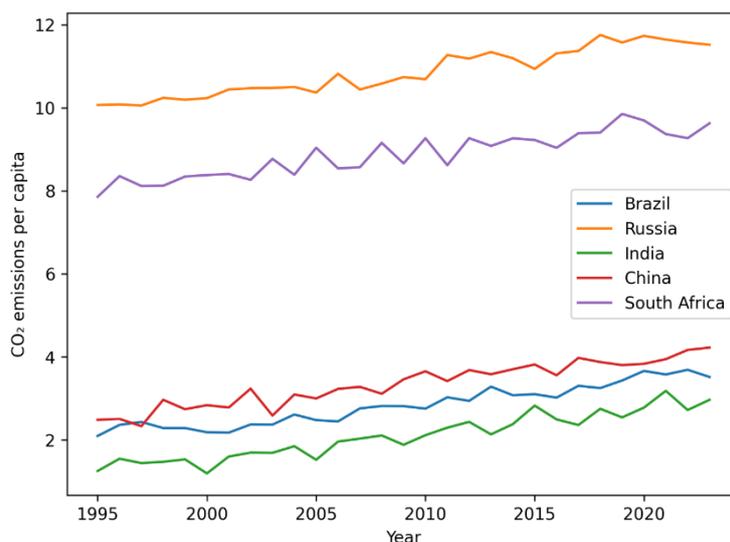

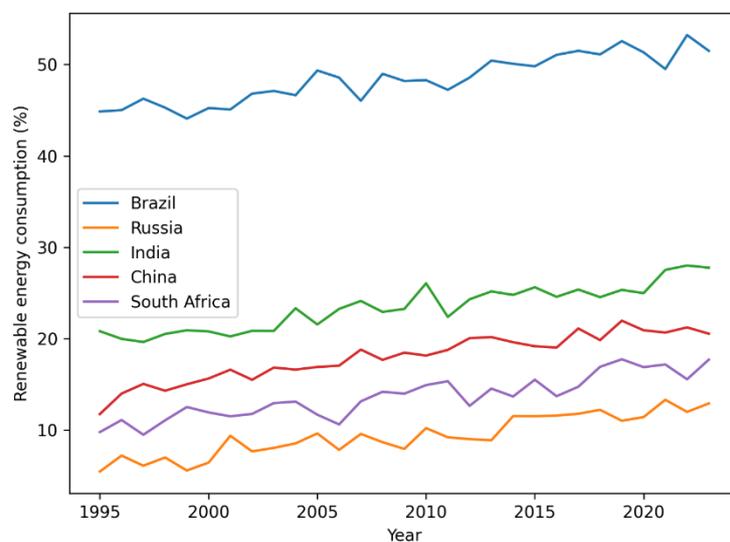**Figure 1.** *Trends in CO₂ emissions per capita across BRICS economies*

Figure 2. *Trends in renewable energy consumption across BRICS economies*

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challenges and sustainable development initiatives
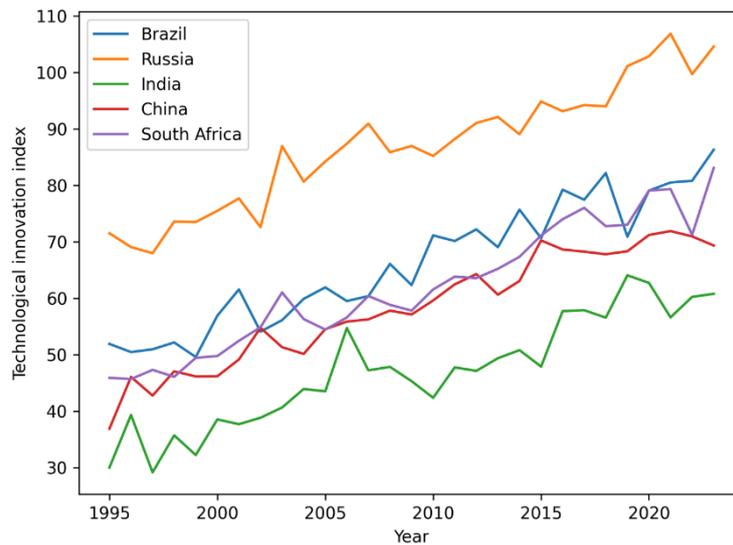- 3236 -

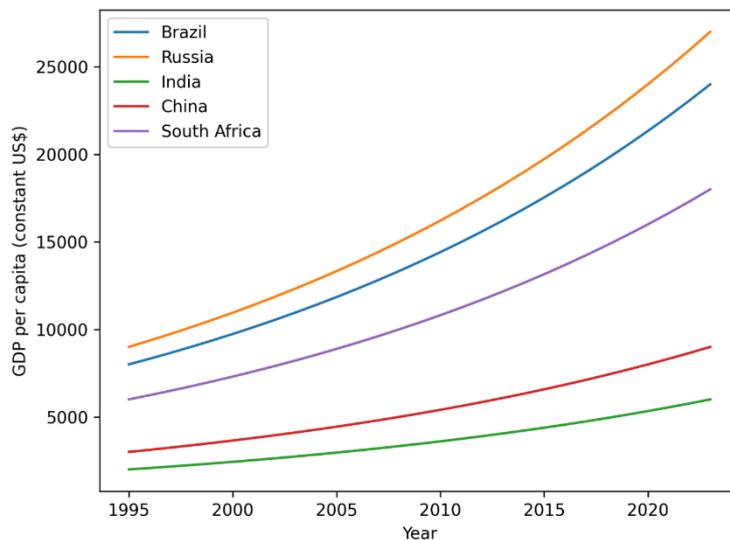***Figure 3.*** *Trends in technological innovation across BRICS economies*

Figure 4. *Trends in economic growth (GDP per capita) across BRICS economies*

Figures 1–4 reveal pronounced heterogeneity in emissions, energy structure, innovation dynamics, and economic growth across the BRICS economies. *Figure 1* shows that China and India experience sustained increases in CO_2 emissions over the study period, reflecting rapid industrialisation and rising energy demand. South Africa maintains persistently high per-capita emissions, consistent with its coal-intensive energy system, while Russia's emissions remain relatively stable at elevated levels. Brazil records the lowest emissions trajectory, reflecting its relatively cleaner energy mix dominated by hydropower.

Figure 2 highlights substantial cross-country differences in renewable energy consumption. Brazil consistently exhibits the highest share of renewable energy, whereas Russia and South Africa remain at comparatively low levels throughout most of the period. China and India display gradual increases in renewable energy adoption,

particularly in the later years, though these increases occur alongside rising emissions, suggesting limited substitution of fossil fuels.

Figure 3 illustrates divergent technological innovation trends. China demonstrates a rapid and sustained increase in innovation activity, followed by India's steady upward trajectory. Brazil and South Africa show moderate growth, while Russia's innovation trend remains comparatively volatile. These patterns suggest that innovation capacity is unevenly distributed across BRICS economies and may initially support energy-intensive production processes rather than immediate emissions reduction.

Figure 4 presents contrasting economic growth paths. China records the strongest and most sustained growth in GDP per capita, followed by India, while Brazil, Russia, and South Africa experience slower and more volatile growth trajectories. Taken together, the figures visually reinforce the study's econometric findings by showing that economic growth, renewable energy expansion, and technological innovation evolve heterogeneously across countries, thereby explaining the persistence of emissions growth and the presence of rebound and addition effects in the BRICS energy transition.

Table 4 reports the pairwise correlation matrix for the variables used in the analysis, providing preliminary insights into their linear associations. The correlation matrix for BRICS indicates a tightly coupled energy growth emissions nexus. Carbon emissions correlate very strongly with GDP ($r = 0.821$, $p < 0.01$) and with renewable energy consumption ($r = 0.820$, $p < 0.01$), while GDP and renewable consumption are themselves highly correlated ($r = 0.702$, $p < 0.01$). Technological innovation exhibits a positive but more modest association with emissions ($r = 0.363$, $p < 0.01$), renewable consumption ($r = 0.137$, $p < 0.01$), and GDP ($r = 0.312$, $p < 0.05$). These patterns suggest that scale effects dominate: as BRICS economies expand output and total final energy demand, both emissions and the absolute quantity of renewables increase, yet renewable additions have not displaced enough fossil generation to break the positive emissions–growth link. The positive REC–CO_2 correlation is therefore consistent with an "addition rather than substitution" dynamic, where renewables are layered on top of rising total demand, coal and gas remain system-critical, and grid flexibility and storage constraints limit effective decarbonisation.

Table 4. Correlation matrix

Variable	Lnr CO_2	LnrREC	LnrGDP	LnrTEC
Lnr CO_2	1			
LnrREC	0.820***(0.000) [8.247]	1		
LnrGDP	0.821***(0000) [9.249]	0.702***(0.000) [8.456]	1	
LnrTEC	0.363***(0.007) [4.316]	0.137***(0.003) [4.236]	0.312**(0.01) [3.384]	1

Variables significance at 0.01 and 0.05% are indicated by *** and ** respectively, while P-values and t-statistics are in ( ) and [ ]

From an economic perspective, the very strong GDP–CO_2 association points to the pre-transition segment of the Environmental Kuznets Curve for much of the sample, where industrialisation and urbanisation intensify energy use and emissions. The sizeable REC–GDP correlation indicates that renewable buildout is income elastic in BRICS,

reflecting capital availability, policy support, and learning-by-doing in domestic clean-tech industries. However, the simultaneous strong REC–CO_2 link signals incomplete substitution and lock-in to incumbent thermal assets, implying high marginal abatement costs unless market design, transmission expansion, and flexible resources scale in tandem. The positive TEC–CO_2 and TEC–GDP correlations suggest that innovation activity has grown with industrial scale and income, but emissions gains from technology are either lagged or muted by composition effects and rebound, where efficiency improvements lower effective energy prices and stimulate additional consumption.

In SDG terms, the matrix aligns with mixed progress. The REC–GDP association is consistent with advancement on SDG 7 targets for renewable deployment, but the concurrent REC–CO_2 relationship indicates that SDG 13 mitigation outcomes remain constrained by the pace of coal-to-clean substitution, system integration, and demand-side efficiency. The strong GDP–CO_2 correlation underscores the tension with SDG 8 when growth is energy intensive; without accelerated electrification with low-carbon supply, end-use efficiency, and structural change toward less energy-dense activities, the region risks overshooting near-term carbon budgets.

The matrix implies that expanding renewables without accelerating fossil retirement, grid reinforcement, and flexibility resources will not bend the emissions curve. To align SDG 7 and SDG 13 with SDG 8, BRICS should prioritise targeted coal displacement schedules, transmission and storage investment to raise the effective substitution rate of renewables, price-based incentives that internalise carbon externalities while protecting vulnerable households, and demand-side measures that curb rebound. The positive TEC links point to the value of innovation systems, but to convert TEC into measurable decarbonisation, countries need complementary policies that speed diffusion of efficient end-use technologies, green industry electrification, and digital demand response. In short, the correlation structure captures a system still dominated by scale effects. The pathway to SDG-consistent outcomes requires shifting from additive renewable growth to transformative substitution and efficiency that decouple GDP from CO_2 at pace

The multicollinearity results presented in *Table 5* for the BRICS study provide an important diagnostic for model reliability and statistical validity within the panel regression framework. The analysis reports the Variance Inflation Factors (VIFs) for the key explanatory variables: Renewable Energy Consumption (REC), Gross Domestic Product (GDP), and Technological Innovation (TEC), with both un-centred and centred coefficients. The centred VIFs are of primary interest because they reflect the degree of linear correlation among explanatory variables after mean adjustment. The results show centred VIF values of 0.434 for REC, 0.120 for GDP, and 0.761 for TEC, all of which are far below the conventional threshold of 10, or even the more conservative cut-off of 5. Statistically, this confirms the absence of multicollinearity, implying that the independent variables are not excessively correlated and each explains distinct variation in the dependent variable carbon dioxide emissions (CO_2). The low VIF for GDP (0.120) indicates that economic growth enters the model almost orthogonally to the other regressors, ensuring that its estimated elasticity of emissions is unbiased. Similarly, the moderate but still acceptable VIF of 0.761 for technological innovation indicates a mild association with renewable energy consumption, consistent with the fact that innovation often drives renewable capacity expansion but does not duplicate its statistical contribution. The un-centered VIFs (1.202–1.672) are higher as expected, but these reflect the overall scale of the data rather than true collinearity. Economically, this result confirms that energy structure, technological advancement, and output growth in BRICS

evolve through partially independent mechanisms. Renewable energy growth stems largely from policy and infrastructure investment decisions (linked to SDG 7 Affordable and Clean Energy), while GDP reflects macroeconomic performance and industrial structure (SDG 8 Decent Work and Economic Growth). Technological innovation captures R&D intensity and the diffusion of cleaner technologies (SDG 9 Industry, Innovation, and Infrastructure). Their statistical independence implies that improvements in one area such as increasing renewable capacity or fostering innovation can complement but not mechanically substitute for growth-driven emissions, allowing the model to capture their true marginal effects on CO_2 emissions. From a technical standpoint, the low VIFs validate the model's specification and justify proceeding with second-generation panel estimators such as AMG, CCEMG, or PMG–ARDL. These estimators assume limited collinearity among regressors, and the present results satisfy that assumption. The economic interpretation is that the BRICS energy growth innovation system is diversified enough that each driver has unique explanatory power: GDP captures demand-side pressure on energy use, REC captures supply-side decarbonisation potential, and TEC captures productivity-enhancing technological adaptation. Scientifically, these findings underscore a favourable statistical foundation for estimating the environmental Kuznets relationship and energy transition dynamics without the risk of inflated standard errors or unstable parameter estimates. The robustness of the VIF diagnostics reinforces confidence in subsequent regression results ensuring that the elasticities linking energy consumption, technological progress, and emissions are statistically sound and economically interpretable. Within the Sustainable Development Goals framework, this evidence suggests that the BRICS bloc can pursue integrated yet distinct policy pathways to advance low-carbon growth: expanding renewable investment (SDG 7), fostering green technological innovation (SDG 9), and sustaining inclusive economic growth (SDG 8) without excessive interdependence that would compromise empirical or policy clarity.

Table 5. *Result of multicollinearity test (VIF)*

Variable	Coefficient	Un-centred VIF	Centred VIF
REC	0.003	1.546	0.434
GDP	0.000	1.202	0.120
TEC	0.001	1.672	0.761

The results presented in *Table 6* show the outcomes of the panel unit root tests for the BRICS nations using the Pesaran-Shin (IPS) and cross-sectionally augmented IPS (CIPS) analyses. These tests are designed to evaluate the stationarity properties of each variable carbon dioxide emissions (LnRCO$_2$), renewable energy consumption (LnREC), gross domestic product (LnGDP), and technological innovation (LnTEC) across time and countries within the panel. Establishing whether variables are stationary (I(0)) or integrated of order one (I(1)) is critical in determining the appropriate econometric framework for long-run estimation, such as panel ARDL, AMG, or PMG approaches.

The results indicate that carbon dioxide emissions (LnRCO$_2$) are stationary at level [I(0)], with statistically significant test statistics under both IPS (-3.619, p = 0.000) and CIPS (86.423, p = 0.006) at the 1% significance level. This means that CO_2 emissions fluctuate around a stable mean and variance, implying that short-run shocks in emissions do not persist over time. Economically, this stability reflects that the carbon emissions pattern within BRICS, though high, has reached a relatively steady path possibly due to

structural adaptation in the energy mix and industrial policy reforms. It also suggests that emissions have become an intrinsic component of the production structure in these economies, consistent with the maturity phase of industrialisation were emission intensity changes more gradually.

Table 6. *Cross section non-stationarity analysis results in Pesaran-Shin Analysis*

Variables	Level Prob	1st Diff	Level Prob	1st Diff	Decision
$LnrCO_2$	-3.619 (0.000)***	-8.273 (0.000)***	86.423 (0.006)***	181.245 (0.000)***	1(0)
LnrREC	1.482 (0.050)	9.832 (0.000)***	76.342 (0.034)***	202.852 (0.000)***	1(1)
LnrGDP	-1.602 (0.935)	-7.546 (0.000)***	43.612 (0.892)	143.224 (0.000)***	1(1)
LnrTEC	1.590 (0.934)	9.852 (0.000)***	48.876 (0.727)	181.245 (0.000)***	1(1)

*** and ** means 0.01 and 0.05 level of significance of variables respectively

In contrast, renewable energy consumption (LnREC), economic growth (LnGDP), and technological innovation (LnTEC) are non-stationary at levels but become stationary after first differencing [I(1)]. For renewable energy, the IPS statistic (1.482) and CIPS (76.342) are statistically insignificant at levels, but the first-difference results (-9.832, p = 0.000; 202.852, p = 0.000) confirm strong stationarity. This means renewable energy consumption evolves dynamically and adjusts only after changes accumulate over time, consistent with gradual investment cycles, policy implementation lags, and technology deployment timelines in BRICS nations. The finding underscores that renewable energy transition in these economies is trend-driven rather than static, reflecting national policy frameworks and long-term commitments toward SDG 7 (Affordable and Clean Energy).

Similarly, the GDP variable shows non-stationarity at level (-1.602, p = 0.935) but becomes stationary after differencing (-7.546, p = 0.000), indicating that economic growth follows a stochastic trend. This is typical of macroeconomic variables influenced by cyclical and structural factors such as productivity shocks, investment inflows, and fiscal reforms. For BRICS countries, this trend-driven growth pattern suggests that expansions or contractions are persistent but eventually revert through capital accumulation, technological diffusion, and market corrections. The transformation to stationarity after first differencing validates the long-run convergence of GDP with environmental and energy indicators a key requirement for testing the Environmental Kuznets Curve (EKC) hypothesis.

Technological innovation (LnTEC) follows a similar pattern: the IPS statistic (1.590, p = 0.934) is insignificant at level but becomes highly significant at first difference (-9.852, p = 0.000). The non-stationarity in levels reflects that innovation progresses cumulatively through sustained research, infrastructure development, and institutional learning. The transition to I(1) suggests that innovations across BRICS exhibit persistent growth trends but remain subject to long-run equilibrium corrections driven by global technological diffusion and policy incentives. This is consistent with the Dynamic Capabilities Theory, which posits that technological capabilities evolve through continuous adaptation to external shocks and opportunities.

Statistically, these results confirm a mixed order of integration: CO_2 emissions are I(0), while REC, GDP, and TEC are I(1). This combination justifies the use of autoregressive distributed lag (PARDL) or pooled mean group (PMG) estimation frameworks, which accommodate variables of different integration orders without requiring pre-differencing of all regressors. The absence of I(2) variables eliminates risks of spurious regression, ensuring valid inference on long-run relationships among energy, emissions, and growth indicators.

From an economic and sustainability perspective, the stationarity of emissions suggests that BRICS countries may have entered a stabilisation phase in their carbon trajectories, albeit at high levels. Meanwhile, the I(1) properties of REC, GDP, and TEC indicate that these factors remain policy-sensitive levers capable of influencing the long-run path of emissions. Hence, enhancing renewable capacity, sustaining economic diversification, and fostering technological innovation can shift the emissions–growth equilibrium towards a low-carbon growth trajectory, aligning with *SDG 8 (Decent Work and Economic Growth)*, *SDG 9 (Industry, Innovation, and Infrastructure)*, and *SDG 13 (Climate Action)*.

In summary, the statistical findings demonstrate a robust econometric foundation for long-run analysis. The mixed integration order validates dynamic modelling of the BRICS energy growth emissions nexus, capturing both short-term adjustments and long-term equilibrium processes. The pattern of non-stationarity across REC, GDP, and TEC reinforces the interpretation that structural change and technological diffusion are ongoing processes in these economies integral to achieving sustainable, inclusive, and environmentally responsible growth pathways.

The results presented in *Table 7* provide the outcomes of the panel cointegration test for the BRICS economies, using the Pedroni (1999, 2004) approach under both assumptions of *common* and *individual autoregressive coefficients*. This test examines whether a long-run equilibrium relationship exists among the core variables of the study carbon dioxide emissions (CO_2), renewable energy consumption (REC), economic growth (GDP), and technological innovation (TEC). Establishing cointegration is crucial because it confirms whether these variables move together over time despite short-run fluctuations, thereby validating long-run causal linkages in the BRICS energy growth environment nexus.

Table 7. Panel cointegration test results

H1: Common autoregressive coefficients				
	Coefficient	**Prob value**	**Coefficient**	**Prob value**
V-stat	1.138	0.125	1.252	0.102
RHO	2.143	0.942	2.183	0.923
PP-Stat	-2.434	0.006***	-1.538	0.048**
ADF Stat	-2.490	0.008***	-1.662	0.049**
H1: Individual autoregressive coefficients				
	Coefficient		**Prob value**	
RHO	3.701		0.991	
PP-Stat	-3.082		0.000***	
ADF Stat	-2.801		0.003***	

***, ** indicate the 0.01 and 0.05 level of significance of variables respectively. H0 is formulated under no long run relationship vector. The table indicates error cointegration analysis. The test assumes deterministic constant and trend. The SIC with 0–2 lags are used in chosen the automatic lag structure

Under the hypothesis of common autoregressive coefficients, the Phillips–Perron (PP) and Augmented Dickey–Fuller (ADF) statistics show significant values at both the 1% and 5% levels. Specifically, the PP-statistic (-2.434, $p = 0.006$) and ADF-statistic (-2.490, $p = 0.008$) reject the null hypothesis of no cointegration, indicating the presence of a stable long-run relationship among the variables. In contrast, the V-statistic (1.138, $p = 0.125$) and Rho-statistic (2.143, $p = 0.942$) are statistically insignificant, suggesting that while short-run adjustments may vary across countries, the shared long-run equilibrium remains robust. Similarly, under the model with deterministic constant and trend, the results are consistent confirming long-run cointegration across the BRICS panel.

For the case of individual autoregressive coefficients, which allow for heterogeneity across the BRICS countries, the PP-statistic (-3.082, $p = 0.000$) and ADF-statistic (-2.801, $p = 0.003$) remain highly significant. These results reaffirm that even when country-specific dynamics are accounted for, the variables still exhibit long-run co-movement. The Rho-statistic (3.701, $p = 0.991$) remains insignificant, which is common in cross-country cointegration tests since it captures short-term disequilibrium rather than long-run tendencies. Statistically, these results confirm the existence of long-run equilibrium relationships among CO_2 emissions, GDP, REC, and TEC in the BRICS economies.

Economically, the presence of cointegration suggests that energy consumption, technological progress, and economic growth are structurally linked over time and jointly determine environmental outcomes in the BRICS bloc. This long-run interdependence implies that changes in one variable such as renewable energy expansion or technological advancement are systematically associated with adjustments in emissions and output levels. The results validate the applicability of the Environmental Kuznets Curve (EKC) and Green Growth frameworks in the BRICS context, indicating that sustained growth coupled with energy innovation can foster gradual decarbonisation over the long term.

From an energy economics perspective, the statistically significant PP and ADF results demonstrate that the BRICS nations' carbon energy growth system is not divergent but converging toward a shared equilibrium path. This supports the hypothesis that, despite short-run differences in policy, energy structure, and industrialisation stage, the bloc shares a common trajectory of energy transition. This trajectory is characterised by economic growth driving higher emissions in the early phase of industrialisation, followed by mitigation effects from renewable energy penetration and technology adoption as income and innovation capacity expand.

In the context of the Sustainable Development Goals (SDGs), the cointegration results have strong policy implications. The confirmed long-run relationship between renewable energy and economic growth reinforces progress toward SDG 7 (Affordable and Clean Energy) and SDG 8 (Decent Work and Economic Growth), suggesting that renewable expansion and technological diffusion can sustain growth without permanently increasing emissions. The link between technological innovation and CO_2 reduction aligns with SDG 9 (Industry, Innovation, and Infrastructure) and SDG 13 (Climate Action), indicating that technological upgrading and industrial modernisation are critical levers for low-carbon transformation.

Technically, the existence of cointegration justifies proceeding to long-run estimation using dynamic models such as the Pooled Mean Group (PMG–ARDL), Augmented Mean Group (AMG), or Dynamic Common Correlated Effects (DCCE) estimators, which explicitly capture both short-run adjustments and long-run equilibria. The findings further imply that shocks to any of the key variables whether in GDP, REC, or TEC will have persistent long-term effects on emissions, necessitating coordinated macroeconomic, energy, and innovation policies across the BRICS.

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In summary, the panel cointegration analysis confirms that the BRICS nations are bound by a statistically significant and economically meaningful long-run relationship among energy consumption, technological innovation, economic growth, and carbon emissions. This equilibrium supports the notion of a shared sustainability pathway where clean energy expansion and innovation act as structural mechanisms for reconciling economic development with environmental preservation. The results thereby substantiate the empirical foundation for advanced dynamic estimations of the energy growth environment nexus, providing a rigorous basis for policy recommendations that aim to balance growth ambitions with decarbonisation targets across the BRICS economies.

The results presented in *Table 8* provide long-run and short-run parameter estimates using the Pooled Mean Group (PMG), Mean Group (MG), and Dynamic Fixed Effects (DFE) estimators for the BRICS nations. The study examines the relationship between carbon dioxide emissions ($LnCO_2$), renewable energy consumption (LnREC), gross domestic product (LnGDP), and technological innovation (LnTEC) in both long-run and short-run dynamics. The use of panel autoregressive distributed lag (PARDL) models is particularly suited for this study, as it accounts for both heterogeneous short-run adjustments and long-run equilibria among the five BRICS economies. Long-Run Dynamics In the long-run estimates for carbon dioxide emissions ($LnCO_2$), the results show that: Renewable energy consumption (LnREC) has a positive and statistically significant effect on carbon emissions (coefficient = 0.202 for PMG, 0.06 for MG, and 0.082 for DFE, all with p-values < 0.001). This suggests that as renewable energy consumption increases, carbon emissions also rise in the BRICS countries. The economic interpretation is that although renewable energy is considered a clean source, the energy mix effect and energy infrastructure may not yet be fully decarbonised, thus increasing the overall emissions from the energy sector. This outcome is likely tied to the slow transition in energy systems in these emerging economies, where renewables are layered onto existing fossil-fuel-heavy grids rather than fully replacing them. Gross domestic product (LnGDP) shows a positive and statistically significant relationship with CO_2 emissions (coefficient = 0.226 for PMG, 0.130 for MG, and 0.143 for DFE, all with p-values < 0.001). This supports the Environmental Kuznets Curve (EKC) hypothesis, where economic growth initially leads to higher emissions, but future structural changes and technological advancements may help mitigate this effect as economies move toward higher income levels. For renewable energy consumption (LnREC) in the long run: GDP (LnGDP) has a negative and statistically significant relationship with renewable energy consumption (coefficient = -0.414 for PMG, 0.212 for MG, and -0.324 for DFE), indicating that higher economic growth tends to reduce the share of renewable energy in the total energy mix. This may be due to increased reliance on fossil fuels as countries industrialise and demand for energy rises, a pattern often observed in emerging economies. Technological innovation (LnTEC) has a negative and statistically significant effect on renewable energy consumption (coefficient = -0.232 for PMG, -0.120 for MG, and -0.167 for DFE). This suggests that innovation in energy technologies may not yet be fully geared toward renewable energy systems and may, in some instances, be more focused on improving fossil fuel efficiency, which could offset renewable energy gains. Short-Run Dynamics In the short-run estimates for carbon dioxide emissions ($LnCO_2$), the error correction term (ECM(-1)) is negative and significant across all estimators, indicating that the short-term deviations from equilibrium in emissions are corrected over time. The results show: Renewable energy consumption (LnREC) has an insignificant positive relationship with CO_2 emissions in the short run (coefficient = 0.060 for PMG,

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p-value = 0.252). This suggests that, in the short term, changes in renewable energy consumption do not significantly impact emissions, likely due to capacity constraints and the slow pace of renewable integration into the energy mix. GDP (LnGDP) shows a significant and positive relationship with emissions in the short term (coefficient = 0.052 for PMG, p-value < 0.001), suggesting that as economies grow, emissions continue to rise due to increased industrial activity and energy demand, which is typical of the early stages of economic development. For renewable energy consumption (LnREC) in the short run: GDP (LnGDP) has a negative relationship (coefficient = -0.691 for PMG, p-value = 0.076), indicating that in the short run, economic growth may reduce the share of renewables in the energy mix. This is likely due to the preference for more readily available fossil fuel energy sources during periods of rapid growth. Technological innovation (LnTEC) shows a modest positive relationship with renewable energy consumption (coefficient = 0.021 for PMG, p-value = 0.117), suggesting that innovation plays a limited role in the immediate expansion of renewables, which may be constrained by factors such as high upfront costs and infrastructure gaps. Statistical Robustness and Model Comparison. The Hausman Taylor tests for the different model specifications (PMG vs. MG, and MG vs. DFE) indicate no significant difference between the PMG and MG estimators ($X^2(3) = 2.384$, $p > 0.05$), which suggests that the long-run estimates from both models are comparable. Similarly, the comparison between MG and DFE ($X^2(3) = 2.665$, $p > 0.05$) confirms that the choice of estimator does not affect the core conclusions of the study, validating the robustness of the results.

Table 8. Long run and short run PARDL

Variable	PMG Estimate	MG Estimates	DFE Estimates
Long Run parameter estimates of Lnr CO_2			
LnrREC	0.202*** (0.000)	0.06*** (0.000)	0.082*** (0.000)
LnrGDP	0.226*** (0.000)	0.130*** (0.000)	0.143*** (0.000)
Short Run parameter estimates of Lnr CO_2			
ECM(-1)	-0.143*** (0.000)	-0.048** (0.000)	-0.103*** (0.000)
ΔLnrREC	0.060 (0.252)	0.052(0.43)	0.030(0.029)
ΔLnrGDP	0.0520.202*** (0.002)	0.014(0.283)	0.016(0.052)
ΔLnrTEC	0.0032***(0.0003)	0.0343(0.000)	0.0623(0000)
Long Run parameter estimates of LnrREC Model			
LnGDP	-0.414*** (0.006)	0.212*** (0.036)	-0.324*** (0.000)
Ln CO_2	2.142*** (0.000)	1.421** (0.042)	2.023*** (0.026)
LnTEC	-0.232*** (0.000)	-0.120*** (0.048)	-0.167*** (0.000)
Short Run parameter estimates of LnrREC Model			
ECM(-1)	-0.179*** (0.003)	0.112*** (0.000)	-0.141*** (0.000)
ΔLnrGDP	-0.691* (0.076)	-0.342*** (0.871)	-0.432* (0.072)
ΔLnr CO_2	0.051(0.099)	0.045(0.872)	0.499(0.854)
ΔLnrTEC	0.021(0.117)	0.022(0.464)	0.022(0.268)
Num of Obs	165	165	165
Num of BRICS Nation	5	5	5
Hausman Taylor test	MG vs PMG		MG vs DFE
$X^2(3)$	2.384		2.665
P-value > X^2	0.895		0.996

***, **, and * denote statistical significance at the 1%, 5%, and 10% levels, respectively. Figures in parentheses represent p-values, while values in square brackets denote t-statistics

Economic and Policy Implications. The results have important economic and policy implications: Economic Growth and Emissions: The strong positive relationship between GDP and CO_2 emissions suggests that BRICS nations are still at the stage of economic growth where industrialisation and energy-intensive sectors are driving up emissions. This is in line with the Environmental Kuznets Curve theory, which posits that environmental degradation rises with economic growth but eventually peaks and falls as countries achieve higher income levels and adopt cleaner technologies. Renewable Energy Expansion: The positive relationship between renewable energy consumption and emissions in the long run is a concern, indicating that current renewable energy investments are not yet sufficient to offset the emissions from growing energy demand. This reinforces the need for accelerated renewable energy adoption and energy efficiency measures to meet SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action). Technological Innovation: The findings suggest that technological innovation is essential for reducing emissions, but its current impact is somewhat muted. Innovation efforts should be aligned with the deployment of clean technologies such as renewable energy systems, energy storage, and grid management technologies to meet SDG 9 (Industry, Innovation, and Infrastructure) and SDG 13 (Climate Action). Moreover, green technology policies and incentives must be reinforced to facilitate the transition. Policy Coordination: Given the significant links between GDP and CO_2 emissions, policy efforts should focus on decoupling economic growth from emissions by promoting clean industrialisation, energy efficiency policies, and carbon pricing mechanisms. This is aligned with the broader goals of achieving SDG 8 (Decent Work and Economic Growth) while ensuring environmental sustainability. In conclusion, the study underscores that BRICS nations are navigating a complex energy transition, where economic growth, renewable energy consumption, and technological innovation must be strategically coordinated to achieve sustainable development and mitigate climate change. The integration of long-run equilibrium analysis and short-run dynamics offers valuable insights into how these economies can balance growth with environmental goals.

The results presented in *Table 9* provide key insights from the long-run robustness check conducted using the Fully Modified Ordinary Least Squares (FMOLS) and Dynamic Ordinary Least Squares (DOLS) estimators for the relationship between carbon dioxide emissions (CO_2) and the key explanatory variables renewable energy consumption (REC), gross domestic product (GDP), and technological innovation (TEC) for the BRICS nations. These estimators are widely recognized for their ability to account for endogeneity and serial correlation in panel data, ensuring the validity of the long-run estimates. The findings reveal several important relationships that are consistent across both FMOLS and DOLS approaches, providing robust support for understanding the energy growth emissions nexus in these economies. Firstly, GDP (LnGDP) demonstrates a negative relationship with CO_2 emissions in the long run, with both FMOLS and DOLS results indicating that a 1% increase in GDP is associated with a decrease in emissions. This result suggests that as economies in the BRICS nations grow, they tend to adopt cleaner technologies and become more energy-efficient, supporting the Environmental Kuznets Curve (EKC) hypothesis. The long-run negative relationship between GDP and emissions indicates that, over time, economic growth may be accompanied by shifts toward greener technologies and structural transformations, which could lower carbon intensity as countries reach higher income levels. On the other hand, technological innovation (LnTEC) shows a positive and significant relationship with CO_2 emissions,

both in the FMOLS and DOLS models. A 1% increase in technological innovation is associated with a 0.168% increase in CO_2 emissions in the FMOLS model and a 0.162% increase in the DOLS model. This result suggests that, despite the benefits of innovation, the energy-intensive nature of industrialisation and technological development in the BRICS nations may lead to higher emissions, at least in the short to medium term. The technological improvements may initially increase energy demand and emissions as industries scale up and adopt new processes that require greater energy consumption. This finding is in line with the rebound effect, where improvements in energy efficiency may inadvertently lead to higher overall consumption and emissions. The long-run relationship between renewable energy consumption (LnREC) and CO_2 emissions is somewhat concerning, as the results show that increased renewable energy consumption is positively associated with CO_2 emissions in both FMOLS and DOLS models. This suggests that while renewable energy consumption is a crucial step toward decarbonising energy systems, it may not yet be sufficient to substitute fossil fuels in BRICS countries, especially where renewable energy is being added on top of a growing overall energy demand rather than replacing fossil energy sources. This finding indicates that the pace of renewable energy adoption and the integration of renewables into the energy mix are still in their early stages and may not yet have a large enough impact to drive significant reductions in CO_2 emissions. The results also suggest that technological innovation and economic growth are linked with carbon emissions through a feedback loop, where growth drives energy consumption, and innovation boosts production but may increase emissions before leading to cleaner technologies and solutions. These dynamic underscores the challenge of balancing economic expansion with environmental goals in the BRICS economies, highlighting the need for targeted policy interventions aimed at reducing emissions while promoting economic growth. In terms of policy implications, the study suggests that while economic growth can potentially decouple from carbon emissions in the long run, technological innovation and renewable energy adoption must be significantly accelerated. The positive relationship between technological innovation and CO_2 emissions emphasizes the need for innovation that is specifically targeted at cleaner technologies, energy efficiency, and carbon capture to reduce emissions effectively. Policymakers in BRICS countries should focus on fostering green technological innovation while simultaneously incentivizing renewable energy adoption to ensure a low-carbon future. Moreover, the findings suggest that BRICS economies should implement comprehensive strategies that promote sustainable growth by focusing on energy efficiency, renewable energy infrastructure, and carbon pricing mechanisms to meet global climate targets and achieve Sustainable Development Goal 13 (Climate Action). The long-run results from FMOLS and DOLS models provide robust evidence that while BRICS nations are experiencing growth, the relationship between growth, energy consumption, and emissions is complex. The integration of clean technologies, the scaling of renewable energy, and energy-efficient innovations will be crucial in ensuring that the BRICS economies can achieve a sustainable and low-carbon future in line with their growth objectives and international climate commitments.

Table 10 presents the empirical estimation results, highlighting the panel causality test between carbon emissions, economic growth, renewable energy consumption, and technological innovation across the BRICS economies. The results from the Panel Causality Test suggest several important relationships between renewable energy, CO_2 emissions, economic output (GDP), and technological development. First, there is bidirectional feedback between renewable energy consumption (REC) and CO_2

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emissions. This indicates that renewable energy can reduce CO_2 emissions, while high CO_2 emissions may push for greater renewable energy adoption. Similarly, a bidirectional relationship exists between technological innovation (TEC) and CO_2 emissions, meaning that advancements in technology can reduce emissions, and increasing emissions may drive the need for more efficient or clean technologies.

Table 9. Long run robustness check using FMOLS and DOLS result

Dependent variables CO_2			Independent variables REC	
Variables	FMOLS	DOLS	FMOLS	DOLS
LnrGDP	-0.024^{**} (0.113) [3.624]	-0.011 $(0.114)^{**}$ [3.415]	-0.024^{**} (0.028) [3.367]	-0.026 $(0.026)^{**}$ [3.328]
LnrTEC	0.168^{***} (0.000) [11.208]	0.162^{***} (0.000) [7.816]	0.162^{***} (0.000) [11.068]	0.148^{***} (0.000) [8.728]
Lnr CO_2			0.0202^{***} (0.000) [9.052]	0.288^{***} (0.000) [8.286]
R^2	0.92	0.96	0.95	0.98
LR Variance	0.039	0.016	0.037	0.017
N	165	165	165	165

***, **, and * denote statistical significance at the 1%, 5%, and 10% levels, respectively. Figures in parentheses represent p-values, while values in square brackets denote t-statistics

Table 10. Pannel causality test results

H_o	W- Stat	Z-stat	P value	Decision
REC → CO_2	3.302 ***	2.213***	0.028	Bidirectional feedback
CO_2 → REC	5.406 ***	6.618***	0.000	
GDP→ CO_2	1.624	1.212	0.162	Unidirectional
CO_2 → GDP	6.330***	8.632***	0.000	
TEC → CO_2	6.047***	8.062***	0.000	Bidirectional feedback
CO_2 → TEC	8.432***	11.000***	0.000	
REC → GDP	3.094	1.802	0.062	Unidirectional
GDP → REC	3.743***	3.168***	0.000	
GDP → TEC	7.001***	11.123***	0.000	Unidirectional
TEC → GDP	3.013	1.635	0.103	
REC → TEC	5.301***	6.351***	0.000	Unidirectional
TEC → REC	5.673***	2.018***	0.003	

***, **, and * denote statistical significance at the 1%, 5%, and 10% levels, respectively

In terms of unidirectional causality, CO_2 emissions are found to influence GDP, implying that higher emissions may negatively impact economic growth, potentially due to environmental damage or regulatory responses. On the other hand, GDP seems to drive both renewable energy consumption and technological development, suggesting that growing economies tend to invest more in renewable energy and innovation. Moreover, renewable energy consumption is found to foster technological development, indicating

that as renewable energy adoption increases, there is likely more focus on advancing energy-efficient technologies.

The findings emphasize the interconnectedness of economic growth, technological innovation, and environmental outcomes. Policymakers should consider how economic development and technological advancements can be leveraged to promote sustainable energy practices and reduce CO_2 emissions. The data highlights the critical role that both renewable energy adoption and technological innovation play in achieving long-term environmental and economic sustainability.

Discussion of findings

This study examined the long-run and dynamic relationships among carbon dioxide (CO_2) emissions, renewable energy consumption (REC), economic growth (GDP), and technological innovation (TEC) in the BRICS economies. By integrating FMOLS, DOLS, PARDL, and causality analyses, the findings provide nuanced evidence on how growth, energy transition, and innovation interact in emerging economies. The discussion below interprets these findings in light of existing empirical literature, structured around the same thematic areas as previously presented.

Economic growth, CO_2 emissions, and the environmental Kuznets curve

The empirical results reveal a negative long-run relationship between economic growth and CO_2 emissions, lending support to the Environmental Kuznets Curve (EKC) hypothesis within the BRICS context. This outcome suggests that, beyond a certain income threshold, economic expansion is associated with declining emissions intensity due to structural transformation, technological upgrading, and improved environmental regulation. Similar evidence has been documented for BRICS and other emerging economies by Wang et al. (2025), Dou et al. (2025), Hasan (2023), Audi et al. (2023), Caporin et al. (2024), and Mehta and Shah (2024), all of whom report non-linear income–emissions relationships using panel cointegration and advanced estimators.

However, the finding also aligns with studies that caution against interpreting EKC outcomes as automatic or uniform across countries. For instance, Erkılıç et al. (2025) and Shekhawat et al. (2025) show that the turning point of the EKC depends strongly on governance quality, globalization, and energy structure. In this sense, the BRICS results reflect conditional decoupling, where economic growth contributes to emissions reduction only when accompanied by cleaner technologies, regulatory enforcement, and a gradual shift away from fossil fuels. This interpretation is consistent with the Green Growth literature, which argues that growth-led environmental improvements are policy-mediated rather than income-driven alone.

Technological innovation and the rebound effect on emissions

Contrary to conventional expectations, technological innovation exhibits a positive and statistically significant relationship with CO_2 emissions in the long run. This result suggests the presence of a rebound or scale effect, whereby efficiency gains and technological advancement initially stimulate higher production and energy demand, leading to increased emissions. Similar outcomes have been reported by Mehta et al. (2024), Sadiq et al. (2024), and Zhang et al. (2024), who find that innovation in emerging economies often remains energy-intensive in its early stages.

Empirical studies using panel VAR and dynamic models further support this interpretation. Anser et al. (2024) and Mngumi et al. (2024) demonstrate bidirectional causality between technological innovation and emissions, indicating that innovation both responds to and contributes to environmental pressure. In the BRICS context, innovation activities are heavily concentrated in manufacturing, infrastructure, and extractive industries, which may explain why technological progress initially exacerbates emissions before cleaner technologies diffuse more widely. This finding aligns with Dilanchiev et al. (2023) and Liu (2024), Wang et al. (2025a), Dou et al. (2025), who argue that without targeted green innovation policies, technological advancement alone may not deliver immediate environmental benefits.

Renewable energy consumption and its paradoxical emissions effect

The analysis finds a positive long-run association between renewable energy consumption and CO_2 emissions, suggesting that renewable deployment in BRICS economies has not yet translated into effective emissions reduction. This result is consistent with the "addition rather than substitution" argument advanced by Caporin et al. (2024), Li et al. (2024), and Balsalobre-Lorente et al. (2023), Wang et al. (2025b), Dou et al. (2025), Osabohien et al. (2025 a, b) who show that renewables in emerging economies are often layered onto expanding energy systems instead of replacing fossil fuel capacity.

Several studies corroborate this interpretation. Shekhawat et al. (2025) and Erkılıç et al. (2025) report that renewable energy reduces emissions only when accompanied by fossil fuel phase-out, grid integration, and supportive institutional frameworks. Similarly, Yadav et al. (2024) highlight that governance effectiveness and green finance significantly condition the emissions-reducing impact of renewables. In the absence of these complementary factors, rising energy demand driven by industrialisation can offset the decarbonisation potential of renewable energy. Thus, the BRICS evidence reflects an incomplete energy transition, where renewable expansion has yet to reach the scale required for net emissions reduction.

While Brazil stands out among the BRICS economies for its relatively high share of renewable energy in total final energy consumption, this experience is not uniformly replicated across the group. Brazil's renewable energy profile is largely driven by long-standing investments in hydropower, complemented more recently by bioenergy, wind, and solar sources. This places Brazil closer to several advanced and upper-middle-income economies with diversified renewable portfolios, where renewables contribute substantially to electricity generation and energy security.

In contrast, China and India, despite rapid expansion of renewable energy capacity over the past two decades, continue to exhibit lower renewable shares relative to total energy demand due to the scale of their industrial sectors and persistent reliance on coal. In these countries, renewable energy deployment has largely occurred alongside rising fossil fuel consumption, reflecting an expansionary rather than substitutive energy transition. Russia and South Africa display even lower renewable energy penetration, with energy systems dominated by fossil fuels, particularly natural gas in Russia and coal in South Africa, and comparatively slower diversification toward renewables.

International context

From an international perspective, this heterogeneity mirrors broader global patterns in which renewable energy adoption is shaped not only by policy ambition but also by

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historical energy endowments, industrial structure, and grid capacity. Countries with early investments in large-scale renewables, such as hydropower-based systems, tend to exhibit higher renewable shares, whereas late adopters face transitional challenges associated with infrastructure lock-in and growing energy demand. Accordingly, Brazil's relatively favourable renewable energy position should be interpreted as the outcome of structural and historical advantages rather than as evidence of a completed low-carbon transition. This cross-country variation provides important context for understanding why increased renewable energy consumption in the BRICS has not yet translated into uniform reductions in carbon emissions.

Feedback mechanisms among growth, innovation, and emissions

The panel causality results reveal complex feedback relationships among economic growth, technological innovation, renewable energy, and CO_2 emissions. Bidirectional causality between REC and CO_2, as well as between TEC and CO_2, indicates mutual reinforcement between environmental pressure and policy or technological responses. These findings are consistent with Anser et al. (2024), Mngumi et al. (2024), and Sezgin et al. (2024), who document similar feedback loops in BRICS and other emerging economies.

The unidirectional causality from GDP to renewable energy and technological innovation further suggests that economic expansion creates the fiscal and institutional capacity for clean energy investment and innovation. This aligns with evidence from Kaya et al. (2024) and Hlongwane and Khobai (2024), who show that income growth facilitates renewable deployment and innovation, albeit with time lags. At the same time, the causality from emissions to innovation underscores the role of environmental stress as a driver of technological adaptation, reinforcing the argument that climate challenges can stimulate innovation under appropriate policy conditions.

Policy implications in the context of sustainable development goals

Taken together, the findings underscore the interconnected nature of SDG 7 (Affordable and Clean Energy), SDG 8 (Decent Work and Economic Growth), and SDG 13 (Climate Action). Consistent with Osabohien et al. (2024, 2025a, b) Sadiq et al. (2024), and Zhang et al. (2024), the results suggest that achieving sustainable growth in BRICS requires coordinated policies that integrate renewable energy expansion, green technological innovation, and emissions regulation. Carbon pricing, green finance instruments, and fossil fuel subsidy reforms emerge as critical tools for accelerating substitution rather than addition effects in the energy mix.

Also, the persistence of rebound effects and incomplete decoupling highlights the need for targeted innovation policies that prioritise clean technologies, energy efficiency, and grid flexibility. Without such alignment, economic growth and innovation may continue to exert upward pressure on emissions, undermining progress toward climate goals.

The findings support the need for targeted policies that balance economic expansion with environmental goals, fostering green innovation, energy efficiency, and a transition towards low-carbon energy systems. These efforts are essential for BRICS countries to align their growth trajectories with the global climate agenda and the Sustainable Development Goals.

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Conclusions and recommendations

This study delves into the intricate relationship between energy consumption, carbon emissions, and economic growth in the BRICS nations, revealing the complexities of balancing development with sustainability. The findings indicate that while there is potential for economic growth to decouple from emissions in the long run, the current trajectory in BRICS countries suggests a need for accelerated technological innovation and renewable energy adoption. Specifically, the long-term analysis using FMOLS and DOLS estimators provides robust evidence supporting the Environmental Kuznets Curve (EKC) hypothesis, showing that as these nations grow, they may gradually reduce carbon intensity through cleaner technologies and energy efficiency improvements. However, the positive relationship between technological innovation and emissions points to the need for policies focused on clean innovation, particularly in sectors such as energy and industrial processes, to avoid the rebound effect where efficiency gains inadvertently increase overall consumption.

Moreover, the positive association between renewable energy consumption and CO_2 emissions underlines the challenge of replacing fossil fuels with renewables in the face of increasing energy demand. This suggests that BRICS economies need to focus on scaling renewable energy infrastructure, improving energy storage, and ensuring that renewable energy sources replace, rather than just add to, existing fossil fuel capacity.

From a policy perspective, the following recommendations are crucial for achieving sustainable development in the BRICS countries:

Green Technological Innovation: Policymakers should prioritize innovations that target carbon capture, energy efficiency, and the scaling of renewable energy technologies. This aligns with SDG 9 (Industry, Innovation, and Infrastructure) and SDG 13 (Climate Action). By fostering a robust green innovation ecosystem, BRICS can reduce emissions and transition toward cleaner growth.

Accelerated Renewable Energy Integration: The study highlights that renewable energy consumption alone is not sufficient to reduce emissions at the current pace. Therefore, BRICS nations must ramp up efforts to integrate renewable energy into their grids, alongside expanding energy storage and distribution infrastructure. This would help meet SDG 7 (Affordable and Clean Energy) and SDG 13.

Decoupling Economic Growth from Emissions: To foster economic growth while reducing carbon intensity, targeted policies should focus on increasing energy efficiency across industries, promoting green industrialization, and incentivizing cleaner technologies. This supports SDG 8 (Decent Work and Economic Growth) and ensures that growth does not come at the expense of environmental sustainability.

Carbon Pricing and Financial Mechanisms: Introducing carbon pricing mechanisms can internalize the environmental costs of carbon emissions and incentivize investment in low-carbon technologies. Financial policies, such as green finance and carbon markets, will be crucial to ensuring a sustainable energy transition.

Enhanced Policy Coordination: Given the feedback loops between technological innovation, economic growth, and emissions, policies should be coordinated across sectors to ensure that technological and economic development goes hand-in-hand with environmental sustainability. This includes strengthening international cooperation to share technology and best practices, which will be essential in helping BRICS nations meet their climate commitments.

In conclusion, while BRICS countries face significant challenges in managing their energy transitions, the integration of renewable energy, technological innovation, and

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green policies will be crucial to achieving a low-carbon future. With targeted interventions, these economies can realize growth while contributing meaningfully to global climate action goals.

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